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Neogene and Quaternary coexisting in the geological time scale: The inclusive compromise

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ABSTRACT

Removing the Tertiary and Quaternary Periods whilst conserving the Paleogene and Neogene Periods in *The Geological Timescale 2004* caused a storm of protest. One response was to advocate restoring an enlarged Quaternary and consigning the Neogene to a minor role within the Tertiary. Amongst an array of practical, traditional, sentimental and anthropocentric reasons for this response, the one hard-core justification was that the rigidly nested hierarchy of the geological timescale must be preserved.

The central objective of this paper is conserving the historically legitimate, Miocene-present, Neogene Period and System. There are two options for conserving the Quaternary concurrently with the Neogene: (i) an inclusive compromise in a flexible hierarchy, and (ii) an upgrading of Pliocene and Pleistocene divisions to the level of epoch. In the inclusive compromise there coexist alternative pathways through the hierarchical ranks. Thus geohistorians and biohistorians have two options for traversing the hierarchy from era to age, as in this example using the hierarchical positioning of the Calabrian Age and Stage:

either Cenozoic [era]↔Neogene [period]↔Pleistocene [epoch]↔Calabrian [age],
or Cenozoic [era]↔Quaternary [subera]↔Pleistocene [epoch]↔Calabrian [age].

We reaffirm that the inclusive compromise is entirely viable. In so doing we (i) challenge the necessity of the rigidly nested hierarchy, which should be capable of a little flexibility; (ii) reject all analogies of the arbitrary and conventional chronostratigraphic hierarchy with three natural biological hierarchies; (iii) reaffirm the integrity of the Neogene extending to the present; and (iv) see no reason to doubt the harmonious coexistence of the two options preserving the Quaternary and Neogene traditions in an orderly working and stable time scale.

In the alternative schema conserving the Neogene, divisions of the Pliocene and Pleistocene are upgraded, so that the Late Pleistocene, Early Pleistocene and Late Pliocene Epochs comprise the Quaternary Subperiod, itself equivalent to Late Neogene. The inflexibly nested hierarchy is preserved but the Tertiary is lost.

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1. Introduction

Two great traditions arose from the surge in historical geology early in the nineteenth century. One arose in the terrestrial environmental realm and manifested in the vertebrate paleontology of Cuvier, the paleobotany of Brongniart and the ice ages of Agassiz. In due course we arrived at the Quaternary division of strata and time at the top, the young end of the time scale, in the reinvention of the fourth division in the four-part timescale handed down from Arduino (Vai, 2007) and the Enlightenment (the Primary and Secondary divisions going extinct, the Tertiary surviving). The second tradition arose in the shallow-marine or neritic realm and expanded into the deep-marine or pelagic realm. It flowered in Lyell's percentage method of classifying Cenozoic strata, which exploited the grand monographing works of the French malacologists. It flourished upon the discovery of rich, diverse and well-skeletonized marine microfossils (although the molluscs were preeminent). In due course there emerged the Neogene division of time-rocks also at the young end of the scale.

Two grand traditions, two terms encompassing coeval strata, fossils and events—all being anchored in "the" geological time scale. Was there potential for confusion in this competing nomenclature? What to do? It became a matter of managing in an orderly way the turbulent, burgeoning, increasingly complex building of geohistory and biohistory. Hence a passion of a very human kind—our passions tend to erupt more in how we express the results of our science (and especially historical science) than in the results themselves, and the dating disputes, the "time wars", are newsworthy (Giles, 2006; Kerr, 2008). In the present case of how to classify the youngest of earth's strata, one solution was to abandon the Tertiary/Quaternary divisions of the Cenozoic Era/Erathem altogether and to award sole tenure to the Paleogene/Neogene. This solution appeared in the most recent and comprehensive work of its kind, the very successful *Geological time scale 2004* (GTS 2004) (Gradstein et al., 2004).

Left intact were the Holocene, Pleistocene, Pliocene, Miocene and so on, and their components, and the necessary work of fixing by GSSPs the hierarchy of age/stage, epoch/series and period/system was nearing completion in the pelagic realm. We had a chronostratigraphy coping very well with an explosion in Cenozoic science—the upheavals of the Deep Sea Drilling Project and its successors, diverse advances in chronological resolution, correlation and age determination, and the rise and rise of geochemical time series and paleoceanography. The crowning ambition was (is) our ever more ambitious global environmental science spanning the three environmental realms—pelagic, neritic, terrestrial—at cyclostratigraphically disciplined time scales.

A problem emerged. The Quaternary community (the Quaternarists) ranging in their specialities from archaeology to soil science to paleobotany and environmental micropalaeontology to geomorphology, were not happy with the exclusion of the Quaternary from GTS 2004. A smaller group felt likewise about the exclusion of the Tertiary (Salvador, 2006). The uprising produced such titles as "The Tertiary is here to stay", "The Tertiary is not toast" and "The Quaternary is here to stay".

Equally swift was a move to compromise and placate (Van Couvering, 2005 (2006)). The first proposal was to define the Quaternary as a "hanging" sub-period within the Neogene, starting at ~2.6 Ma (Pillans, 2004; Pillans and Naish, 2004). Alternatively, but also accepting that numerous scientists identified strongly with the Quaternary, Aubry et al. (2005) presented a scale (Fig. 1) in which the Quaternary and Tertiary were elevated to Sub-Era/Erathem status (after Harland et al., 1990, but then and still the only would-be inhabitants of that rank in the entire geological record) and the Neogene and Paleogene were retained as Periods/Systems of the Cenozoic, not of the Tertiary. Also in acknowledgment and acceptance of an overwhelming shift in Quaternarist preference, Aubry et al. supported lowering the base of the Quaternary to ~2.59 Ma, some 800 kyr older than the base of the Pleistocene. Essentially the same framework was presented soon after by the International Commission on Stratigraphy (ICS) to an ICS meeting in Leuven in 2005, after a working group meeting with the International Union for Quaternary Research (INQUA). The Aubry et al. proposal was approved by the ICS voting members (Gradstein, 2005).

The central thrust of the Aubry et al. paper and the Leuven submission was an *inclusive compromise*—to respect both the mostly terrestrial and mostly marine traditions and to satisfy the respective communities of earth-life scientists. This respect for the two traditions came at the cost of disrupting the rigid nesting of the very short chronostratigraphic hierarchy—a disruption *not* endangering the orderly working and stability of the time scale (Pillans, 2007; McGowran and Li, 2007).

The inclusive compromise was acceptable to the Neogene community but unacceptable to the Quaternarists. The INQUA executive polled members and national Quaternary committees and accordingly rejected, at Ahmedabad (March 2006), the Leuven recommendations on three grounds: the non-hierarchical structure, the Quaternary decoupled from the Pleistocene, and the extension of the Neogene to the present. In the next development, responding to INQUA pressure, the ICS (14 votes for, 2 against, 1 abstention) put the following proposal to IUGS in February 2007 (see Table 1).

Points (2)–(4) in Table 1 address the Quaternarist concern with the extended Quaternary (to ~2.6 Ma) and the attendant dragging down of the base of the Pleistocene. It is the sentence in (1) on the Neogene (our emphasis) that is of overriding concern here. The Neogene System is to be decapitated. We note that the Subcommission for Neogene Stratigraphy (SNS) in the ICS had but one of those votes, but that the SNS were solidly behind the Chair (F.J. Hilgen). We note too that the vote for this submission has been called a vote for "compromise", presumably because "Neogene" and "Quaternary" appear in succession. We reject those comments because the real compromise, the *only* compromise, is in the coexistence of the real Neogene with the Quaternary.

In this paper we reaffirm our commitment to the traditions, virtues and necessity of the real Neogene (misleadingly dubbed the

Table 1
The motion from ICS (triggered in INQUA) forwarded to IUGS, May, 2007.

IUGS establishes the Quaternary as the uppermost System of the Cenozoic Erathem:
1) The Quaternary is a full formal chronostratigraphic unit, the appropriate status for which is the System. *The underlying System is the Neogene*.
2) The base of the Quaternary is placed at the current base of GSSP Gelasian Stage (currently in the Pliocene) at the base of Marine Isotope Stage (MIS) 103, which has been calibrated to an age of ~2.6 Ma.
3) The base of the Pleistocene Series is lowered to coincide with that of the Quaternary System boundary (=Gelasian Stage GSSP).
4) The GSSP at Vrica, Italy (the former Plio-Pleistocene boundary), is retained as the base of the *Calabrian* Stage, the second stage of the revised Pleistocene Series.

