by Lucas J. Lourens

On the Neogene–Quaternary debate

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A proposed resolution to the current Neogene–Quaternary debate involves independent, non-overlapping status for the two units and harks back to Lyell's original denotation of the terms Older and Newer Pliocene.

The Astronomical Tuned Neogene Time Scale 2004

The standard methods to construct geological time scales changed drastically with the advent of the astronomical dating method, which relies on tuning sedimentary cycles or cyclic variations in climate proxy records to target curves derived from astronomical solutions for the solar, planetary and Earth–Moon systems. A major breakthrough of the astronomical theory was established by Milutin Milanković between 1915 and 1940 when he worked out a solid mathematical basis of the late Pleistocene climate cycles (Milankovitch, 1941). With the success of ocean drilling and the development of stable oxygen isotopes ($\delta^{18}\text{O}$) as proxy for global climate change, the astronomical time scale was extended step by step further back in time. Concomitantly, integrated stratigraphic studies of late Cenozoic land-based marine sequences in the Mediterranean yielded an independent astrochronology with many calcareous plankton events, magnetic reversals and Global Stratotype Section and Points (GSSP's), apart from the Aquitanian, directly tied to it. Milestones were the accomplishment of tuning the Brunhes Chron (Johnson, 1982), the Pleistocene (Shackleton et al., 1990), the Late Pliocene (Shackleton et al., 1990; Hilgen, 1991a), the Early Pliocene (Hilgen, 1991b; Tiedemann et al., 1994) and Miocene (Shackleton et al., 2000). Lourens et al. (1996a) verified and slightly modified the astronomical time scale for the Pliocene and early Pleistocene resulting from a comparison with different astronomical solutions. In 2004, the first complete Astronomical Tuned Neogene Time Scale (ATNTS2004) was incorporated in the standard geological time scale (Lourens et al., 2004).

Astronomically tuned ages are typically presented to three decimals without error bar, being the age (in kyr) of the corresponding peak in the selected target curve calculated from a particular astronomical solution. The main uncertainties in astronomical dating and, hence, the astronomical ages in particular, depend on the accuracy of the astronomical solution and the correctness of the tuning. The exact error in the presently used La2004 (Laskar et al., 2004) solution is difficult to calculate due to the complexity of the solution, but the largest uncertainty (i.e., less than a few kyr for the past 3 million years) is thought to be related to the dissipative evolution of the Earth–Moon system; i.e., the dynamical ellipticity of the Earth and/or the tidal dissipation by the Moon (Laskar, 1999; Lourens et al., 2001; 2004).

Another potential error in the astronomical ages stems from the uncertainty in the phase relation between the astronomically-forced variations in the climate proxy records used for tuning and the initial insolation forcing. A fundamental assumption used in many $\delta^{18}\text{O}$ chronologies is that they are tuned to an ice sheet model in which the phase lags of the isotopic signal at the main astronomical frequencies (obliquity and precession) are those of a single-exponential system,

including a fixed ice sheet response time and a non-linearity coefficient (Imbrie and Imbrie, 1980). In their recent global stacked benthic oxygen isotope chronology (LR04) Lisiecki and Raymo (2005 and references therein) applied different values for both parameters to correct for the transition from the nearly ice-free Northern Hemisphere during the early Pliocene (5.3–3.0 Ma) to the full glacial conditions of the late Pleistocene. Although this tuning procedure takes the long-term trends in global ice volume into account, it still fails to resolve the geometry and response time of individual glacial cycles. Moreover, the uncertainty in the size-prediction of ice sheets, and hence their response times, is augmented by the fact that benthic foraminiferal $\delta^{18}\text{O}$ records preserve not only an ice-volume, but also a deep-water temperature component (Shackleton et al., 1990; Bintanja et al., 2005). Nevertheless, the uncertainty in the absolute timing of the glacial–interglacial cycles is supposed to be less than ~5 kyr. Similarly, the uncertainty in the astrochronology of the Mediterranean is on the order of 3 kyr for each calibration point, depending upon the assumed phase relation between insolation and the cyclic sedimentary (i.e., sapropels) expression (Lourens et al., 2004).

Global climate change over the past 5.3 Ma

Figure 1 displays the variations in the global benthic $\delta^{18}\text{O}$ record (Lisiecki and Raymo, 2005) spanning the current Pliocene, Pleistocene and Holocene Epochs. This record depicts a major change towards heavier values around 4 Ma, interpreted as reflecting the beginning of a cooling trend associated with the growth of major Northern Hemisphere ice caps superimposed on short-term obliquity-dominated glacial cycles (Shackleton, 1997). At 3.3 Ma a marked cooling event occurs during the Mammoth subchron (Pell, 1984; Keigwin, 1986). Approximately at this point the background values of the LR04-stacked $\delta^{18}\text{O}$ record passed present-day values for the first time.

