The Neogene and Quaternary: chronostratigraphic compromise or Non-overlapping Magisteria?

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Abstract

The International Commission on Stratigraphy (ICS) and its Subcommission on Neogene Stratigraphy (SNS) and Subcommisson on Quaternary Stratigraphy (SQS) are facing a persistent conundrum regarding the status of the Quaternary, and the implications for the Neogene System/Period and the Pleistocene Series/Epoch. The SQS, in seeking a formal role for the Quaternary in the standard time scale, has put forward reasons not only to redefine and truncate Neogene to accommodate this unit as a third System/Period for the Cenozoic, but furthermore to shift the base of the Pleistocene to c. 2.6 Ma to conform to a new appreciation of when Quaternary climates begin. The authors, as members of SNS, support the well-established concept of a Neogene extending to the Recent, as well as the integrity of the Pleistocene according to its classical meaning, and have published on the theoretical and pragmatic arguments for workable options that avoid this conflict. In this paper, we return to the basic principles that result from the conversion of the essentially marine biostratigraphic/biochronologic units of Lyell and other 19th Century stratigraphers into the modern hierarchical arrangement of chronostratigraphic units by the *stage boundary stratotype* (GSSP) formulation. As one consequence, in that the Quaternary is a conceptually different entity from the Lyellian units, a Neogene-Quaternary boundary may be a *non sequitur.* Secondly, as to retaining the base of the Pleistocene at 1.8 Ma, these basic hierarchical principles dictate that changing the boundary of any non-fundamental “higher” chronostratigraphic unit is not possible without moving the boundary of its constituent fundamental unit. Therefore, to move the base of the Pleistocene from the Calabrian GSSP at 1.8 Ma to the Gelasian GSSP at 2.6 Ma requires action to formally redefine the Pleistocene. Above all, it is important to

distinguish between biostratigraphy and chronostratigraphy. Both are based on the fossil record, but biostratigraphic units are created to subdivide and correlate stratigraphic sequences. The units of chronostratigraphy, however, reflect the history of life through geological time. With this in mind, it is notable that the sharp intensification of climate cycles during the latter half of the Cenozoic, from 23 Ma to the present, is not accompanied by a corresponding acceleration of phyletic changes. The persistence of a characteristic biota in the face of these environmental pressures argues strongly for the concept of an extended Neogene.

We can envisage several ways to accommodate the Quaternary in the standard time scale while preserving the original concepts of the Neogene and Pleistocene. The option presently recommended by SNS, and most compatible with the SQS position, is to denominate the Quaternary as a subperiod/subsystem of the Neogene, decoupled from the Pleistocene so that its base can be defined by the Gelasian GSSP at c. 2.6 Ma. A second option is to retain strict hierarchy by restricting a Quaternary subperiod to the limits of the Pleisticene at 1.8 Ma. As a third option, the Quaternary could be a subera/suberathem or a supersystem/superperiod, decoupled from the Neogene and thus with its base free to coincide with a convenient marker such as the base of the Pleistocene at 1.8 Ma, or to the Gelasian at 2.6 Ma, as paleoclimatic opinion dictates. If no compromise can be reached, however, an alternative might be to consider Quaternary and Neogene as mutually exclusive categories (climatostratigraphic vs. chronostratigraphic) in historical geology. In this case, we would recommend the application of the principle of NOMA, or non-overlapping Magisteria, in the sense of the elegant essay by the late Stephen J. Gould (1999) on the mutually exclusive categories of Religion and Science. In this case the

Quaternary would have its own independent status as a Climatostratigraphic unit with its own subdivisions based on climatic criteria.

Introduction

The tide of protests that arose as the International Commission on Stratigraphy (ICS) omitted the "Quaternary" from the latest incarnation of the Chronostratigraphic Scale (Gradstein et al., 2004), forced the "Neogene community" – principally researchers in marine stratigraphy, but also a significant number of nonmarine workers – to reconsider a position that has been taken for granted for over 40 years, *i.e.*, that the Neogene extends to the present. The final 2.6 my would be considered as an interval of Earth history so dramatically distinct that it should itself constitute a separate Quaternary period (e.g., Gibbard et al., 2005; Bowen and Gibbard, 2007; Head et al., 2008). This is to return to the same strident, seemingly endless debate about the meaning of the "ice ages" that consumed the profession for more than a century up to the establishment of the Pleistocene GSSP at Vrica (cf. Berggren and Van Couvering, 1978; Van Couvering, 1997), but now one in which the division of the Cenozoic itself is at stake. Far from being restricted to two subcommissions of the ICS, the Neogene-Quaternary controversy represents an important debate that concerns the stratigraphic community at large because it brings into question the very fundamental concept of chronostratigraphy and its principles.

Papers about the controversy have either been devoted to justifying the formal use of the term Quaternary (Head et al., 2008; Ogg and Pillans, 2008; and citations therein), to defending the original concept of a Neogene Period that extends to the Present (Berggren, 1998; Hilgen et al., 2008; Lourens, 2008; McGowran et al., in review; and references therein) or to explore solutions to the problem (e.g., Pillans and Naish, 2004; Aubry et al., 2005; Walsh, 2006, 2008). An essential aspect of Earth history has been neglected in these discussions: namely, the role that biotic history plays in the temporal subdivision of the geological record, and in particular its role in the delineation of the Neogene Period. The objective of this paper is to demonstrate that there was no major break in the evolutionary history of life in the past 23 my, that would justify a three-fold subdivision of the Cenozoic era at the period level. Prior to this however, it is necessary to clarify an often-misunderstood relationship between chronostratigraphy and stratigraphic correlation, and in particular biostratigraphy. We first review briefly the content of the Neogene-Quaternary controversy.

The Neogene-Quaternary controversy: a brief overview

The position of the SQS in the Neogene-Quaternary debate is straightforward, inflexible, and exclusive. The SQS requests the formalization of a *Quaternary Period* to recognize what it sees to be an exceptional phase of global history. Continental sedimentary deposits of the last 2.6 my distinctly reflect an intensification of climate cycles superimposed on the general cooling trend in the Cenozoic, that resulted in the periodic development of continental ice sheets in the Northern Hemisphere. For instance, the earliest deposition of glacially-derived Chinese loess across northern China constitutes a prominent—and mappable—lithostratigraphic record of the beginning of this new phase. The appearance of new elements in the continental fauna, including the genus *Homo,* has also been linked (whether casually or coincidentally) to this shift in climate. As a consequence, in the view of SQS, the base of the Pleistocene Series should be lowered to coincide with the new consensus on the beginning of "Quaternary conditions", using the Global Standard Stratotype-section and Point (GSSP) for the Gelasian Stage at San Nicola (Rio et al., 1998). Division of the Cenozoic Erathem would thus be tripartite (as has often been accepted in the past, and still is by some, e.g., Cita, 2008), and, in an unprecedented move, the Quaternary would include stratigraphic units that have *always* been included in the Neogene System and Pliocene Series.