"extended" Neogene). We reaffirm that the large number of workers in the Quaternary are welcome to the *alternative* schema of Tertiary plus Quaternary. Third, and, most crucial, we maintain that the two traditions must coexist. To accommodate this inclusiveness necessitates challenging the inflexible nestedness of the chronostratigraphic and geochronological hierarchy. Accordingly, we address the status of this structure (artificial, human-constructed) and contrast it with three more robust (being natural and discoverable) hierarchies in the biosphere. But there is also a way for the nondecapitated Neogene to coexist with the Quaternary (Lourens, 2008) in a hierarchical schema and we present that option too.

2. The Neogene tradition

2.1. Origins and development of the Neogene Period

Papers supporting the natural Neogene as in GTS 2004 (Lourens et al., 2004) include Berggren (1998, 2005, 2007, Fig. 1), Steininger (2002), Pillans (2004), Pillans and Naish (2004), Aubry et al. (2005, Table 2), Gradstein (2005, Figs. 1 and 2), Van Couvering (2006), McGowran and Li (2007), Lourens (2008, Fig. 1), Hilgen et al. (2008) and Aubry et al. (2009). The figures and tables cited refer to charts showing the Paleogene/Neogene succession alongside and decoupled from the Tertiary/Quaternary (see also Fluegeman, 2007, Fig. 1).

Berggren (1971, 1998, 2005) and Steininger (2002) reviewed the establishment and development of the Neogene in the mid-19th Century. Moritz Hörnes established the Neogene originally to capture the faunas (especially molluscs) and flora of the upper part of the Tertiary, sharply different in character from their Eocene antecedents but similar in many respects to the Pliocene. Like Lyell's epochs, Hörnes' Neogene was initially biochronologic and biostratigraphic but became chronostratigraphic in due course. The Neogene in the Vienna Basin, Hörnes' home ground, included strata up to and including glacial loess and diluvial deposits along with Mediterranean faunas that are now dated as Pleistocene. The Neogene included Lyell's Newer Pliocene, later named the Pleistocene (Berggren, 1998, Fig. 2; 2005, Fig. 1). The strongest subsequent supporter of the Neogene concept was Renevier (1897) who rejected Naumann's (1854, 1866) division of the Cenozoic into Tertiary and Quaternary as being not natural or fundamental, and who tabulated the Neogene as *Néogénique Récent* (*Holocène, Plistocène, Pliocène*), and *Néogénique Ancien* (*Prépliocène, Miocène*).

In the opinion of Denizot in the *Lexique Stratigraphique International* (1957), Hörnes meant his Neogene to include the Miocene–Recent. Denizot thereby influenced the work of Berggren, Van Couvering and others. Various strands of marine and terrestrial research came together, with geomagnetic stratigraphy becoming the backbone of the time scale (Berggren et al., 1985) and more still with isotopic and cyclostratigraphy (Berggren et al., 1995b). It was equally clear to Lourens et al. (2004), in the light of modern correlations and age determinations of the relevant fossils and strata, that Hörnes' original concept of the Neogene included the Miocene, Pliocene, and Pleistocene up to the Pleistocene/Holocene boundary. In GTS 2004 Lourens et al. (2004) divided the Cenozoic Era into the Paleogene and Neogene Periods.

Table 2
Hierarchical relationships of Tertiary, Quaternary, Neogene, Pliocene and Pleistocene as proposed by Aubry et al. (2005, Table 1). Boundary ages (GTS 2004) are shown. Not to scale. The same relationships are shown in Berggren (2007, Fig. 1) and are advocated here.

Era Erathem	Sub-era Sub-Erathem	Period System	Epoch Series
Cenozoic	Quaternary 2.59	Neogene 23.03	Pleistocene 1.81
			Pliocene 5.33
			Miocene
	Tertiary 65.5	Paleogene	Oligocene
			Eocene
			Paleocene

The theme through four decades' research is increased integration, resolution and accuracy in correlation and age determination in the pelagic Neogene, but never losing track of the neritic and terrestrial realms. It is clear whence Walsh, working on vertebrate fossils in terrestrial siliciclastics, derived his charge that "Motivations for the extension of the Neogene to the present include the desire to establish a monopoly for marine biochronology in the definition of standard global chronostratigraphic boundaries" (2008, p. 42), but the charge (not speculation or suggestion) is simply false. The critical data and the continuous records are mostly in the pelagic realm (Hilgen et al., 2006). Indeed, the chronology of the Quaternary continental record itself is partly determined with reference to the marine record.

According to Head et al. (2008), "Historical claims that the Neogene period extends to the present day, thereby rendering the term Quaternary superfluous, have been robustly refuted" by Walsh (2006, 2008). Robustly, we agree; refuted, we reject. Walsh (2008) perceived some ambiguity in Hörnes' concept of the Neogene in the 1850s. He strived to show that Hörnes' most likely intention was to include only the Miocene and Pliocene (as we now know them, more or less), emphasizing Hörnes' exclusion of the Diluvium and Alluvium. It was highly useful to the drive to decapitate the Neogene below the Quaternary to be able to demonstrate that the Neogene historiographically never extended beyond the Tertiary. Walsh surely tried, but he had to resort to debating ploys such as "null hypothesis" and "reasonable to assume" in a highly partisan account.

We find, contra Walsh, that the trail from Bronn (1838) through Hörnes is intact. One of us has revisited the original literature (see Appendix A). We reaffirm that Bronn included his Third Molasse-Group (= Newer Pliocene or Pleistocene, plus Contemporary, i.e. Quaternary in toto) (Berggren, 1998, Fig. 2; 2005, Fig. 1) in his—Bronn's—Tertiary, and that Hörnes included all this in his Neogene. Notwithstanding subsequent superposing of Diluvium and Alluvium above the Neogene and Tertiary (Walsh, 2008), the onus would now seem to be on those who wish to disprove that the real Neogene in its original form extends unto the present day.

2.2. The rise of planktonic foraminiferal biostratigraphy in the Neogene tradition

Although the term "Neogene" in its full, Miocene–Holocene sense dates back to the late 19th century (e.g., Renevier, 1897), its current impetus comes from the article by Denizot for the International Stratigraphic Lexicon (1957). Brouwer (1978), Berggren and Van Couvering (1974), Berggren et al. (1995a,b), Berggren (1998), Steininger (1981a,b) and others followed suit. In fact in an unpublished manuscript sent to one of us (WAB) in the mid-1960s entitled Subsection II (Principles: Concepts of "Age" and "Stage"; Geochronology and Stratigraphy) of Section I (Geostratigraphy and the Geostratigraphical Basis for Correlation) and dating to the mid-late 1960s Blow and Banner (MS, p. 17–18) in a discussion of the "Geostratigraphic" subdivision of (Cenozoic) Erathem" suggested that the case could be made for "[the rank] suberathem to be available and that Paleogene and Neogene would be suberathems of the Cenozoic Erathem; the earliest stage agreed to occur in the earliest series of the earliest system of a suberathem would define the base of that suberathem". They go on to state that "we would prefer not to employ formally the terms "Tertiary" and "Quaternary" for the interval we group as Cainozoic; the history of these terms and their present disputed application is so confused that we believe their use to be both inadvisable and unnecessary". A modified form of this unpublished text appeared as Chapter 9 ("Geostratigraphy and a Philosophical Basis for the Interpretation of the Geohistorical Record") in the single-authored monograph by Blow (1979), published posthumously following his untimely death in 1972. However, in this revised/updated version there was no mention of the subdivision of the Cenozoic Era.

The full Neogene came strongly into favor during the 1970s and was adopted by the marine (bio)stratigraphic community shortly after the inception of the Deep Sea Drilling Project (DSDP) in the late 1960s; it was equally accepted by the terrestrial/vertebrate community. The terms Pleistocene and Quaternary had been used interchangeably by both communities up to the mid-1970s, at which time the Quaternary was essentially relinquished or abandoned in favor of the Pleistocene by the marine stratigraphic community.

The use of planktonic foraminifera in the correlation and age-determination of tropical and subtropical, marine, Miocene–Holocene stratigraphies was a mostly post-World War II enterprise essential to petroleum exploration in the Caribbean region (Cushman and Stainforth, 1945; Bolli, 1957a,b, 1966; Blow, 1959). Since then zonal schemes have been developed for all regions of the world and its oceans to encompass and reflect regional, climate-controlled biogeography.

