by Marie-Pierre Aubry[1]*, Kenneth G. Miller[1], Elena Turco[2], José Abel Flores[3], Andrey Gladenkov[4], Patrick Grunert[5], Frits Hilgen[6], Hiroshi Nishi[7], Ann Holbourn[8], Wout Krijgsman[9], Fabrizio Lirer[10], Werner E. Piller[11], Frédéric Quillévéré[12], Isabella Raffi[13], Marci Robinson[14], Lorenzo Rook[15], Jun Tian[16], Maria Triantaphyllou[17], and Felipe Vallejo[3,18]

Ratification of Neogene subseries as formal units in international chronostratigraphy

[1] Department of Earth and Planetary Sciences, Rutgers University, Piscataway, NJ 08873, USA; *Corresponding author, *E-mail: aubry@eps.rutgers.edu*
[2] Dipartimento di Scienze chimiche, della Vita e della Sostenibilità Ambientale, Università degli Studi di Parma, Parco Area delle Scienze 157/A, 43124 Parma, Italy
[3] Departamento de Geologia, Universidad de Salamanca, 37008 Salamanca, Spain
[4] Geological Institute of Russian Academy of Sciences, Pyzhevsky per., 7. Moscow 119017, Russia
[5] University of Cologne, Institute of Geology and Mineralogy, 50674 Cologne, Germany
[6] Department of Earth Sciences, University of Utrecht, 3508 TA Utrecht, The Netherlands
[7] Institute of Dinosaur Research, Fukui Prefectural University, Eiheijicho, Fukui, 910-1142, Japan
[8] Institute of Geosciences, Christian-Albrechts Universität zu Kiel, D-24118 Kiel, Germany
[9] Department of Earth Sciences, University of Utrecht, 3508 TA Utrecht, The Netherlands
[10] Dipartimento di Scienze della Terra, Sapienza Università di Roma, P. Aldo Moro 5, 00185 Roma, Italy
[11] Institut für Erdwissenschaften, NAWI Graz Geocenter, Universität Graz, 8010 Graz, Austria
[12] Université Claude Bernard Lyon 1, ENS de Lyon, CNRS, UMR 5276 LGL-TPE, F-69622 Villeurbanne, France
[13] Dipartimento di Ingegneria e Geologia (InGeo), Università degli Studi "G. d'Annunzio" di Chieti-Pescara, 66013 Chieti Scalo, Italy
[14] U.S. Geological Survey, Florence Bascom Geoscience Center, Reston, VA 20192, USA
[15] Dipartimento di Scienze della Terra, Università degli Studi di Firenze, 4-50121 Firenze, Italy
[16] State Key Laboratory of Marine Geology, Tongji University, Shanghai, 200092, China
[17] National and Kapodistrian University of Athens, Faculty of Geology & Geoenvironment, Athens, Greece
[18] Instituto de Investigaciones en Estratigrafía (IIES), Universidad de Caldas, Calle 65 # 26-10, Manizales, Colombia

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The International Union of Geological Sciences Executive Committee (IUGS EC) voted on 13 October 2021 to ratify a proposal for the Neogene subseries/subepochs to have formal status. They are now incorporated into a six-tiered chronostratigraphic hierarchy within the International Chronostratigraphic Chart (ICC). The Lower/Early Miocene Subseries/Subepoch comprises the Aquitanian and Burdigalian stages/ages, the Middle Miocene Subseries/Subepoch comprises the Langhian and Serravallian stages/ages, the Upper/Late Miocene Subseries/Subepoch comprises the Tortonian and Messinian stages/ages, the Lower/Early Pliocene Subseries/Subepoch comprises the Zanclean Stage/Age and the Upper/Late Pliocene Subseries/Subepoch comprises the Piacenzian Stage/Age. This ratification is an important move towards both a common language in the wider Earth Sciences community and a step forward in the unification of Cenozoic chronostratigraphy, with Neogene and Quaternary subseries/subepochs now formalized.