The position of the SNS is also straightforward, but more flexible and inclusive. For reasons that are historical (original definition of the Neogene by Hörnes, 1853), methodological (astrochronological calibration of the stratigraphic record to refine the numerical time scale) and rational (the first Northern Hemisphere continental ice sheets, whatever their local impact, represents little more than a slight intensification of the cooling that began in the late Eocene), the SNS holds the view that the Cenozoic Erathem/Era comprises only two systems/periods—Paleogene and Neogene—and the Pleistocene Series must remain tied to the Calabrian Stage (Berggren, 1998; Aubry et al., 2005; Hilgen et al., 2008; Lourens, 2008; McGowran et al., in review). This position has also been found acceptable to some members of the Quaternary community (Pillans et Naish, 2004). In accordance with the rules of chronostratigraphy, in which series are defined by their lowest stage, the base of the Calabian Stage and the Pleistocene Series were simultaneously formalized by the GSSP at Vrica (Van Couvering, 1997; see review in Aubry et al., 1999). The recent proposal of a unit-stratotype of the Calabrian Stage at Vrica (Cita et al., 2006, 2008) further enforces the role of the base of the Calabrian Stage in fixing the base of the Pleistocene Series.

Although uncompromising with regard to the limits of the Neogene, the SNS has offered several possible solutions to the Neogene-Quaternary controversy that are *inclusive solutions* allowing both communities to conduct their research within a sound, formal chronostratigraphic framework (Fig. 1).

The concept of an extended Neogene is supported by a majority of earth scientists working in the marine realm, whether paleontologists, stratigraphers, or paleoceanographers, as well as by a substantial number of (terrestrial) vertebrate paleontologists. On the other hand, while the concept of a formal Quaternary System is widely supported (cf. Open Meeting on the Neogene-Quaternary, at the 33 IGC, Oslo, 9 August 2008) there is some disagreement among these supporters as to the appropriate location and status of its base. This may be due to the fact that the formal definition of the Pleistocene in the GSSP of the Calabrian Stage at Vrica was set forth by IGCP 41, which was created to carry out the resolution adopted at the 1948 London IGC to establish a physical reference point for the base of the Pleistocene which would also mark the beginning of the Quaternary (Van Couvering, 1997). Accordingly, a number of the organizations that support formalization of the Quaternary, such as the Austrian Geological Survey and the United States Geological Survey, and the national stratigraphic committees of Austria (P. Smolka, personal communication, August 2008), Italy (G. B., Vai, personal communication, August 2008), Russia (Y. Gladenkov, personal communication, August 2008), as well as the North American Commission on Stratigraphic Nomenclature (NACSN), accept the IGCP 41 determination. The conflicting proposal by SQS is based on the fact that is has become possible to recognize the earliest signs of the present *Glacial Age* further back in time (see Hilgen et al., 2008, fig. 2). The basic premise of the SQS is that the Quaternary deserves special recognition. Some see it as a grand conceptual "Age" compared to the Tertiary "Age of Mammals", the Mesozoic "Age of Reptiles" and the Paleozoic "Age of Fishes", but whether as an "Age of Man" or "Age of Ice" is not agreed. In actual practice, however, the Quaternary is distinct, in the minds of most geologists, not in the time sense but in its medieval sense as the fourth stage of lithification, in which unconsolidated deposits are automatically mapped as "Qt" and "Qal".

The role of marine biostratigraphy in global chronostratigraphy

Although the late Stephen Walsh wavered on the status of the Quaternary in chronostratigraphy (compare Walsh, 2006 and 2008), his analysis of the concept "Neogene" provided the SQS with documentation that appeared to reinforce the legitimacy of its request. Walsh's argument (2008) revolves around two propositions. One is that Bronn's intent in introducing the Neogene was ambiguous. The other is that marine biostratigraphy has overextended its "monopoly" in the matter of chronostratigraphy. In Walsh's opinion there is no reason that climatic criteria cannot play a decisive role in the *definition* of chronostratigraphic units. The first proposition is dealt with in McGowran et al. (2008) who reaffirmed the continuity of the Neogene extending to the present, while clarifying a common confusion between the hierarchical model in taxonomy and that in chronostratigraphy. Walsh's far-reaching second proposition requires scrutiny here, even though one might have hoped that the long years of discussion on this subject would have already sufficed to clarify the role of paleontology in Earth Sciences.

Principles of an historical geology

The time had to be right for stratigraphy, that quintessentially historical science, to flourish. For long years Nicolaus Steno's 17th-century principles of rock relationships (1669) languished without meaningful application or even discussion. Robert Hooke who (1705) speculated that one might erect a chronology based on the fossils in strata, may have been the first of several who glimpsed this association during the 18th-century. Among them was the prolific lateral thinker Johann Wolfgang von Goethe, who (1782) wrote in a letter to his friend Merck: "*Es wird bald die Zeit kommen wo man Versteinerungen nicht mehr durcheinanderwerfen, sondern verhältnismäßig zu den Epochen der Welt rangieren wird* [The time will soon come when one will not mix up fossils, but order them to the Epochs of the world]'. The time, in fact, had already arrived. While many emphasize the significance of the "deep time" theory of James Hutton vis-à-vis the "deep space" theory of William Herschel (Holmes, 2008), an appreciation of the duration of geological time was indeed by then commonplace in Europe (Rudwick, 2005). Likewise, credit is widely given to William Smith for the careful use of fossils to identify stratigraphic units, but Georges Cuvier and Alexandre Brongniart soon went beyond Smith in reconstructing an alternation of marine and freshwater environments from evidence of molluscan assemblages and (thence) a *geohistory* of the Paris region: “They reconstructed a complex story in which the seas had alternated in the deep past with freshwater lakes or lagoons: it was a geohistory as unpredictable and contingent as the turbulent politics they had both lived through in the past two decades” (Rudwick, 2005, p. 648).

The study of fossils in sedimentary strata was absolutely central to the interpretation of earth history (Laudan, 1987; McGowran, 2005; Rudwick, 2005). Fossils could be grouped in specific assemblages, each assemblage characteristic of correlative strata, i.e., strata thus deposited during the same interval of time and following above and after the previous. Rudwick (2008) describes the emerging realization that successional fossil assemblages of molluscs, first two, then three, could be distinguished in the various sedimentary basins of the European marine “Tertiary”. The agreed departure point was the assemblages from the Paris Basin, painstakingly described in the great malacological school in Paris and especially by Gérard-Paul Deshayes. This systematic paleontology was then exploited by Lyell (1830-1833) to subdivide the “Tertiary” record into series and epochs (Fig. 2).

Our Cenozoic chronostratigraphic framework is directly inherited from Lyell’s biochronologic framework, expanded to include the Paleocene and Oligocene by Schimper (1873) and Beyrich (1854), respectively, and with a somewhat profound conceptual shift, as explained below. The periods Paleogene and Neogene were also introduced as biochronologic units (Hörnes, 1853; Naumann, 1866; see Berggren and Van Couvering, 1978), and so too were the three eras of the Phanerozoic (Phillips, 1840) (Fig. 2). There is thus no question that biostratigraphy/biochronology was utterly paramount in the establishment of a relative chronology and time scale of Earth history. Geo-historicism emerged from 18th-century neptunism but the standard lithological succession (Arduino, 1760) collapsed. It is also interesting and important that the successional, non-iterative history of life could be used to build the time scale without an acceptable theory of speciation to match the fact of extinction established by Cuvier in the 1790s. Indeed, Philips himself could not accept Darwin's theory of the *Origin of species* (Darwin, 1859; Phillips, 1861), and even Lyell did not embrace it immediately (Gould, 1987).