Marine Isotopic Stage (MIS) 100 to 96 are clearly-defined glacial periods and are associated with a significant amount of ice rafted debris (IRD) in the North Atlantic (Shackleton et al., 1984; Raymo et al., 1989). The immediately preceding MIS102–114 are less amplified, but already contain trace amounts of IRD in the Northern Atlantic Deep Sea Drilling (DSDP) Sites 607 and 609 (Raymo et al., 1989). Besides isotopic evidence, this climatic deterioration is denoted by the first occurrence of the extinct polar water planktonic foraminiferal species *Neogloboquadrina atlantica* in the Mediterranean during MIS 110 at 2.72 Ma (Lourens et al., 1996a). *Neogloboquadrina atlantica* became extinct at the end of MIS 96 (Zachariasse et al., 1990), indicating a return to warmer background climate conditions between the less prominent glacial cycles of MIS 96 to 82. Two punctuated glacial stages, MIS 78 and 82, occur again around 2.1 Ma.

The Pliocene/Pleistocene boundary at 1.806 Ma (Hilgen, 1991a; Lourens et al., 1996b; 1998; 2004) as defined in the Vrica section (Aguirre and Pasini, 1985) is not represented by an extreme climatic event in the global $\delta^{18}\text{O}$ record (Figure 1), but its significance in terms of cooling is corroborated by the first common occurrence of sinistrally-coiled *Neogloboquadrina pachyderma* in the North Atlantic DSDP Site 607 and the Mediterranean (Lourens and Hilgen, 1997). Until MIS 25, the early Pleistocene is characterized

Figure 1 Comparison between major events in the global benthic foraminiferal $\delta^{18}\text{O}$ stacked record (Lisiecki and Raymo, 2005) and the historical (Lyell, 1833–73; Haug, 1908–1911; Rio et al., 1991) and present (Lourens et al., 2004) chronostratigraphic subdivision of the late Cenozoic.

by very regular glacial cycles. Thereafter, a marked transition (known as the mid-Pleistocene transition) to the approximately 100 kyr dominated and strongly amplified glacial-interglacial oscillations occurred. Four major glacial periods stand out in the late Pleistocene $\delta^{18}\text{O}$ record; MIS 2, 6, 12 and 16. Only during these glacial periods were climate conditions in Europe cold enough to permit the Fennoscandian ice cap to expand south of the Baltic (Boulton et al., 1997). Moreover, these intervals correspond with the thickest units (i.e., cycles B, C, F and H) in the loess–palaeosol record of Central Europe (Kukla, 1975).

The Plio–Pleistocene and Neogene–Quaternary debate

In 2007 the International Commission on Stratigraphy (ICS) held a ballot to place the Quaternary System above the Neogene with its base at the GSSP of the Gelasian Stage. Following the ballot, which was passed with a majority of votes, an official proposal was sent to the International Union of Geological Sciences (IUGS). The main arguments in favor of this proposal are that the Quaternary is of special significance in terms of climate cycles and human evolution, and that the historical usage of the term Neogene has been variable. In turn, arguments in favor of retaining the Neogene extending to the Recent are its original definition, its widely adopted concept in terms of (marine) biostratigraphical zonation schemes, and also that its astrochronology has now become an integral part of the late Cenozoic chronostratigraphic time scale. Moreover, in view of the fact that the Primary, Secondary and Tertiary have been eliminated from the geologic time scale, it is legitimate to ask as to why the Quaternary should still remain a part of the standard geologic time scale? In fact, the climatic argument to define the Quaternary as the glacial age (c.f. Forbes 1846) is now no longer strictly correct, since extensive ice-rafted debris, including macroscopic dropstones, have been iden-

tified in upper Eocene to lower Oligocene and in upper middle to upper Miocene sediments in the Norwegian–Greenland Sea, indicating glaciations of East Greenland long before 2.6 Ma (Wolf-Welling et al., 1996; Thiede et al., 1998; Eldrett et al., 2007).

The recent historical overview of Stephen L. Walsh (2008) on the origin, adoption, evolution, and controversy of the term Neogene (Höernes, 1853, 1864) proves on the other hand that historical arguments to extend the Neogene to and including the Recent (Lyell, 1857) and Holocene of Gervais (1867; see Berggren, 1998) are difficult to substantiate from the original publications and communications of Höernes. But, it also makes clear that whether or not the Diluvium (or post-Pliocene sensu Lyell, 1857) was part of the Neogene, the latter term certainly included various Newer Pliocene (Lyell, 1857) deposits that are now considered to be Early, Middle and possibly even Late Pleistocene in age (Rio et al., 1991; Vai, 1997; Walsh, 2008) (Figure 1).