The first zonal scheme to specifically use the Neogene in its extended, Miocene–Holocene connotation was erected by Banner and Blow (1965: 1164), as seen in choice of title for their seminal paper introducing a new zonal biostratigraphy for late Cenozoic marine sediments: "Progress in the planktonic foraminiferal biostratigraphy of the Neogene", and then formulating a 23-fold zonal scheme denoted by the prefix N (for "Neogene"). In its original formulation the Banner–Blow zonation extended down to the base of the Mediterranean Bormidian Stage (equivalent to the Chattian of Boreal Europe) (Zones N1–N3) which they considered to comprise the lowest part of the Neogene (Eames et al., 1960, 1962). Responding to criticism by Stainforth (1959, 1960, 1967/1969) and Berggren (1963) and the decision by the Committee on Mediterrranean Neogene Stratigraphy (CMNS) to place the base of the Neogene at the base of Zone N4, Blow restricted the Neogene part of his and their zonation to Zones N4–N23, while designating the terminal part of the Paleogene zonation as Zones P21–P23 (=N1–N3; Blow, 1969).

Zonal successions have been developed for extended Neogene sections in various biogeographic regions (Table 3).

2.3. Neogene in the pelagic realm: progress in the deep-marine

The marine stratigraphic community embraced the extended Neogene from the mid-20th century onward while showing a strong preference for the Pleistocene to the expense of the Quaternary.

Walsh (2008, p. 60) commented that certain distinguished micropaleontologists did not follow this trend, "but the traditional usage of these workers soon became unpopular in their own field". The first zonal schemes proposed on the basis of the calcareous nannoplankton for the younger part of the Cenozoic were established in references to the series (Miocene, Pliocene, Pleistocene) and without any reference to chronostratigraphic units of higher rank (Miocene: Bramlette and Wilcoxon, 1967, Tables 1, 2; Upper Oligocene–Upper Miocene interval: Hay and Roth in Hay et al., 1967; Pliocene interval: Hay and Schmidt in Hay et al., 1967; Latest Pliocene–Recent: Boudreaux and Hay in Hay et al., 1967; Late Pliocene–Pleistocene–Recent: Boudreaux and Hay, 1967, Fig. 1). Gartner (1969) modified Hay et al.'s zonation (1967) and correlated his zones to Blow's (1969) zones. He used the term Quaternary, but clearly substituted it for Pleistocene (Miocene–Pliocene–Quaternary, Fig. 10). Further, the title of his paper "*Correlation of Neogene planktonic foraminifer and calcareous nannoplankton Zones*" clearly indicates that he united the three series under the Neogene umbrella. A careful reading of the papers by Martini (1971a,b) and Martini and Worsley (1970) shows that whereas the terms Quaternary and Neogene were used interchangeably in the text, figures show consistently that the Quaternary was always considered as an epoch above the Pliocene, while the Neogene encompassed the Miocene through Quaternary (Martini and Worsley, 1970, Fig. 1; Martini, 1971a, Tables 3, 4, 6; Martini, 1971b, Fig. 39.1, 39.2). This is in agreement with the concept of the NN-zonal system (NN stands for Neogene nannoplankton) (Martini and Worsley, 1970). It is true however, that Martini (1971a,b) entitled his Tables 3, 4 as follows: "Ranges of calcareous nannoplankton datum indicators (and "additional calcareous nannoplankton species [Table 4] Neogene–Quaternary". The same relationship between Quaternary, Pleistocene and Neogene is seen in Okada and Bukry (1980, Table 1) who codified Bukry's zonal scheme (1973, 1975) for low latitudes ("CN" means "Neogene coccolith" zone). However, Bukry (1973, Tables 1, 2; 1975, Table 1) used Pleistocene instead of Quaternary. This implies that authors who used the term Quaternary saw this unit as equivalent to the Pleistocene and (mostly) subordinate to the Neogene.

Deep-sea drilling resulted in the recovery of numerous deep marine cores, promoting the study of the paleoclimatic and oceanographic history of the entire Cenozoic. Although core recovery was

Table 3
Global and regional Neogene: planktonic foraminiferal zones and astronomical biochronology of datum events.

Area/region	Bio/chronostratigraphic extent	Reference
Mid-(temperate/transitional) and high latitude Austral	Miocene–Holocene	(Jenkins, 1960, 1967, 1971, 1975; Berggren, 1977a,b; Srinivasan and Kennett, 1981a,b, 1983; Berggren et al., 1983; Kennett and Srinivasan, 1983, 1984; Jenkins, 1985, 1992; Berggren, 1992; Jenkins, 1993a,b)
Northern Hemisphere temperate/ transitional	Miocene–Holocene	(Berggren, 1972; Poore and Berggren, 1975; Weaver and Clement, 1986, 1987; Berggren in Berggren et al., 1995a,b)
(Sub)tropical global/Caribbean/ Mediterranean	Miocene–Holocene	(Bolli, 1957a,b; Banner and Blow, 1965; Bolli and Bemúdez, 1965; Bolli, 1966; Blow, 1969; Bolli and Premoli Silva, 1973; Stainforth et al., 1975; Bolli and Saunders, 1985; Berggren et al., 1995a,b; Lourens et al., 2004)
(Sub)tropical global	Pliocene	(Berggren, 1973; Berggren in Berggren et al., 1995a,b)
(Sub)tropical global	Pliocene–Pleistocene astronomical biochronology of datum events	Berggren et al. (1995a,b)
Tropical Atlantic	Middle Miocene–Pleistocene astronomical biochronology of datum events	(Chaisson and Pearson, 1997; Pearson and Chaisson, 1997; Norris, 1998; Turco et al., 2002)
Mid-(temperate/transitional) latitude, Pacific	Miocene	Keller (1978, 1979a,b, 1980a,b, 1981)
Tropical Pacific	Miocene astronomical biochronology of datum events	Shackleton et al. (1995), Chaisson and Leckie (1993)
Mediterranean	Miocene–Pleistocene	(Bizon and Bizon, 1972; Borsetti et al., 1979; Iaccarino and Salvatorini, 1982; Iaccarino, 1985);
Mediterranean	Late Miocene	D'Onofrio et al. (1975)
Mediterranean	Pliocene	Cita (1973)
Mediterranean	Pliocene astronomical biochronology of datum events	Sprovieri et al. (2006)
Mediterranean	Middle-Late Miocene astronomical biochronology of datum events	(Sprovieri et al., 1996a,b; Hilgen et al., 2000a,b; Turco et al., 2001; Di Stefano et al., 2002; Caruso et al., 2002)
Mediterranean	Middle Miocene astronomical biochronology of datum events	(Foresi et al., 1998, 2002; Lirer et al., 2002; Sprovieri et al., 2002a,b; Lirer and Iaccarino, 2005)

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initially relatively low, improvements in drilling techniques soon resulted in less disturbed and more complete deep-sea records. The definitive advance came from drilling multiple holes at a single site, guaranteeing complete recovery of stratigraphic successions (Ruddiman et al., 1986).

In tandem, significant progress was made towards an integrated high-resolution stratigraphy and astronomical tuning of the deep-marine record (Hilgen et al., 1997). Until the mid-20th century attempts to demonstrate an astronomical origin of the Pleistocene ice ages and establish an astronomical tuning remained inconclusive due to incompleteness of the continental record which in addition proved difficult to date. This key scientific issue was only solved by the detailed study of deep-sea sediments recovered in ordinary piston-cores, using novel climate proxies (e.g., $\delta^{18}O$), dating techniques (e.g., magnetostratigraphy, K/Ar dating) and statistical analysis (i.e., spectral analysis). The landmark paper in the marine studies of the ice ages is by Hays et al. (1976) who demonstrated the concomitant influence of all three orbital parameters (precession, obliquity and eccentricity) on Pleistocene ice ages for the first time. This breakthrough was soon followed by the astronomical tuning of cyclic variations in $\delta^{18}O$ over the last 800,000 years to an astronomical target curve, resulting in what became known as the SPECMAP isotope chronology and time scale (Imbrie et al., 1984). Presently the entire Neogene has been astronomically dated (Lourens et al., 2004) and attempts are being made to tune the Paleogene and even parts of the Cretaceous (e.g., Pälike et al., 2006; Westerhold et al., 2008; Mitchell et al., 2008). Important constraints for the tuning of the older successions will necessarily come from the intercalibration of the astronomical and radio-isotopic methods and, in particular, from the application of astronomically calibrated standards in Ar/Ar dating (Kuiper et al., 2008).