Establishing chronostratigraphy

Following upon the discussions of the late 19th and early 20th-centuries regarding the reliability of paleontologic groups for correct age assignment, Hedberg (1948) envisioned a new method of relative dating, based on the rock strata themselves, divided into stages. Chronostratigraphy would constitute an independent means of relative chronology. Strata themselves would be grouped in packages holding the key to relative time (see review in Aubry et al., 1999). It took several decades of engaging discussions for Hedberg's vision to become accepted, but ultimately the concepts of unit- and boundary-stratotypes were born (Hedberg ed., 1976). The change was radical, and would establish chronostratigraphy as an independent science because the criteria for definition and for correlation would be different. In other words, the means of correlation would differ from the definition itself. The introduction of GSSPs with rules for chronostratigraphic procedures (Cowie, 1986; Cowie et al., 1986; Remane et al., 1996) would further characterize a now formalized chronostratigraphy.

The conventional acceptance of boundary stratotypes and the subsequent formal definition of GSSPs for the base of stages have ensured the conversion of biochronological units (the original epochs of Lyell, Beyrich and Schimper; the periods of Hörnes, the era of Philips) into chronostratigraphic units (the epochs, periods and eras of the modern time scales, beginning with Berggren, 1971, 1972) (Fig. 3). The choice of stages and their hierarchical grouping into series/epochs, then into systems/periods, and ultimately into erathem/era is a matter of convention, as part of the framework category of Harland (1973, 1975; see McGowran and Li, 2007), although the strata included in each category would be as respectful as possible of the historical definition. In these circumstances, how could there be, for anyone who clearly understands the purpose of chronostratigraphy, a "desire to establish *a monopoly for marine biochronology in the definition* of standard global chronostratigraphic boundaries" as Walsh (2008, p. 42; emphasis in the original text) writes? Chronostratigraphy—the relative dating of rocks based on selected stratigraphic horizons and units— can only be chronostratigraphy. There cannot be a biochronostratigraphy, a magnetochronostratigraphy, a cryochronostratigraphy, a climatochronostratigraphy; for definitions in chronostratigraphy are independent of fossils, magnetic reversals, isotopic signatures. The introduction of rules in chronostratigraphy has another significant implication: the resolution of current chronostratigraphic problems can only be dealt with regard to these rules. In the case of the Neogene-Quaternary controversy, reference to the recommendation made at the IGC in London in 1948 (to equate the Pliocene/Pleistocene boundary with the Tertiary/Quaternary boundary but apparently not with the top of the Neogene) is less than relevant; therefore the ambiguity of the text of this decision and its varied interpretation (see Hilgen et al., 2008) play no role in the Neogene-Quaternary argument.

Correlation of chronostratigraphic boundaries

Chronostratigraphy, on the other hand, relies on various stratigraphic means for the purpose of correlation. The role of biostratigraphy in this endeavor is foremost, particularly in the Paleozoic and Mesozoic (http://www.stratigraphy.org/). But magnetic reversals and isotopic signatures are also successfully used. Fundamental here is the weight given to these latter two criteria, in particular to isotope signals. Several large amplitude, negative or positive, short-term shifts of $\delta^{13}C$ or $\delta^{18}O$ are now used as primary means of chronostratigraphic correlation (e.g., distinctive pattern of ^{13}C variations associated with the base of the Ediacaran System [Knoll et al., 2004]; 3-4‰ $\delta^{13}C$ shift at the Paleocene/Eocene epochal boundary [Aubry et al., 2007]; 1-2‰ $\delta^{18}O$ shift Mi3b at the base of the Serravallian Stage [Hilgen et al., 2008]). These isotopic signals are used *only* because of their characteristic signature in the stratigraphic record. Their significance as proxies for paleoceanographic/paleoclimatologic history is wholly irrelevant to chronostratigraphy. With regard to the correlation of the base of a Quaternary at 2.6 Ma, marine isotopic stage 103 is used simply as a geochemical event, regardless of its significance as a marker of intensification of glacial conditions. If it should be shown that a chemostratigraphic signal used for chronostratigraphic purpose has been incorrectly interpreted in the reconstruction of Earth history this would have no consequence for chronostratigraphic correlations although the consequences may be enormous with regard to interpreting the dynamics of the Earth system. In chronostratigraphy, a magnetic reversal or an isotopic event is of value only if it can serve for global recognition of a specific horizon in marine and terrestrial stratigraphies. This horizon marks a specific moment in time, irrelevant of what happened on Earth at this time other than the deposition of this horizon.

Even when non-paleontologic criteria are primary markers of chronostratigraphic horizons, biostratigraphic involvement is required (Fig. 4). Organic evolution is an ordinal phenomenon that provides a unique signal in stratigraphic correlation. With the exception of radioisotopic and biotic chronology, all other aspects of Earth history are iterative, including glacial climates (see also McGowran et al., 2008). Whereas associations/denominations such as the Age of Fishes with the Paleozoic Era can be somehow justified, there is no such thing as *the Ice Ages*, because ice ages have occurred repeatedly throughout Earth history (the Proterozoic snowball Earth [Kirschvink, 1992; Hoffman et al., 1998; Crowell, 1999]; the Ordovician widespread Glaciation [Crowell, 1999]; the early Oligocene southern hemisphere glaciation which initiated the 'ice-house mode' of the Neogene [Miller et al., 1991; Coxall et al., 2005]). Additionally, the beginning and termination of "ice ages" are difficult to delineate since climatic changes are incremental. Major northern hemisphere ice-sheets can be dated at ~3 Ma. Ice rafting is seen in the north Atlantic off Greenland back to 7 Ma, and recent modeling studies have shown that intermittent ice-sheets may have been present in the northern polar regions as far back as 25 Ma (DeConto et al., 2008); and indeed ice-rafting has recently been depicted off Greenland in the middle Eocene at ~44 Ma (Tripati et al., 2008).

In summary, biochronology has been a major player in the conceptualization of the larger divisions of Earth history. Because of its ordinal character, the evolution of life is the most conspicuous and accessible means of characterizing large intervals of time. Biochronology does not rule chronostratigraphy. It assists, directly and indirectly, with the correlation of chronostratigraphic horizons and units.

Should Pleistocene and Quaternary be equated with a common base at 2.6 Ma?

Ever since Forbes (1846) equated the Pleistocene with the "Ice Ages", the Quaternary community has equated the Quaternary with the Pleistocene (plus Holocene). Accordingly, the SQS requests that the base of the Pleistocene Series be lowered in concert with the pragmatic lowering of the base of the Quaternary (at this time so as to encompass as many glacial deposits as possible, and also include the oldest Chinese Loess units; see Hilgen et al., 2008, fig. 2).

In the light of the above discussion, the answer to this request can only be an unequivoval "no". The two units were originally introduced on different conceptual grounds (Fig. 2). The linkage of the *base* of the Pleistocene Series to the *base* of the Calabrian Stage has converted a biochronologic unit (the Pleistocene of Lyell) into a chronostratigraphic one (the GSSP-defined Pleistocene, Aguirre and Pasini, 1985, and Calabrian, Van Couvering, 1997). This conversion was officially ratified by the IUGS, at the International Geological Congress in Moscow, 1984.