The current Neogene–Quaternary debate as such does not originate from the proposition to lower the base of the Quaternary (and hence the top of the Tertiary; Head et al., this volume), but from the fact that this proposal decapitates the Neogene as well as extending the Pleistocene Series to include strata that for more than a century and a half have been considered by (marine) stratigraphers to be Pliocene deposits (Figure 1). Several (compromise) proposals that have been submitted to unify the opposing viewpoints (see Ogg, 2004; Pillans and Naish, 2004; Aubry et al., 2005; Walsh, 2006) have not garnered broad support from the (late Cenozoic) chronostratigraphic community, largely because they lack a chronostratigraphic hierarchy.

Another major shortcoming in the present debate is that the arguments of lowering the Pleistocene/Pliocene (and Tertiary/Quaternary) boundary to 2.6 Ma (i.e., Head et al., and Ogg and Pillans this volume) are on historical grounds no more logical than raising it to ~0.6 Ma. Moreover, it could be argued that the climatic transition between 0.6 and 0.9 Ma from the less-amplified 41 kyr glacial cycles to the large scale 100 kyr dominated glacial cycle had a larger impact on ecosystems, including human evolution (origin of *Homo sapi-*

ens), than the gradual transition around 2.7 Ma (Figure 1). Finally, in terms of climate science, only the last ~0.6 Myr of Earth's history can be studied in all geological archives, including ice core records, making the younger option, also in that sense, more relevant than the older option.

To conclude, I am of the opinion that a general consensus on the “time war over the Period we live in debate” (Kerr, 2008) can only be reached if the Neogene remains extended to the present, and that the position of the present Pliocene/Pleistocene boundary remains unchanged. If the Quaternary (and Tertiary) retains a formal chronostratigraphic status in the standard Geological Time Scale with its base at a refined Gelasian GSSP (i.e., the FO *N. atlantica* in the Mediterranean at 2.72 Ma) then a solution for the hierarchical inconsistency of the chronostratigraphic chart may have been found. Such a solution would hark back to Lyell's original Older and Newer Pliocene Epochs, could upgrade the present Upper, Middle and Lower Pliocene Subseries to separate Late Pliocene and Early Pliocene Epochs with its boundary at 2.72 Ma. In addition, the present Pleistocene could be split into separate Early, (Middle) and Late Pleistocene Epochs.

With the renewed introduction of the Early and Late Pliocene as separate Epochs, all stratigraphic criteria to define the base of the Quaternary as a Subperiod (Subsystem) of the Neogene are fulfilled. Namely 1) the boundary-stratotype is fixed by its lower boundary, 2) it follows the principles of “base defines boundary”, 3) the boundary stratotype can be fixed in marine sediments, 4) it respects the historical usage (albeit not a true historical priority and age), and 5) it focuses as much as possible on the best correlation potential, which is in this case the base of the (refined) Gelasian Stage (Rio et al., 1998) as the basal unit or the base of the Late Pliocene Epoch. Hence the Quaternary will encompass the Late Pliocene, Early, (Middle) and Late Pleistocene and Holocene Epochs, thereby respecting its historical usage in its broadest sense and its consistence with the principles of hierarchical classification.

A redefinition of the Quaternary as Subperiod will imply that an official end has come to the Tertiary (Arduino, 1760) as a formal unit of the GTS (see also Pillans, 2004). But, if the Tertiary and Quaternary are to be formally defined and ranked again (Walsh, 2006; Head et al., this volume) then one should rank them as Suberas of the Cenozoic (Aubry et al., 2005) and split the Neogene into an Early, Middle and Late Neogene Period. A split Neogene is not new: Renevier (1874; 1897) for instance already included the Holocene, Pliocene (Renevier's spelling) and Pliocene in his Recent Neogenic, and Prepliocene and Miocene within the Ancient Neogenic, whereas the Nummulitic represented the Paleogene. Accordingly, the Middle–Late Neogene boundary would correspond to the base of the (refined) Gelasian Stage or Early–Late Pliocene boundary, and the Late Neogene would encompass the same time interval as the Quaternary, thereby respecting the usage of both terms in the current literature.

Acknowledgements

I thank Frits Hilgen, Brad Pillans, Bill Berggren, Jim Ogg and Brian McGowran for discussion and additional comments on earlier draft versions of the manuscript.

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