Most biostratigraphic datums and magnetic reversals are directly tied to the astronomical time scale via first-order correlations, because they are found in tuned marine sections underpinning the time scale (e.g., Raffi et al., 2006). The same also applies to most GSSPs, also defined in the tuned sections on which the standard time scale is built.

The importance of astronomically calibrated geological time scales is evident from their unprecedented accuracy, precision and resolution (down to ~10 kyr). The new time scale has been successfully applied to solve key scientific issues related, for instance, to the Messinian Salinity Crisis and the subsequent Pliocene flooding of the Mediterranean (Krijgsman et al., 1999; van der Laan et al., 2006). Moreover such time scales are vital to unravelling Cenozoic climate history, especially because several key steps in the evolution of the ocean–climate system are potentially related to very long period astronomical climate forcing (Shackleton et al., 2000; Lourens et al., 2005; Abels et al., 2005).

The tuning approach also argues for the re-introduction of unit stratotypes for global stages and the formal designation of Milankovitch cycles as chronostratigraphic units of minor rank (i.e., the chronozones of Hedberg, 1976).

This revolution in (global) chronostratigraphy and numerical dating happened in the marine tradition of the extended Neogene, largely at odds with the continental tradition of the Quaternary, tending to argue against the insertion of the Quaternary in global chronostratigraphic schemes at the expense of the Neogene. Walsh (2008) remarked:

"The latest proponents of the extended Neogene belong to the "astrochronological community" (e.g., Lourens et al., 2004). These are again primarily marine stratigraphers, and so, working with the time scales of Berggren et al. (1985, 1995a,b), used the extended Neogene as a matter of course." This is another attempt to downplay the superiority of the marine record in defining global chronostratigraphic units and in building the integrated standard GTS.

Notwithstanding our arguments for the more versatile role of marine facies in stratigraphy, we must refer to the excellent sections in the Chinese Loess Plateau–continuous, detailed, well-dated geomagnetically and astrochronologically, spanning the Quaternary and extending back into the Miocene (Hao and Guo, 2004; Sun et al., 2006).

3. Chronostratigraphy and Neogene geohistory and biohistory

3.1. Chronostratigraphic classification and nomenclature are in the framework category

Harland (1973, 1975) made and McGowran (2005, Ch. 7) emphasized the distinction of the phenomenon category from the framework category in stratigraphy. It is in the phenomenon category that the actual science happens—the back-and-forth of theory, observation, and research programs in earth history. Meanwhile the framework category takes care of the conventions, the rules, the definitions controlling orderly transaction and ease and clarity of communication, the committee manoeuvrings and the politics, the nationalist and chauvinist sensitivities. Harland et al. (1990) and McGowran (2005) pointed to this contrast within the geochronological scale itself. Calibration in years on the chronometric side is a matter of discovery and estimation according to rigorous protocols and susceptible to rigorous testing (phenomenon), in contrast to the chronostratigraphic scale which is a matter of convention, agreement and rules (framework). We might compare the phenomenon/framework contrast to the general contrast between seeking the truth and seeking an outcome—between investigating "what is the case", as scientists usually do, and "making a case", as lawyers prosper in so doing.

It is important to anticipate possible confusion in words like "arbitrary", "ratify", and "decision by committee". The items we vote on are in the framework category. We do not vote in committee on the real science in the phenomenon category. For example, placing the base of the Cenozoic at the base of the Danian because it "ought" to be there was an action in the framework category. But the case for the action, the "ought", was built on all the science that we had available in the phenomenon category—the real science. Real science in the phenomenon category informs the arguments for arriving at the best framework.

3.2. Challenging the necessity of the rigidly nested chronostratigraphic hierarchy

The conventional chronostratigraphic/geochronological hierarchy is a ranked and nested hierarchy in which each unit (except the highest) is entirely enclosed within the unit at the next rank above. There are usually only six ranks: Eonothem/Eon, Erathem/Era, System/Period, Series/Epoch, Stage/Age, Substage/Subage; with provision also for Sub- and Super- at the System and Series levels (Salvador, 1994).

For Vai (2007; his emphasis) "chronostratigraphy's development has followed two basic criteria since the beginning:

(i) A *hierarchical classification* securing conventional stability to the whole frame.
(ii) An *historical approach* implying gradual improvement only by additions and some pragmatism and flexibility."

Until the recent flurry over the Quaternary and Neogene and especially the advocacy by the late Stephen Walsh (2006, 2008), there has been remarkably little discussion of the ranked and nested chronostratigraphic hierarchy. The hierarchy evolved through a century and more (e.g., Aubry et al., 1999; McGowran, 2005, Table 7.1), but its basic structure has been agreed without dispassionate scrutiny. It would seem that "conventional stability" says all that needs be said. Tablets are handed down from time to time, thus: "The Global Chronostratigraphic Scale must, however, comprise strictly contiguous units, without overlaps and with no gaps between them" (Remane et al., 1996). To a query, what is so sacred about the rigidly constructed nested hierarchy; why the "must"?, there is no clear answer.

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Our argument here is as follows:

(i) Comparisons of the chronostratigraphic hierarchy with hierarchies in the biosphere are misplaced, for ours is in the framework category whilst theirs are active players in historical science—they are in the phenomenon category. (We actually have glimpses of a stratigraphic and geohistorical hierarchy in the phenomenon category: it extends from the Milankovitch band to the two Phanerozoic supercycles, is eminently discoverable and being rapidly discovered in cyclostratigraphy (Strasser et al., 2006) and sequence stratigraphy (Catuneanu et al., 1999) not voted in or out.)
(ii) Assertions demand a rigidly nested chronostratigraphic hierarchy in the present case; arguments supporting the same are very weak.
(iii) These arguments in any case can be sidestepped by offering alternative pathways from Era to Epoch within the Cenozoic hierarchy—*either* the route of Tertiary and Quaternary Suberas, *or* the route of Paleogene and Neogene Periods.
(iv) The Quaternary being a special case, on several grounds, we assert that: (a) offering alternative pathways within a hierarchy of very few ranks presents no risk of confusion in Cenozoic geohistory and biohistory; and (b) the special case at the young end of (and 0.05% of) the geological time scale provokes no risk of precedent down the column.

By far the strongest objection to our proposals as in Aubry et al. (2005) has been to the flexible not rigidly nested hierarchy, and the most vociferous objector has been Walsh (2006, 2008), supported by Head et al. (2008).

Walsh (2008) listed four arguments against retaining a ranked Tertiary and Quaternary in the hierarchy: they are obsolete, being hangovers from the Neptunist 18thC; they are enormously disparate in their durations; there is an analogy with the unranked Precambrian; and there is a supposed ambiguity in their use—arguments all "readily refuted" by Walsh. Arguments in favour of retaining a ranked Tertiary and Quaternary include their widespread use, their practical relevance for maps, and their role in honouring the pioneers of stratigraphy. Put like that, chronostratigraphy is the tepid stuff of a dusty accounting practice.

However, Walsh's advocacy focuses the second and more basic of the two specific problems that pervaded the uproar of recent years. (The first was the disappearance altogether of the Quaternary from GTS 2004, not relevant here, because Aubry et al. (2005) and Gradstein (2005) accommodated the Quaternary.) The second problem was the perceived insult to the rigid hierarchy. Walsh charged repeatedly that we violated the most fundamental rule in hierarchical classification in including a unit of superior rank within a unit of inferior rank.

Our compromise as in Fig. 1 flouts the "thou shalt not..." but neither the reaction nor the antecedent literature actually confronts what is so forbidding and prohibited about tinkering with the hierarchy to make it a little flexible. We note "some pragmatism and flexibility" in the ageless criteria listed by Vai (above). A few authors (Ghiselin, 1997; Walsh, 2006) briefly compared the stratigraphic hierarchy with biological hierarchies. We need to discuss the biological hierarchies to show how isolated, arbitrary and indeed superficial the stratigraphic hierarchy really is, compared with other members of the class "hierarchy".

3.3. The biological hierarchies are natural and discoverable...

There are three hierarchies in the realm of historical biology—the venerable Linnaean taxonomic hierarchy, the evolutionary "extension of Darwinism", and the deep-time ecological hierarchy. All are natural in so far as they are based on discoverable patterns in nature and all are controversial.