We see no reason to change the terms of this conversion that was effectuated in full historical respect of original age assignment. The stratigraphic units and their fossils that were intended to characterize the Pleistocene and Pliocene biochronologic divisions of Lyell are now unambiguously and soundly placed into the GSSP-defined Pliocene and Pleistocene Series/Epochs. As noted above, the definition of a unit-stratotype for the Calabrian Stage further strengthens the role of this stage in defining the Pleistocene Series: "The GSSP of the Calabrian Stage in the Vrica section corresponds to the GSSP where the Plio/Pleistocene boundary was defined and ratified (Aguire & Pasini, 1985; Bassett, 1985). This point is well constrained in terms of calcareous nannoplankton biostratigraphy, magnetostratigraphy and marine isotope stratigraphy. […] Consequently the base of the Calabrian Stage can be easily detected both in the tuned Mediterranean and extra-Mediterranean record…" (Cita et al., 2008, p. 9). It would be acceptable to slightly adjust the base of the Calabrian (with corresponding adjustment of the base of the Pleistocene) should (the unlikely) demand for better correlation arise, but an independent reassignment of the base of the Pleistocene to the base of another stage (in this case the Gelasian) is a *non-sequitur*. Such a re-assignment would simply be in flagrant contradiction of the current rules of chronostratigraphy (see also Walsh, 2006). The introduction of the Gelasian Stage does not facilitate the lowering of the base of the Pleistocene to the base of the Gelasian Stage as one might think. Because series are tied to the base of a stage, the lowering of the base of the Pleistocene would require the concomitant lowering of the base of the Calabrian Stage. This would have been possible prior to the introduction of the *Pliocene* Gelasian Stage (Rio et al., 1998). This is now impossible because the two stages would overlap.

The Pleistocene is a formal series defined by its lower stage (Calabrian), also formally defined; the formalization of two other stages (Ionian and Tarantian Stages) is anticipated for 2009 (http://www.stratigraphy.org/gssp.htm). The status of the Quaternary is ambiguous (see Cita et al., 2008), and this unit has no subdivisions ((http://www.stratigraphy.org/gssp.htm). Formal definition of the Quaternary by the base of the marine claystone that overlies sapropel bed “e” at Vrica and serves as GSSP for the base of the Pleistocene, was rejected by INQUA (1995; in Cita et al., 2008). Although Remane (2000) stated that this level defined the base of *both* the Pleistocene and the Quaternary, the issue is somewhat clouded by the fact that the ICS and INQUA have recently recommended (2007) that the Quaternary be considered “as a formal Period/System of the Cenozoic. It is the interval of oscillating climatic extremes (glacial and interglacial episodes) that was initiated at about 2.6 Ma (set equal to base of Gelasian stage), therefore it encompasses the Holocene and Pleistocene epochs and the late Pliocene” (http://www.stratigraphy.org/gssp.htm). The situation then is the following. 1) If the base of the Quaternary is formally defined by the base of the Calabrian (Remane, 2000), its base cannot be changed, for the same reasons that the base of the Pleistocene cannot be lowered. 2) If the Quaternary is informal, its introduction in the chronostratigraphic framework should be made with respect for the existing hierarchical framework. Lowering the base of the Pleistocene to fit an incongruous Neogene/Quaternary boundary as requested by the SQS would needlessly disrupt current standard chronostratigraphy. This would decrease chronostratigraphic resolution at the series level, and have a destabilizing effect on the literature. Wanting to formalize the Quaternary for mapping purpose (i.e., grouping under one formalized name all glacial deposits and their correlative) and forcing marine chronostratigraphy into this simplified scheme ignores the essence of chronostratigraphy and reflects the inability of Quaternarists to think outside of the climatic paradigm (e.g., Bowen and Gibbard, 2007).

In discussing the problem of the Quaternary and Pleistocene, several authors (including Walsh, 2008) have referred to the case of the Paleocene/Eocene boundary. To clarify any misunderstanding in using one case to attempt at resolving the other, we point out here that the two problems are unrelated. In the case of the Quaternary, the demand is on changing the concept of a formalized series, by disconnecting it from its defining lower stage. In the case of the Eocene, the demand is on introducing a new stage name in the chronostratigraphic hagiography to which to tie the GSSP of the Eocene Series (Aubry et al., 2003). The Ypresian Stage is regionally well defined in northwestern Europe where its base in outcrops is substantially younger than the base of the GSSP-defined Eocene (Aubry and Berggren, 2001). Although introduction of the Sparnacian Stage has been recommended, the Eocene is currently defined *without* reference to a formal lower stage (Aubry et al., 2007).

Subdivision of the Cenozoic Era: Two or three periods?

We recognize two subdivisions of the Cenozoic, Paleogene and Neogene. The Paleogene includes Paleocene, Eocene and Oligocene Epoch/Series and span the interval ~66 to 23 Ma. The Neogene comprises the Miocene to the Recent, and spans the interval from 23 Ma to 0 Ma. The GSSP for the Miocene has been placed at 35 m (as measured downward) at Lemme (Steininger et al., 1997) and is denoted by the Chron $C6n.2n_{(o)}$ currently estimated at 23.03 Ma (Lourens et al., 2004). It also coincides with $\delta^{18}O$ Mi1 of Wright et al. (1992). There is no mass extinction associated with this boundary, but there are major turnovers (e.g., in molluscans, vertebrates, and protists) spanning the late Oligocene-early Miocene (Chattian-Aquitanian) interval, as life forms assume a modern aspect.

Walsh (2008, p. 61) asked: "How can we resolve the dilemma of the Neogene divide in Cenozoic chronostratigraphy? […] We must begin with challenging the central assumption […] which is the view that *marine biochronology should hold a monopoly in the determination of Phanerozoic standard global geochronologic units*". We have answered Walsh on this central assumption: Biochronology is not chronostratigraphy; but biochronology is the readily accessible means of demonstrating and organizing historical progression. It cannot be ignored in chronostratigraphic division at the higher ranks. Would it make sense to locate the boundary between the Mesozoic and Cenozoic Era at a stratigraphic level within the Chalk? We thus need to examine here the role of chronostratigraphy in describing biotic history.

Chronostratigraphy and the description of the evolution of life

We agree with Harland (1973, 1975) that chronostratigraphy is, in principle, a matter of convention in the framework category of classification, but we also recognize that it follows the logic of the 19th-century discovery of Earth history, which was based on fossils (e.g., Lyell, Hörnes, and many others) and on surfaces (the unconformities of d'Orbigny, 1849, 1851). In as much as biotic evolution is shaped, at least to some extent, by abiotic forcing, the temporal propinquity/association between short-term evolutionary changes and major disruptions of the Earth system is predictable. These cause-effect relationships were inherent to early divisions of the stratigraphic record/geological time, and are therefore incorporated in the current chronostratigraphic classification. For instance, the beginning of the Archean Eon is associated with the appearance of life (Cloud, 1987, 1988; see also Robb et al., 2004); the beginning of the Phanerozoic Eon is marked by widespread biomineralization in the Kingdom Animalia (Brazier et al., 1994, 1996); two of the largest mass extinctions of the last 542 my separate its three eras (Sepkoski, 1982; Raup and Sepkoski, 1982); the beginning of the Eocene is marked by, e.g., on land, the appearance of modern orders of mammals (e.g., Gingerich, 2001) and, in the deep sea, by the extinction of the long-lived Late Cretaceous-Paleocene *Stensioina beccariiformis* benthic foraminiferal assemblage (Thomas, 1992). The list goes on. The unprecedented advantage of this is that the history of life (and, consequently, to a large extent, Earth history) is easily described in chronostratigraphic terms, with biotic changes (mass extinctions and turnovers) associated with chronostratigraphic boundaries and evolutionary radiations occurring in the course of epochs and periods.

The propinquity of chronostratigraphic boundaries and biotic events does not imply that the chronostratigraphic hierarchy parallels the taxonomic hierarchy in any fossil group. Conceptually different (McGowran and Li, 2007; McGowran et al., 2008), taxonomic and chronostratigraphic hierarchies are also structurally independent. Thus, the second largest mass extinction (in terms of the number of taxa affected; see McGhee et al., 2004) occurred near the boundary between the Ordovician and Silurian Periods, whereas the fifth largest marks the boundary between the Mesozoic and Cenozoic eras. The Paleocene/Eocene epochal boundary was marked by evolutionary events at the order level among Eutherian mammals, whereas differences in the class Eutheria between the late Paleogene and the Neogene Periods concern families (e.g., the appearance of Bovidae, Giraffidae, and Hyaenidae in the early Miocene; Carroll., 1988).

The Neogene and its biotas

We introduce this discussion with a quote by Stanley in his textbook *Earth System History* (2009, p. 456): “Because it leads to the Present, the Neogene Period holds special interest for us. It was during the Neogene that the modern world took shape—that is, when global ecosystems arrived at their present state and prominent topographic features assumed the configurations we observe today. […] The most far-reaching biotic changes were the spread of grasses and weedy plants and the modernization of vertebrate life. Snakes, songbirds, frogs, rats, and mice expanded dramatically, and apes—and then humans— evolved […]. In general, the animals and plants that inhabit Earth today are representative of Neogene life …”. Whether we study the progression of life through the fossil record, or the origin of living faunas and floras by tracing backwards their lineages using molecular biology, a remarkable evolutionary continuum from Miocene to Recent is obvious, with groups that arose during the Miocene still undergoing an adaptive radiation (Stanley, 1990; Fig. 5).

The cascading radiation of plant and animal lineages during the Neogene appears to have been driven directly and indirectly by cooler and drier climates (Stanley, 1986, 1990) as a result of intensification of cooling and glaciation, first in the southern hemisphere (following the early Oligocene establishment of a permanent ice-cap on Antarctica), then (~7 Ma) in the northern hemisphere (Zachos et al., 2001; Miller et al., 2005), and finally the intensification of northern hemisphere glaciation at ~3 Ma (de Menocal, 1995; Lourens, 2008). Habitats changed progressively, dense forests being replaced by increasingly open habitats. Grasslands, from the (sub)tropical savannas to the Arctic tundra, are now widespread on all continents except Antarctica. Two groups of plants benefited from this habitat transformation. One group comprises the herbs of the sunflower alliance of families (including the Family Compositaceae [= Asteraceae]) which now consist of >23,000 species divided among >1,500 genera (Bremer, 1994). The family originated in the late Eocene, but diversified in the earliest Miocene (Kim et al., 2005) when its pollen became very abundant worldwide (Graham, 1996). The other group consists of the grasses (Family Graminaceae) which comprise ~10,000 species in >700 genera and occupy a greater area of the world's land surface than any other plant family (Chapman and Peat, 1992; Cheplick, 1998). Grasses and other C4 plants expanded between 9 and 6 Ma (Cerling et al., 1993; Retallack, 1997; Osborne and Beerling, 2006).

This progressive change in vegetation led to a cascade of adaptive radiations as well as extinctions among herbivorous terrestrial animals. The early Miocene radiation of *Merychippus* (~20-15 Ma) from *Parahyppus* (23 Ma), the middle Miocene radiation of *Hipparion* (15 Ma) and the evolution of *Equus* (~3.5 Ma) are well known because of an abundant fossil record (Carroll, 1988; McFadden, 1988, McFadden and Hubbert, 1988; Prothero and Schoch, (eds.), 1989; Radinsky, 1984). Less known are the Neogene radiations of the Family Passeridae (or song birds, which represent 50% of living birds, i.e. >5,000 species; Mayr, 1946; Barker et al. 2004) and of the rodents (mice and rats; ~1700 species; Carroll, 1998), which in turn led to the radiation of specialized predators, among which the largest family of snakes (Family Colubridae, the most rapidly evolving reptiles; ~1600 species; Carroll, 1988; Stanley, 1990; Shine, 1998) and the carnivorous mammals (Carroll, 1988). The history of the Felidae (cats) from an ancestor of Asian origin is entirely contained in the last 11 my (Johnson et al., 2006). Encephalisation in crown canids occurred near the Miocene/Pliocene boundary, coincident with rapid diversification and expansion throughout Eurasia (Finarelli, 2008). Our own ancestry is a Neogene one, with deep roots into the Miocene. *Sahelanthropus* (~6.5 Ma; Brunet et al., 2002) is the oldest (late Miocene) genus of the Family Hominidae, which includes also *Orrorin, Kenyanthropus,* and *Ardipithicus*, as well as the Ponginae (gibbons, gorillas, and chimpanzees) and Homininae (*Australopithecus, Paranthropus* and *Homo)*. From a broader taxonomic perspective, the record of the Hominoidea coincides almost exactly with the Neogene. *Kamoyapithecus*, the first hominoid, was recovered from strata just below the Oligocene-Miocene boundary (26 Ma) at Lothidok, a site discovered by Camille Arambourg in the Rift Valley back in the 1930s (Boschetto et al., 1992).

Modern marine vertebrates also have deep roots in the Neogene (Carroll, 1988). Marine carnivores (seals, sea-lions and walruses) have a fossil record that extends back to the latest Oligocene. They diversified during the middle and Late Miocene. The evolution and radiation of modern whales (Odontocetes and Mysticeti, tooth and balein whales, respectively) during the Neogene was triggered by changes in oceanic circulation and increased ocean productivity (Carroll, 1988, Fordyce, 1980; Prothero and Schoch, 2002).

In addition to these evolutionary radiations, Neogene morphologic trends are pronounced whether on land or in the ocean. Large herbivorous mammals show a progressive increase in hypsodonty as a result of the expansion of grasslands (Carroll, 1988). Trends towards increasing shell size span the last 23 my in the planktonic foraminifera (Schmidt et al., 2004, 2006), the diatoms (Finkel et al., 2005) and the ostracods (Hunt and Roy, 2006), whereas a parallel trend but towards decreasing size occurs in the coccolithophorids (Aubry, 2007).

No "Quaternary Period"

As briefly reviewed above, much of today's biodiversity results from evolutionary radiations that occurred during the last 23 my. Indeed, several of the taxa involved (e.g., Compositaceae, graminaceae, rodents, Passerida) are in the midst of an adaptive radiation. For the last thirty years, these taxa have been referred collectively and naturally as *Neogene*.