It is well known how the Linnaean system brought order into the chaos that was 18thC biosystematics. Further, it is celebrated that discovering the essences, the natural kinds populating 18thC metaphysics, produced a pattern that could be absorbed holus-bolus into an utterly different world-view in due course—Darwinian organic evolution and evolutionary taxonomy (Simpson, 1961; Mayr, 1969). Further still, after a distracting sideshow known as numerical phenetics, we come to the taxonomic revolution known as cladistics (Ridley, 1986; Hull, 1988). A textbook example (e.g., Ridley, 1996, Fig. 14.5) demonstrates the simple relationship between (a) the evolutionary relationships of several species, (b) their phylogenetic or cladistic classification, and (c) the Linnean classification of one of the species into its Genus, Family, Suborder and Order. To be sure, our scenario of the real world of species is full of gaps and ambiguities, and cladistics is not without its controversies. Notwithstanding, there is a real genealogical tree "out there", comprising real entities or individuals (in the philosophical sense: Ghiselin, 2005; in the robust biological sense: Mayr, 1996) known as species (Ereshefsky, 2007). The processes of splitting (speciation) and terminating (extinction) produce real lineages or clades with a real sequence of branchings, and it largely awaits discovery and reconstruction.

That statement holds even as the Linnaean hierarchy struggles to cope with modern insights into biodiversity—its 21 and more categorical ranks hardly suffice for modern taxonomy—and its very existence in future biosystematics is under scrutiny ("The poverty of the Linnean hierarchy": Ereshefsky, 2001). But the need to reconstruct the genealogical tree will forever remain and so too will the fallacy of comparing it with the stratigraphic record.

The second biological hierarchy addresses the extension of Darwinism, in its narrow sense of evolution by natural selection within populations of individuals (commonly known as microevolution), upwards to specific and supra-specific levels (that is, macroevolution). The question is whether upwards extrapolation suffices to explain higher-level effects. There is a long history of debate over evolution by natural selection, one view asserting that intrapopulational selection and microevolution is sufficient to extrapolate to macroevolutionary levels. In this view, hierarchy is a useful tool for ordering and classifying, but that is all. In contrast, we have Gould's (2002) exposition of evolutionary hierarchy (Table 4) in radical denial of extrapolation and in radical affirmation of its opposite, emergence. In this view the organic world is tiered nonfractally, a different process operating at each level (of the upper three) in the hierarchy, so that the hierarchy is very important indeed. Without necessarily supporting this scenario in all respects, we can state that hierarchical thinking has a strong and solid presence in macroevolutionary thinking (Jablonski, 2007).

The third biological hierarchy is ecological and environmental. Paleoecology has been more an applied discipline, i.e. biofacies rather than communities, illuminating geological questions such as depth of water, shoreline position, structure of the stratigraphic package and so

Table 4
Gould's (2002) argument of non-fractal and non-extratrapolational hierarchy in the individuated organic world, three Darwinian individuals being produced by tiered evolutionary processes at their respective ranks. Speciational and transformational evolution are *both* variational, i.e., "Darwinian", but hierarchical (Mayr, 1992). McGowran (2005, Table 8.2).

Level	Darwinian individual		Non-fractal tiering
VI	Clade-individual	Third Tier	Catastrophic mass extinction derails punctuated equilibrium
V	Species-individual	Second Tier	Punctuated equilibrium undoes anagenesis; differential success within clades [Speciational evolution]
IV	Deme-individual	First Tier	Anagenesis within populations in ecological time [Transformational evolution; phyletic gradualism]
III	Organism-individual		
II	Cell-individual		
I	Gene-individual		

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on. Whilst regarded as a deep-time extension of modern ecology, on the other hand, paleoecology took quite some time to find its own voice as being more autonomous than that, capable of posing and answering questions that are beyond the time-frames and therefore beyond the competence of (neo)ecology. However, the hierarchical structure of ecosystems is now being taken seriously as essential to understanding their origins and development in deep time (Miller, 2008). Eldredge (2008) has tied the ecological hierarchy rather tightly to the evolutionary hierarchy in his sloshing bucket theory of evolution—environmental-biotic perturbations begin at low levels and the interactions gear up through both hierarchies until we attain mass extinctions at the level of the biosphere. “[T]he larger the environmental jolt, the bigger the environmental reaction, an inherently hierarchical approach” (Miller, 2008).

To summarize: these biological hierarchies are much more than a mere organizing of data and its retrieval and communication (itself essential). The hierarchies are the locus and impetus for developing deep insights and theoretical advances into the evolution of the biosphere. Extrapolation versus emergence is far from settled and the hierarchies are major players in the contest. Perhaps the most thoughtful discussion of these matters thus far (Hottinger, 2001) is saturated with scale (in space and time) and hierarchy. With the relatively trivial exception of adhering to the rules of biological nomenclature, these questions of evolution and earthly biohistory are well and truly in the phenomenal category. Committees do not materialize in macroevolution to vote for, say, Vrba's (1985) turnover pulse versus the Brett and Baird (1995) coordinated stasis. Transnational politics play little part in how we respond to Gould's (2002) splendid vision of emergent levels of biospheric evolution intertwined with global environmental shifts.

3.4. The chronostratigraphic hierarchy is arbitrary and conventional

The contrast with the chronostratigraphic hierarchy could hardly be greater. Our hierarchy is squarely in the framework category. Hollis Hedberg took pains over many years to keep the hierarchy clear of the dramas in the phenomenon category, such as Stille's global episodic cycles, Umbgrove's pulse of the earth, or the Russians' holistic view of the ordering of the stratigraphic record. Hedberg abjured all search for natural divisions of the stratigraphic record, *not* in pursuing the science of understanding earth history as found among its documents, the strata, *but* in erecting chronostratigraphic frameworks according to one's perception of that history. In the Preface to the *Guide* he delivered this warning on the dangers inherent in imposing our Boardroom decisions upon the subtleties and mysteries of nature:

“All of our classifications and terminologies of natural bodies are no more than an attempted ordering contrived by human beings for the purpose of aiding our own imperfect conception and understanding of the infinite complexities of nature; and as such they have all the weaknesses of the human minds in which they have originated. Classification and terminology of rock strata are no exception.” (Hedberg, 1976, v; Salvador, 1994, xvii.)

Harland et al. (1990) in introducing their well-respected time scale observed that “three kinds of decision or agreement need to be made, and made by a single authority (e.g., ICS of IUGS): (1) a scheme of divisions with appropriate rank and classification together with (2) agreed names for each division that shall correspond to the time spans between the boundaries and (3) agreed standardization of the boundaries.” On point (1): “The number of ranks is not a matter of principle but of convenience and is an accident of history.” It “*matters little whether a rigid hierarchy be strictly maintained*” (our emphasis). “Conterminosity. A convenient feature of the hierarchical classification is that boundaries of divisions of higher rank shall coincide with those of lower rank: this is the convention of conterminosity.” Note the tone: convenient, accident, agreement, convention, decision.

Does this mean that chronostratigraphy is dry-as-dust after all? We respond: not at all (McGowran and Li, 2007). But it does mean that we cannot make facile withdrawals from the three biological hierarchies for examples of nested hierarchies or rigid hierarchies to suit ourselves in chronostratigraphy. We see two traditions in late Cenozoic chronostratigraphy but we see no day-to-day problems at all in living with a flexible and very short hierarchy.

We give the concluding comment to an historian of geology, Oldroyd (2005, p. 37), in contrasting stratigraphy and the golden spike with biosystematics in a collection on *Darwinism and Philosophy*. “The decisions as to where to locate the “spikes” are taken by commissions of the International Union of Geological Sciences and have to be ratified by that body. Politics can enter the story. Different countries have vied with one another to “host” stratotype sections. And in any case, the decisions are ultimately decided by voting—or achieving consensual agreement. Thus the ontology of stages and zones falls within the purview of the sociology of knowledge. Stratigraphic subdivisions are evidently not produced by emanation from some Platonic heaven—they are clearly “in” the rocks in some sense; but they are also “in” the geological community, which changes them from time to time. Their ontological status seems ambiguous, in fact more so than that of biospecies, for stratotypes cannot be treated cladistically..., and though they may change they do not reproduce themselves like living organisms! (Moreover, some stratigraphers think that “golden spikes” are of doubtful use.)”

4. The integrity of the Neogene and its natural divisions

We have demonstrated (Hilgen et al., 2008) the progressive lowering of the base of the Quaternary as it consumes preceding stages, lately the Gelasian Stage (Head et al., 2008). This is a climatostratigraphic argument for chronostratigraphic revisionism, in search of a natural and hopefully compelling boundary. There need not be anything inherently wrong with this approach except that there are usually going to be alternative natural boundaries: hence the expansion downwards as (marine!) studies reveal ice ages further back in time. This kind of search for the real beginning underlay Hedberg's deep suspicion of any mingling of chronostratigraphy with one's perception of the nature of the stratigraphic record and what it might be telling us about earth history.