Introducing a 'Quaternary period' for the last 2.6 my (or the last 1.8 my) of the Neogene would obviously require a change in denomination, from 'Neogene' to 'Neogene-Quaternary', which would represent more than an inconvenience. First, truncation of the Neogene System/Period to satisfy the SQS would lead to the juxtaposition of two terms with fundamentally different connotations. The term Neogene applies well to the radiation and establishment of modern faunas and floras, but the term Quaternary is meaningless in this regard. The term Neogene has also come to be associated with the long-term climatic, paleoceanographic and tectonic history of the Earth for the last 23 my (see overview in Stanley, 2009). The term Quaternary is also meaningless in this regard, being relevant only to a short-term climatic deterioration. Second, truncation of the Neogene would suggest an evolutionary break at a 'Neogene/Quaternary boundary'. This is because by tradition, changes in diversity are associated with chronostratigraphic boundaries, as explained above. There is however no profound faunal change near 2.6 Ma. A reorganization of herbivore communities occurred in Europe around 2.6 Ma, marked by the extinction of small-sized Pliocene deer (seven species), and the immigration of *Equus*, but this occurred against a background of decreasing diversity among families of herbivorous mammals that began in the late Miocene (Brugal and Croitor, 2007). The "setting up of a modern Paleoarctic zoogeographical region in northern Eurasia" (op. cit., p. 145) is an insufficient criterion upon which to consider introduction of a chonostratigraphic unit. The late Miocene spread of grass-dominated open environments (savannahs) had a far more significant impact on the evolution of mammalian faunas than the mid-Pliocene cooling did, yet we see no reason why it should be associated with a chronostratigraphic boundary. Sequential extinctions among the calcareous plankton (Berggren et al., 1995; Aubry, 2007) and mollusks (Stanley and Campbell, 1981; Jackson et al., 1993) mark the upper Pliocene Gelasian Stage, but these are rather minor, slightly above background events.

Does the appearance of our own genus deserve recognition as a major evolutionary break justifying a formal period? It can be argued that the appearance of *Homo sapiens* in the latest Pleistocene (c. 125 Ka) has had an extraordinary impact on the global ecosystem, as well as on the terrestrial surface. It is, however, not as well realized that the earlier species assigned to this genus were neither numerous nor environmentally significant. Fossil remains of humans at the "*erectus*" grade preceding *sapiens* (i.e. *H. erectus*, *H. ergaster*, *H. antecessor*, *H. steinheimensis*, *H. neanderthalensis*, and several less well recognized taxa) are among the rarest constituents of mid-Pleistocene mammal faunas. There is no suggestion that "*erectus*" grade humans lived in communities or were cultivators, and it is now widely accepted that with regard to predation on large mammals the preserved tools – projectiles such as "hand axes" and coarsely flaked choppers and scrapers - are not consistent with hunting large animals, but with driving away the actual predators and scavenging their kills (Stanford and Bunn, 2001; Pickering and Bunn, 2007). The remains of earliest "*habilis*" grade humans (*H. habilis*, *H. rudolfensis*, *H. georgicus*) are even more spectacularly rare despite the most intensive search, and the associated crudely flaked "olduwan"-type tools are even less effective for hunting. Thus, early humans must be regarded as inconspicuous skulkers with virtually no effect on the global ecosystem.

In another aspect, recent detailed studies indicate that the linkage of "first *Homo*" and the "earliest glaciation" may be misplaced. The earliest records that may be dubiously referred to genus *Homo* are associated with the sharp shift in the African ecosystem at c. 2.4 Ma, in synchrony with the development of Walker circulation in the Indian Ocean (Prat, 2007). This event was distinct from, and much stronger than the local effects of the earlier climate change that brought about the formation of continental ice fields in high latitudes some 200,000 years previously. We can only conclude, from the virtually imperceptible record of *Homo* during most of its history, and also the poor correlation between its first occurrence and the beginning of the Quaternary as proposed by SQS, that our ancestry should not be considered as a guide fossil for this interval.

Discussion and conclusions

We have clarified the role of biochronology in chronostratigraphy, and shown that, even though the two have always been closely linked, chronostratigraphy is independently regulated. We have reiterated the fundamental role of the stage as the basic unit of chronostratigraphic hierarchy, and explained why, as a consequence, the lowering of the base of the Pleistocene Series without the simultaneous lowering of the base of the Calabrian Stage would violate chronostratigraphic principles and procedures. The logic would apply as well to the Quaternary, if defined by the base of the Calabrian Stage as maintained by some. We have explained that the modern world, and in particular its biodiversity, took shape progressively through the last 23 my of Earth history. There is nothing major and/or unique to the last 2.6 my: polar glaciation began much earlier in the northern hemisphere (~7 Ma, and perhaps earlier), and even earlier on Antarctica (~34 Ma). Current biodiversity stems from evolutionary radiations deep in the Miocene from late Eocene and Oligocene stocks, not from radiations that occurred during the last 2.6 my. As fascinating as it may be for us, the evolution of *Homo* (ca 2.5-2.0 Ma) can be seen as remarkable, or as banal, as the evolution of any other genus. It was within the last one hundred thousand years that human evolution took a great leap forward with the dispersion of humans around the world. After all, we now understand that mitochondrial Eve lived in Africa ~150 ky ago, and that the last common ancestor of men (i.e., the man from whom all men alive today derive their Y-chromosomes) lived ~60 ky ago in Africa! Whereas *Homo erectus* left Africa ~2 Ma, modern humans appeared only ~100 ky ago, migrated out of Africa ~/<60 ky ago, and colonized the rest of the world ~50 ky ago (Wells, 2002).

We reiterate our firm commitment to the philosophical approach to chronostratigraphy promulgated by Hedberg, such that it is a distinct discipline, independent in its definitions from any aspect of Earth history. However, for historical reasons, chronostratigraphic boundaries correspond to natural boundaries, representing transitions in Earth history. Remane et al. (1996, p. 78) recognized this when they stated: "Placing a boundary within such an interval [critical biotic or climatic transition] will preserve the advantage of having successive units which are distinguished by their content". The interval of time we call *Neogene* has historical integrity. It is well characterized by its content, whether biotic, climatic, or tectonic. It must be retained as a period incorporating the Miocene-

Recent (extending from 23 Ma to today). Introducing a Quaternary Period by decapitating the Neogene at 2.6 Ma would be a logical *non sequitur*.

The longstanding debate on the connotation and denotation of the stratigraphic terms *Neogene* and *Quaternary* is moving towards a resolution—at least for this generation. The Neogene is firmly ensconced in the conceptual hierarchy of chronostratigraphic classification and is generally considered by the marine and a significant component of the terrestrial (vertebrate) community as the younger of a two-fold system/period subdivision of the Cenozoic Erathem/Era that includes the Miocene-Recent (23-0 Ma) interval. The Quaternary, on the other hand, has a long-standing history as a climatostratigraphic unit, with a historically ill-defined and unsettled basal boundary, based on different interpretations of the nature and initiation of Northern Hemisphere glaciation. In this regard the Neogene and Quaternary are conceptually different and can be compared to Gould's categorization and assignment of Religion and Science to Non-Overlapping Magisteria[(1)] (NOMA).

If the Quaternary community wishes to remain independent of the rest of the chronostratigraphic community with subdivision of geologic history based on its climatic record, the NOMA[(1)] paradigm may be appropriate for a solution of the disparate approaches to Earth history espoused by the two communities. On the other hand the Quaternary community has recently requested formalization of the Quaternary as a chronostratigraphic unit with its base linked to the GSSP definition of the Gelasian Stage at 2.6 Ma and the simultaneous lowering of the base of the Pleistocene. Redefinition of the Pleistocene is quite impossible inasmuch as the hierarchical principles of chronostratigraphy require that the lowering of any chronostratigraphic unit be accompanied by, and predicated on, the lowering of its lowest contiguous unit, in this case the Calabrian Stage, which is manifestly impossible given the subjacent position of the upper Pliocene Gelasian Stage.