In this vein Lourens (2008) has shown that there are other possibilities with nontrivial cases for the base of the Quaternary. The most impressive is the mid-Pleistocene transition beginning with marine isotopic stage 25 and leading into the seriously cold or “real” Pleistocene with its most intense ice ages at stages 16, 12, 6 and 2.

In this section we take the same approach as the Quaternarists have been taking on the Quaternary to look to the integrity of the Neogene Period and System, firstly by examining its beginning. We have long known that the Cenozoic bio- and geohistorical pattern is broadly twofold on numerous environmental and evolutionary patterns in the pelagic, neritic and terrestrial environmental realms. One example: a bottoming-out in a compiled oxygen-isotopic curve between warming and cooling cycles Pi and Ni (Abreu et al., 1998), a sharp drop in the putative eustatic curve between the (second-order) supercycle sets Tejas B and Tejas A (Haq et al., 1988), and a pronounced waisting in the species diversity pattern of planktonic foraminifera (Norris, 1991) come together in the mid-Oligocene (the two physical curves between 30 and 25 Ma, the biotic plots a little more smoothly) (McGowran, 2005, Fig. 6.2). Truly there is a natural Paleogene and a natural Neogene! Equally truly, the natural Neogene has its ups and downs but is not in itself truncated somewhere towards the present. This of course is the basis for Hörnes' recognition of a two-part Cenozoic–Eocene vis-à-vis the Miocene plus post-Miocene in biotas in the neritic realm (before Beyrich erected the Oligocene).

A.G. Fischer furthered the theory of natural divisions of the biogeohistorical record (Fischer and Arthur, 1977; Fischer, 1981; McGowran, 2005, Fig. 6.1). Fischer's most recent *polytaxic pulse* or *Grabau pulse*—cyclical episode of marine transgression, diversification and ecological expansiveness, of ~32 myrs duration—began in the late Oligocene. As stated above, the planktonic forammininiferal N-zones began there too. The warm-water, photosymbiotic, large-foraminiferal succession in the Tethyan is a succession of chronofaunas (Hottinger, 1997; McGowran and Li, 2000; McGowran, 2005). The Oligo-Miocene chronofauna, recovering after the late Eocene crises, expanded within the late Oligocene. In the Indo-Pacific region, the real beginning of the Neogene larger foraminiferal succession is in van der Vlerk's Tertiary e(1–4) "Stage" within the Chattian (Van der Vlerk, 1955; Adams, 1984). In Paratethys itself the Egerian Stage straddling the Oligocene/Miocene boundary begins the Neogene succession (Steininger, 1977; Piller et al., 2007).

The "real" beginning of the Neogene is in the environmental recovery from the deep, cold spell centred in the mid-Oligocene, ~26 Ma. After this the global oxygen-isotopic signal indicates strong warming and the carbon values increase; meanwhile the high and strongly fluctuating estimates of paleo-CO_2 levels are settling to "modern" values (Thomas, 2008). All of this marks the beginning of Neogene warm times in the Early Miocene. Yet the actual base of the Neogene is slightly higher at what is now seen clearly as a sharp, deep cooling known as glaciation Mi-1—a natural break, sharp and well recognized, but not as comprehensively natural as down in the Chattian; wisely chosen, even so. Should we not adjust the base of the Neogene accordingly, by absorbing some of the Chattian? Our answer is: well, the Paleogene/Neogene = Oligocene/Miocene = Chattian/Aquitanian boundary has been adequately and appropriately defined by a GSSP at a specific level in a marine stratigraphic section at Lemme, Italy (Steininger et al., 1997).

Taking our deep-time and forward-modelling view of the Neogene as a whole, it is clear that the main internal shift is not at the base of the Gelasian (~2.6 Ma), the level that impresses the shallower-time Quaternarists peering down from above. The main shift is at the termination of the Neogene climatic optimum at ~14 Ma within the Serravallian Stage within the middle Miocene. We see it in the terrestrial realm in the shrinking of rainforests and spread of grasslands under C-4 photosynthesis, and in the onset of the Clarendonian chronofauna in the North American mammal succession (Webb and Opdyke, 1995). We see it in the neritic realm in major disruption of both Tethyan and IndoPacific larger-foraminiferal faunas (McGowran and Li, 2000). We see it in oceanic signals firstly of the Monterey carbon shift and then of the rapid expansion of polar ice, so soon after the Neogene climatic optimum (Thomas, 2008). It is a natural early/middle Neogene boundary, conveniently marked micropaleontologically, geochemically and sequence-stratigraphically.

In a Neogene perspective the stratigraphic, environmental and biotic record of the cooling at ~3–2.6 Ma is much less impressive as a natural break than is the Serravallian transition at ~14 Ma, and less impressive still than the beginnings of the natural Neogene. There is a chronological and macroecological parallel in the late Pliocene between the North Atlantic pelagic microfauna (Chapman, 2000) and the Caribbean neritic macrofauna (Jackson and Johnson, 2000). According to the latter, "the modern era began with the extinction of large proportions of the marine and terrestrial biota between 2 and 1 Ma". But we see this as turnover within the continuing Neogene, which is still very much with us in all three modern environmental realms.

To summarize: succeeding a natural Paleogene there is a natural Neogene, a high-level slice of geohistorical and biohistorical record maintaining its integrity through to the present. (Parenthetically, one could never make a comparable case for a natural Tertiary. Just as "reptiles" do not exist as a biotaxon, except as non-amphibians, non-birds, and non-mammals, so too does the "Tertiary" not exist in any natural sense, being merely non-Quaternary, i.e., the "pre-Quaternary" of some authors (e.g., Martini, 1971a,b) The argument for the integrity of the Neogene is developed further in Aubry et al. (2009).

5. The arguments by Stephen Walsh

In his last two papers Walsh (2006, 2008) attacked three positions: (i) replacing the Tertiary/Quaternary with the Paleogene/Neogene, (ii) recognizing the Neogene as extending to the Recent, and (iii) the drive to shift the Pleistocene/Pliocene boundary down to the base of the Gelasian. His arguments and opinions carry the strong imprint of upbringing amongst the "nonmarine siliciclastics" where biocorrelation and age determination are a long way from the deep-marine facies. For example, one of his strongest reasons for retaining the Tertiary is the need for a timeslice which has no evidence for a better chronological resolution than that. One might point out that there is very little difference between a dating as Tertiary and a dating as Cenozoic. Ironically, Walsh dismissed the not dissimilar needs of the advocates for the Neogene—the name "late Cenozoic" would cover all eventualities. As another example, Walsh objected strongly to the normal tendency to relate the zones of biostratigraphy to the biochrons of biochronology, again revealing the perceptual distance between the bones and teeth in molassic wedges and the pelagic microfossils by the million under rigorous cyclostratigraphic constraint.

He attempted to balance the weight of tradition and historical usage with the needs of present and future chronostratigraphy; he saw clearly enough that the disagreements were in the framework category (although not using those categories). However, there is one case, critically important to our case, where historical development could, he thought, be used in his most passionately fought cause. There are three steps: (a) suppressing the full Neogene whilst (b) the Tertiary and Quaternary are here to stay in (c) the rigidly nested hierarchy. He developed the following argument (2006) starting from the "objective common ground" which we can all inhabit in comfort: (i) The Tertiary is of longer duration than the Paleogene, the latter is included entirely within the former, therefore the Tertiary must outrank the Paleogene (the "fundamental principle of hierarchical classification"). (ii) Let us rank the Paleogene and Neogene as Periods, which makes the Tertiary a Subera. (iii) The Tertiary and Quaternary exhaustively subdivide the Cenozoic, so must have the same rank of Subera. (iv) The Quaternary then outranks the Neogene, which cannot be extended to the present, because an inferior unit would then enclose a superior, thereby violating that "most fundamental principle of hierarchical classification". (v) Therefore, the Neogene has to be compressed into the later Tertiary.

We point again to the key assumption driving suppression of the Neogene tradition—that the rigidly nested hierarchy is sacrosanct. However, one might run Walsh's argument from an alternative starting-point (i), namely, that the Neogene is of longer duration than the Quaternary... and so on, along the same lines.