Several solutions have been proposed to satisfy the request of the SQS while simultaneously preserving the integrity of the Neogene System/Epoch. One possibility is to denominate the Quaternary as a subsystem or a superseries, equivalent to the Holocene, Pleistocene and upper Pliocene. Another possibility is to recognize it as a suberathem. For the reasons explained above and elsewhere, the truncation of the Neogene Period, whether at 2.6 Ma or at 1.8 Ma is unadvisable. This truncation is not in the interest of science because it would place unjustified emphasis on what are clearly— and for all possible geological reasons— the last 2.6 my of the Neogene Period!

If it is to be considered a chronostratigraphic unit, it must be inserted harmoniously in the current chronostratigraphic hierarchy. Our recommendations therefore are as follows:

1- The Neogene is a system/period that extends to the Recent.

2- The Quaternary should be included either as a subsystem/subperiod (Pillans and Naish, 2004; our preference), a superseries/superepoch (Lourens, 2008) or as a suberathem/subera (Aubry et al., 2005) of the Cenozoic.

3- The lowering of the Quaternary from 1.8 Ma (where it is currently located in some time-scales) to 2.6 Ma (as requested by the SQS) should not involve the lowering of the Pleistocene Series/Epoch, which is defined by its lowest congruent unit, the Calabrian Stage. The lowering of the base of the Calabrian Stage is impossible because of the juxtaposition of the next lower stage, the upper Pliocene Gelasian.

4- The Gelasian Stage should not be transferred to the Pleistocene. It was introduced specifically as a (upper) Pliocene Stage.

If a cogent compromise cannot be found that is satisfactory to both the SNS and the SQS, we suggest recognition that the Neogene and the Quaternary do not belong to the same conceptual category, the former being a chronostratigraphic entity, the latter a climatostratigraphic entity. In this case the application of NOMA[(1)] may be appropriate.

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[(1)] In a very readable account of the long-standing “conflict” between religion and science, the late Stephen J. Gould prepared an elegant “resolution” to the issue. We quote at some length here from Gould’s eloquent review of the argument followed by his proposition, or resolution, to the apparent conundrum, followed, in turn, by our defense of this resolution as an apt metaphor for its adoption to the ongoing Neogene-Quaternary debate.

"Our preferences for synthesis and unification often prevent us from recognizing that many crucial problems in our complex lives find better resolution under the opposite strategy of principled and respectful separation. People of good will wish to see science and religion at peace, working together to enrich our practical and ethical lives….

"I do not see how science and religion could be unified, or even synthesized, under any common scheme or explanation or analysis; but I also do not understand why the two enterprises should experience any conflict. Science tries to document the factual character of the natural world, and to develop theories that coordinate and explain these facts. Religion, on the other hand operates in the equally important, but utterly different, realm of human purposes, meanings and values—subjects that the factual domain of science might illuminate, but can never resolve. Similarly, while scientists must operate with ethical principles, some specific to their practice, the validity of these principles can never be inferred from the factual discoveries of science.

"I propose that we encapsulate this central principle of respectful noninterference—accompanied by intense dialogue between the two distinct subjects, each covering a central facet of human experience—by enunciating the principle of NOMA, or Non-Overlapping Magisteria." (Gould, 1999: 4, 5).

Now we invite the reader to reread the text in quotation marks above and to substitute the words Neogene and Quaternary for the terms Science and Religion in whichever order you wish (no direct comparison is made or implied) and to simply eliminate, or ignore, the irrelevant comments regarding the methodological domains appropriate to Science and Religion. These have been treated in the context of Neogene and Quaternary above. We recognize that the concept of NOMA is not fully applicable to the situation engendered by the Neogene-Quaternary debate but we believe it is sufficiently analogous to warrant further consideration as a means towards resolving the current standoff.

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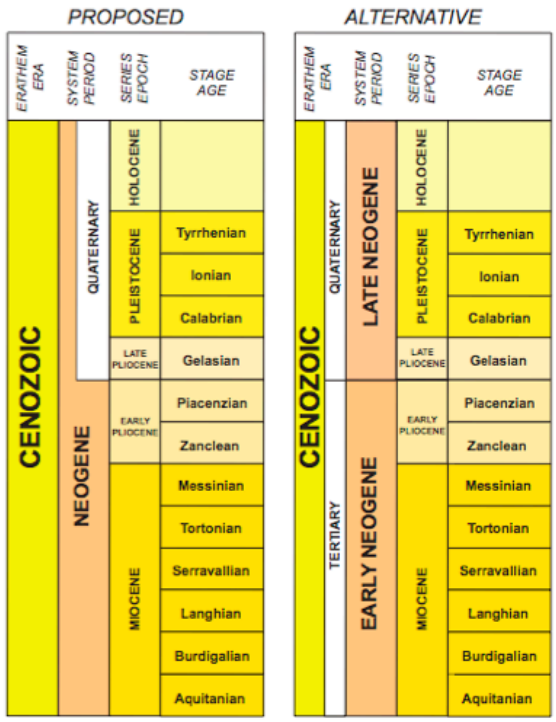
Figure captions.

Figure 1. Solutions proposed by the SNS to resolve the Neogene-Quaternary controversy. One solution (“proposed”) is to formalize the Quaternary as a subsystem/subperiod (shown; our preferred solution) or a superseries/superepoch (Lourens, 2008). The other solution (“alternative”) is to formalize the Quaternary as a subera of the Cenozoic following Aubry et al. (2005). Both solutions are valid whether the base of the Quaternary is defined by the base of the Calabrian Stage at 1.8 Ma (in which case the Quaternary will be equated with the Pleistocene) or by the base of the Gelasian Stage at 2.6 Ma (in which case the Quaternary will encompass the upper Pliocene and the Pleistocene. The ICS and several of its subcommissions will now debate the fate of the Neogene and Quaternary, following submissions by the Subcommissions on Neogene Stratigraphy (SNS) and Quaternary Stratigraphy (SQS) of proposals to the ICS (as requested by ICS Chairman Stan Finney, at the ICS in Oslo, 9 August 2008).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MIOCENE
Tyrrhenian
Ionian
Calabrian
Gelasian
Piacenzian
Zanclean
Messinian
Tortonian
Serravallian
Langhian
Burdigalian
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Aquitanian

FIGURE 1

Figure 2. The periods and epochs of the Cenozoic era. The etymology of their name is indicative of the biostratigraphic/biochronologic concept they originally expressed. This common etymology gives a remarkable integrity to Cenozoic chronostratigraphy. The terms Tertiary and Quaternary are remnants of an antiquated classification of rocks based on an assumed time of formation (Arduino, 1760). The terms *Primary* and *Secondary* have been eliminated from the hiagography. The terms *Tertiary* and *Quaternary* are redundant (Berggren, 1998, contra Salvador, 2006). For full references, the names given to eras were introduced by Philips (1840), those of periods by Hörnes (1856, those of series by Lyell (1830-1833), Hörnes (1853,; but see discussion in Walsh, 2008), Beyrich (1854) and Schimper (1874).