Walsh cited a wide and detailed range of studies and he marshalled arguments in an impressive body of writing ranging more generally on chronostratigaphy centred on the Cenozoic, and now completed by his untimely passing. We share his vast enthusiasm for stratigraphy, always too rare in these times, and we acknowledge his capacity to do the hard yards in the literature and his willing development of argument in copious prose. Our efforts in Aubry et al. (2005) attracted his characteristically robust assessment ("cumbersome, unprincipled, and unnecessary"); and we cherish such charges as "marine hegemony" and "chronostratigraphic imperialism". We are at odds with much of the Walsh viewpoint on strata and geological time, but we concur in spirit with the elegant and warm appreciation given by Philip Gibbard and Tom Deméré at the conclusion of Walsh (2008), which manuscript they ushered into print in Earth-Science Reviews.

6. Conclusion: two options for conserving the historically legitimate Neogene

According to Head et al. (2008) their proposal on the Tertiary and Quaternary "... recognises the distinctive qualities of the Quaternary,

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Table 5A

Two chronostratigraphic configurations as options, each including the real (i.e., Miocene–Recent) Neogene. In each table, time runs right to left, rank increases downwards, and the numerical ages of the boundaries hold. Classification after Lourens (2008). Subdivisions of Pliocene and Pleistocene Epochs are themselves upgraded to epochal level and the rigid hierarchy is preserved. The Quaternary Subperiod is equivalent to the Late Neogene and suspended, and the Tertiary is lost.

		Gelasian Age	Piacenzian A.	Zanclean Age
L Pleistocene Epoch	E Pleistocene Epoch	Late Pliocene Epoch	Early Pliocene Epoch	
Quaternary Subperiod				
Late Neogene Subperiod			Middle Neogene Subperiod	
Neogene Period				
0	0.6 Ma	1.8 Ma		2.72 Ma

Table 5C

Two chronostratigraphic configurations as options, each including the real (i.e., Miocene–Recent) Neogene. In each table, time runs right to left, rank increases downwards, and the numerical ages of the boundaries hold. The Neogene Period and Quaternary and Tertiary Suberas are decoupled into a flexible hierarchy, as in Aubry et al. (2005).

Neogene Period	
Quaternary Subera	Tertiary Subera
Cenozoic Era	

complies *strictly with the hierarchical requirements* of the geological time scale, and respects the historical and widespread current usage of the terms Quaternary and Tertiary" (Abstract; emphasis added). In the Recommendation: "....the term Tertiary has suffered a similar fate to that of the Quaternary....... its attempted suppression was never approved... it enjoys persistent ongoing usage in the literature... *Hence* we reaffirm the legitimacy of the Tertiary and place it in our stratigraphic scheme as a period/system subjacent to the Quaternary Period/System..... *This places* the Paleogene and Neogene as subperiods of the Tertiary... In accepting the Holocene as an epoch distinct from the Pleistocene... *consequently* the terms Pleistocene and Quaternary are both needed... Our proposed scheme...meets INQUA requirements, *obeys the principles of a hierarchical time scale*, and respects historical precedents and established usage" (emphasis added).

Gibbard et al. (2005) added a sociological argument: so many workers produce so many papers that the Pleistocene plus Holocene are almost as important as the whole of the Tertiary, and the [~11–12 kilo-years] Holocene is almost as important as the [40+ mega-years] Paleogene. It was important to their case that the Holocene is scholastically so fecund, because the Holocene needs be kept distinct from the Pleistocene, so that an over-arching term is then needed—the Quaternary. Added to this is the Neolithic human presence (Holocene) and the *Homo* presence (extended Quaternary)—a package neatly congruent with the climatostratigraphic rationale for Gelasian-as-Quaternary. This case is made in the framework category (of course) but with little reference to the phenomenon category (Tables 5A and B).

Our central argument has been to accommodate the Neogene and Quaternary traditions, necessitating a flexible chronostratigraphic hierarchy, in turn necessitating discussion of hierarchies which dominates this paper. The flexible hierarchy (Tables 1 and 5C) is exemplified by two pathways from era to age or back, thus:

either Cenozoic [era]↔Neogene [period]↔Pleistocene [epoch]↔Calabrian [age],
or Cenozoic [era]↔Quaternary [subera]↔Pleistocene [epoch]↔Calabrian [age].

This flexibility violates no natural law, inhibits or obfuscates no scientific or technological enterprise, poses no threat to memory or clarity in so short a hierarchy, and is immune to comparison with the Linnean hierarchy. The Quaternarists emphasize how special and how intensively investigated are the Holocene and Pleistocene. It follows smoothly from their advocacy that as a very special case the Quaternary makes no threat of precedent to chronostratigraphy in the preceding 99.95% of the stratigraphic column. Extreme cases might make bad law, but special treatment can manage extreme cases (McGowran and Li, 2007).

There is another possibility, also based on the conserved Neogene. Lourens (2008) observed that there are options as well as fixing base Quaternary at base Gelasian (where the polar water species *Neogloboquadrina atlantica* is first recorded in the Mediterranean (marine isotopic stage MIS 110 at 2.72 Ma). There are glacials before that, supported by ice-rafted debris in the North Atlantic Ocean. There are warmer times subsequently. The Pliocene/Pleistocene boundary is not an extreme climatic event but even so is well marked. The strongest change comes with the mid-Pleistocene transition to the ~100 kyr-dominated and strongly amplified glacial–interglacial oscillations occur from ~0.6 Ma, with four glacials outstanding: MIS 2, 6, 12 and 16. Lourens pointed out that historical/logical grounds for lowering the Pliocene/Pleistocene = Tertiary/Quaternary boundary to 2.6 Ma are no stronger than for raising it to 0.6 Ma. Moreover, there was stronger environmental impact both climatically and through the advent of *Homo sapiens* (which should appeal to anthropocentric Quaternarists).

Lourens accordingly proposed an upgrading of sub-epochs to epoch (Table 5A). There is an Early Pliocene Epoch comprising the Zanclean and Piacenzian Ages. There are three epochs in the Quaternary Subperiod with boundaries at 0.6 and 1.8 Ma—the Late Pliocene (the Gelasian Age), Early Pleistocene and Late Pleistocene plus Holocene. The Quaternary Subperiod is equivalent to the Late Neogene. The rigid nested hierarchy, not greatly respected according to much of this paper, is here preserved. At first glance the proposed epochs with their 10^5–10^6 years' span would seem to be brief—until we consider the Quaternarists' demand that the Holocene, in all its ~1.10^4 years' extent, one tenth of a Late Pleistocene, be preserved. The Tertiary is lost. However, making the Quaternary a superepoch underpinned by an early Pliocene Epoch softens the sense of the Quaternary being in suspension, within but not of the hierarchy.

Most importantly to the principles informing this paper, the Neogene comprising the Miocene, Pliocene, Pleistocene and Recent, the real Neogene, is conserved in both these chronostratigraphic, framework-category options.

Table 5B

Two chronostratigraphic configurations as options, each including the real (i.e., Miocene–Recent) Neogene. In each table, time runs right to left, rank increases downwards, and the numerical ages of the boundaries hold. The same as in Table 5A, but with the Quaternary ranked as a superepoch and underpinned by the Early Pliocene instead of being suspended.

L Pleistocene Epoch	E Pleistocene Epoch	Late Pliocene Epoch	Early Pliocene Epoch
Quaternary Superepoch			
Late Neogene Subperiod			Middle Neogene Subperiod
Neogene Period			

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Appendix A. Moritz Hörnes and the origins and meaning of the "Neogene"

Fritz Steininger

The term "Neogene" (Hörnes, 1858) was used in writing to Bronn on October 3rd 1853 but published in 1858 (details below). Walsh cited Hörnes (1848) as an earlier reference. There, Hörnes described new discoveries of mammals but did not mention the concept of the Neogene.

In 1853, however, Hörnes himself published a list of Early Miocene molluscs (30 species) from the locality of Ottnang in Upper Austria (the type locality of the Paratethys Stage: Ottnangian, Early Miocene) and in this publication he referred already to the Neogene Epoch ("… Sämtliche Formen gehören der Neogen-Epoche an, und sind größtenteil identisch und jenen des Wiener Beckens….").

After 1853 the term Neogene was clearly well established in the Austrian geological community—Hörnes would have reported on the Neogene in various meetings or seminars with Austrian geologists, especially those working for the Geological Survey. Therefore it is correct to cite the year 1853 for the birth of the expression "Neogen"—the publication and definition appeared in 1858, but the term was used 1853 by Hörnes in the "Ottnang" mollusc publication.

Here are examples demonstrating how widely in the Empire the term was used immediately after its introduction by Hörnes:

Czjzek, J., 1854. Das Rosaliengebirge und der Wechsel in Niederösterreich. Jahrbuch der k.k. geologischen Reichsanstalt, vol. 5, 465–529. Wien.