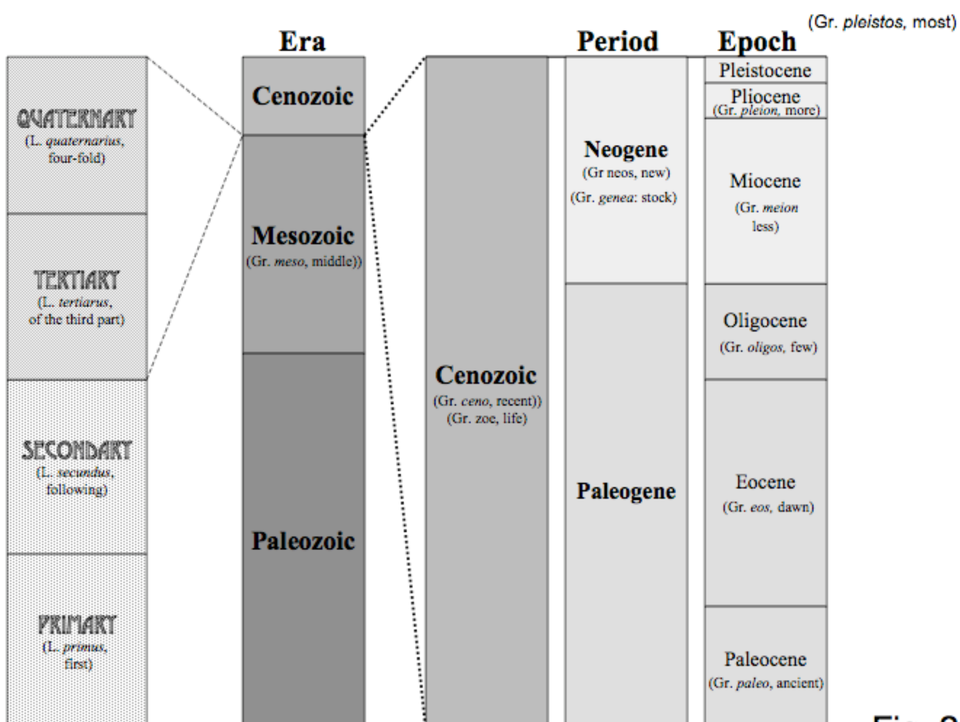

Fig. 2

Figure 3. Conversion of biochronologic units into chronostratigraphic units via the definition of stages. See text for explanation.

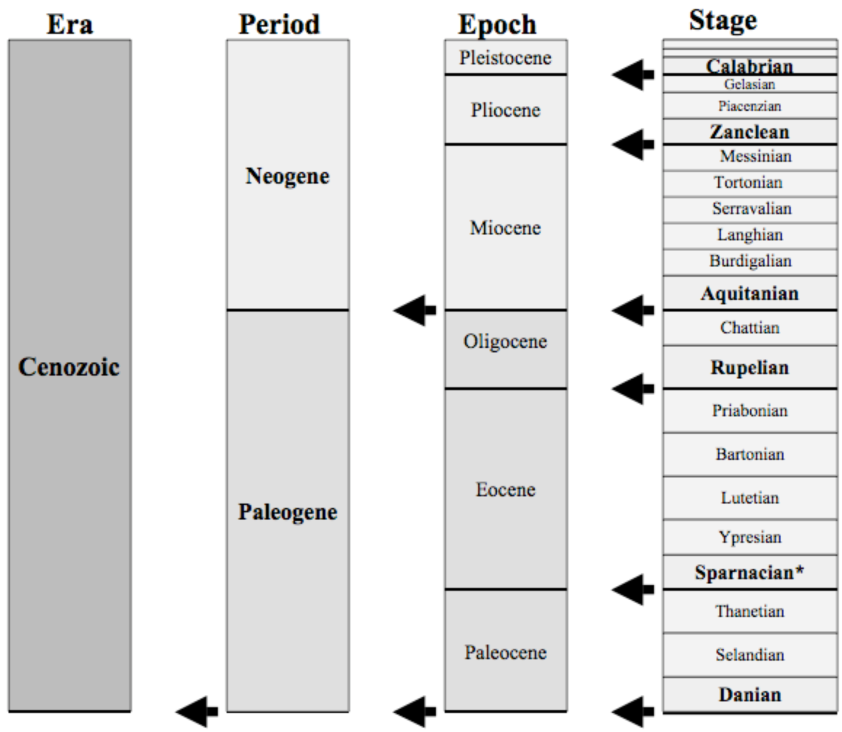

Fig. 3

Figure 4. The paramount role of biostratigraphy in stratigraphic correlations. A. The chrons (dotted oval) represented by this succession of three magnetozones (left) cannot be confidently identified through straightforward pattern matching. Biozonal correlations is required. B. Isotope signatures are iterative. Without paleontology, it would not be possible to determine which of the glacial events (Mi) are recorded in any section. (Aubry, 2004; McGowran, 2005). Time scale from Berggren et al. (1995); $\delta^{18}O$ chronology from Miller et al. (1987) and Wright et al. (1991).

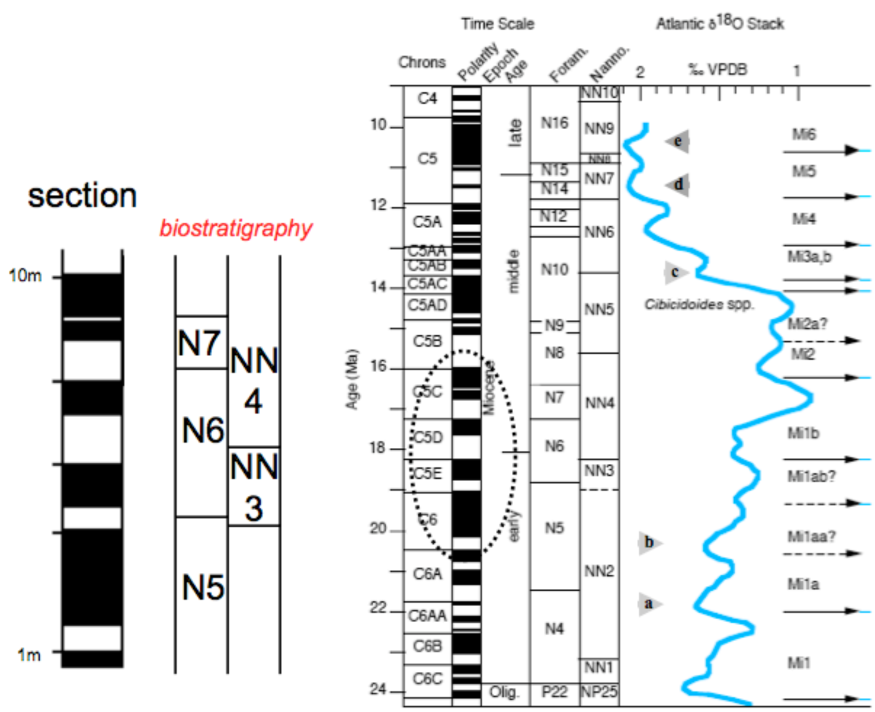

Fig. 4

Figure 5. Cascading radiation of terrestrial plants and vertebrates during the Neogene (modified Stanley, 1990, Fig. 1.4). In the absence of a well preserved fossil record, molecular biology has clarified the time of the origination of these groups, which, for most of them, happened during the Eocene. However, their radiation did not occur until the Neogene. Other radiations include those of the whales, camelids, equids, and the south American Edentates (*Glossotherium*, *Glyptotherium*, *Dasypus*).