P. 519: a chapter on: "Tertiärgebilde der Neogenperiode".

Stur, D., 1855. Über die Ablagerungen des Neogen, Diluvium und Alluvium im Gebiet der nordöstl. Alpen und ihrer Umgebung. Sitzungsberichte der mathematische-naturwissenschaftliche Classe der kaiselichen Akademie der Wissenschaften, vol. XVI, 477–539. Wien.

The original citations as written by Stur:

P. 479: "Daher ist im Verlaufe der Abhandlung immer nur von der jüngeren, neogenen (miocen und pliocen) Epoche die Rede."

P. 524: a chapter on: "B. Niveauverhältnisse des Neogenen Meeres."

P. 527: a chapter on: "C. Niveau-Verhältnisse der Alpen zur Neogen-Zeit."

Lipold, M.V., 1856. Erläuterungen geologischer Durchschnitte aus dem östlichen Kärnten. Jahrbuch der k.k. geologischen Reichsanstalt, vol.7, 332–345. Wien.

P. 334: a chapter on: "Tertiärformationen"; this chapter is subdivided in:

"(a) Neogen" and "(b) Eocen".

Jokély, J., 1858. I. Die Tertiärablagerungen des Saazer Beckens und der Teplitzer Bucht." Jahrbuch der k.k. geologischen Reichsanstalt, vol. 9, 519–548. Wien. (This is in Bohemia.)

P. 539: a chapter on: "Neogenperiode": here he referred to all the areas he thought to be of Neogene age.

P. 540: he wrote in this chapter on: "Unter-Neogenen oder oligocenen Bildungen" and referred to the Eger Basin.

Zollikofer, Th. V., 1859. II. Die geologischen verhältnisse des Drautales in Unter Steiermark. Jahrbuch der k.k. geologischen Reichsanstalt, vol.10, 200–219. Wien.

P. 202: "Zwischen diesen Bildungen [he was discussing Mesozoic limestones] ein ausgedehntes, stark verzweigtes, flaches Hügelland, aus schotterreichem Lehm und Conglomeraten der N e o g e n f o r m a t i o n zusammengesetzt…."

P. 216: a chapter on: "VI Neogene Hügelregion".

Finally:

Hörnes, M., 1864. Die fossilen Mollusken des Tertiärbeckens von Wien. Jahrbuch der k.k. geologischen Reichsanstalt, Vol. 14, 14–15. Wien.

Here he defined his Neogene again. In general he pointed out again the differences in the mollusc faunas between the "Eocen" and the "Neogen" and stated that he had nothing against a further subdivision of the two "Hauptetagen" (i.e., Eocen and Neogen) der "Tertiärablagerungen".

And so to:

Hörnes, M., 1858. Mittheilung an Professor Bronn gerichtet. Wien, 3. Oktober 1853. Neues Jahrbuch für Geologie, Geognosie und Petrefactenkunde, p. 806–810.

At that time Hörnes was working intensively on monographing the molluscan fauna of the Vienna Basin. First, he demonstrated the difference between the Eocene and the Miocene molluscan faunas:

P. 806: line 3 to line 6:

"… desto schärfer tritt die Verschiedenheit der Fauna der Eocän- und der Meiocän-Epoche hervor, und desto mehr schwinden die Grenzen, welche die Meiocän-Epoche von der pleiocänen zu trennen scheinen."

P. 806: line 8 to line 11—the definition, in my opinion:

" …um das ewige Einerlei bei Angabe des Vorkommens [for the molluscs] zu vermeiden, beide Ablagerungen (meaning: Miocene and Pliocene) vorläufig unter dem Namen NEOGEN (explanation of the name Neogene: neos = neu and generate = entstehen) in trennenden Gegensatz zu den eocänen zusammenfassen…."

P. 807: last paragraph:

Beyrich was against the name "Neogene" and Hörnes referred to Lyell etc. to make his point in response, and here it is clear—to me—that he was referring to the entire Pleiocene from Lyell and not only to the "older" Pliocene!

P. 808: line 7 to 9:

"…namentlich haben Sie selbst [meant here is: Bronn] schon im Jahre 1839 bei der Herausgabe der ersten Auflage Ihrer "Lethaea" auf diese Verhältnisse wiederholt hingewiesen;…"

If we go now into Bronn's Lethea we read the following (and this is what Hörnes and Berggren (1998, 2005) referred emphatically to):

Bronn, H. G., 1838. Lethea Geognostica oder Abbildungen und Beschreibungen der für die Gebirgs-Formationen bezeichnendsten Versteinerungen. Vol. 2: das Kreide- und Molasse-Gebirge enthaltend, 769–1346. Schweizerbarth, Stuttgart.

Here Bronn went through the ages. In his:

"VI. Fünfte Periode"

"Molasse Gebirge"

"(Tertiär- und Quartär-Formationen)"

he subdivided the "Molasse-Gebirge" into stratigraphic groups—"Gruppen" or as he also called them, "Tertiär und Quartär Formationen".

P. 776:

O. Die erste Molasse-Gruppe (oder erste Tertiär-Formation, (ältere) Großkalk-Formation des Pariser Beckens, Form. des London-Thons, die eocenen Bildungen Lyell's und Deshayes′, das Lower Tertiary der Nord-Amerikaner).

That is clear!

P. 780:

P. Die zweite oder eigentliche Molassen-Gruppe

This group he divided into two parts: (i) what we call Early Miocene (the Bordeaux Basin is his example) and (ii) what we call Middle Miocene to Pliocene (the Vienna Basin and Piedmont are his examples in general).

P. 790:

Q. Die dritte Molassen-Gruppe (die der neuen Bildungen, Alluvial- und Quartäre-Gebilde zum Theil, das Upper Tertiary wenigstens bei Morton).

Here he discussed all the shell-beds which are classified today as Pleistocene and finally he counted in this group all the following sediments:

"Hiezu gesellen sich noch die neueren Delta's der Flüsse, die Niederschläge des Meeres und der See'n, viele Torfmoore, die Schlamm-, Asche- und Lava-Auswürfe thätiger Vulkane, die Korallen-Riffe der Südsee."

Here it is clear that Bronn was referring to all the Pleistocene and even the Holocene deposits—so Hörnes was encompassing all that in his Neogene, and he gave a clear definition of the lower boundary of the Neogene, but was insightful enough to see that the Neogene goes on even to today.

Also Bronn included the Quaternary into his Tertiary, which point also becomes clear upon reading the title of his third Molasse-Group (above).

It is interesting, further, to consult his atlas, where it becomes very clear from the illustrated fossils what he included in his Tertiary and the "Molasse Periode":

Bronn, G.H., 1837. XLVII Tafeln mit Abbildungen zur Lethäa Geognostica. Stuttgart (Schweizerbarth).

Tafel XLIII:
This plate is labelled:
"Terraines tertiares"–"Molassen Periode"–"Tertiary Formations":
under this title he figures mostly teeth from:
"*Elephas primigenius*", "*Bos ? taurus*", *Cervus*", *Ovis aries*"
Besides: "*Mastodon longiristris*", "*Carcharias megalodon*"
Tafel XLIV:
This plate is labelled:
"Terraines tertiares"–"Molassen Periode"–"Tertiary Formations":
under this title he mostly figures entire skeletons from:
"*Ursus spelaeus*", « *Cervus megaceros*" »
Besides: « *Palaeotherium magnum* », *Mastodon giganteum* »
Tafel XLV:
This plate is labelled:
"Terraines tertiares"–"Molassen Periode"–"Tertiary Formations"
Here he figures mostly skulls and teeth from:
Ursus spelaeus, *Hyaena spelaeus*, *Castor fiber*
Besides: *Dinotherium giganteum*

In my opinion this paleontology indicates strongly that Bronn included all the Quaternary in his Tertiary, because he figured all the well-known Quaternary species under the heading of the plate: "Terraines tertiares"–"Molassen Periode"–"Tertiary Formations".

Note added in proof

In May 2009 the International Commission on Stratigraphy accepted incorporating the Quaternary Period/System in the geological time scale, also shifting its lower boundary from 1.8 Ma down to ~2.6 Ma. The casualty is the Neogene Period/System, decapitated at ~2.6 Ma and demoted to a position within the Tertiary Period/System. The International Union of Geological Sciences ratified that decision in June 2009. However, these actions in the framework category do not invalidate the scientific arguments on chronostratigraphic principles and practice advanced in this paper.

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