Introduction

After several years of intense discussion, the status of subseries/subepochs has been firmly established with the ratification of their formal rank by the IUGS Executive Committee as of 1 May 2021 (Aubry et al., 2021). This makes the rank Subseries/Subepoch available to any subcommission of the International Commission on Stratigraphy (ICS) that sees a need for such units. This also implies that subcommissions which already accept the informal use of such units are encouraged to consider whether these long-standing terms, that are broadly used by the Earth Sciences community from Lyell's time to this day, should be recognized by a formal definition of their chronostratigraphic meaning, or remain informal without precise chronostratigraphic significance.

Brief Historical Background

The Neogene chronostratigraphy has been remarkably stable through time, and subseries/subepochs have been treated as consistent concepts with formal meaning, at least in intent if not officially. The concept of Miocene and Pliocene subseries originated with Lyell (1833, p. 57, 58: "Thus for example, we might have three divisions of the Eocene, — the older, middle and newer; and three similar subdivisions, both of the Miocene and Pliocene epochs."). The simultaneous spreading of stage naming in Europe and development of global plankton stratigraphy worldwide during much of the 20th Century led to concurrent correlations between stages and subseries that became resolved in the consequential publication "Tertiary boundaries and their correlations" in which Berggren (1971) suggested a conventional threefold chronostratigraphic subdivision of the Miocene (p. 755), with the Lower/Early Miocene Subseries/Subepoch comprised of the Aquitanian and Burdigalian stages/ages, the Middle Miocene of the Langhian Stage/Age and the Upper/Late Miocene of the Tortonian and Messinian stages/ages [note the use of upper case initial letters for the positional terms in the original text, indicating an intended formal status for the subseries/subepoch which became broadly accepted by the scientific community; however, formal definitions of chronostratigraphic units would not become mandatory until the late eighties (Cowie et al., 1986; Remane et al., 1996)]. Berggren questioned the usefulness of the Serravallian Stage and recommended extension of the Langhian Stage up to the base of the Tortonian Stage. He also recommended locating the base of the Upper/Late Miocene at the base/onset of the Tortonian Stage/Age rather than at the base/onset of the Messinian, the two stages being "intimately linked both in terms of sedimentology and fauna". This threefold chronostratigraphic subdivision has been followed to this day, but with the addition of the Serravallian Stage/Age to the Middle Miocene Series/Epoch (RCMNS Congress in Bratislava 1975; in Hilgen et al., 2009, p. 153). Conventional chronostratigraphic division of the Pliocene Series/Epoch has varied between twofold and threefold over the years (see review in Berggren, 1971) but was stabilized as threefold with the Zanclean corresponding to the Lower Pliocene and the Piacenzian to the Middle Pliocene when the Gelasian was introduced specifically as an Upper Pliocene stage (Rio et al., 1998). The decapitation of the Neogene System to satisfy requests of the Quaternary community has resulted in the Gelasian Stage reassigned to the Pleistocene Series in the Quaternary System and the Piacenzian reallocated to the Upper Pliocene (Van Couvering et al., 2009 and references therein).

During the late nineties and until recently, references to subseries were systematically made with capitalized positional names when newly ratified Global boundary Stratotype Section and Points (GSSPs) of Miocene and Pliocene stages were described. These units, however, continued to be inconsistently treated as formal or informal in the literature, including scientific journals, textbooks and the various iterations of the Ocean Drilling Program (Head et al., 2017). The Second International Stratigraphic Congress (STRATI 2015, Graz) provided the opportunity to review the status of subseries, and two opposite views were expressed. One view was that, in addition to the very wide use of well-defined subseries in Earth Sciences, the alignment of their lower and upper boundaries with the GSSPs of their bounding stages justified their formal recognition as chronostratigraphic units within the international system (Aubry, 2016; Head et al., 2017). The other view was that a formal rank intermediate between stage and series was unnecessary and, in fact, detrimental to the broad recognition of stage as the fundamental unit of chronostratigraphy (Pearson et al., 2017). For these authors, subseries should be both chronostratigraphic (i.e., tied to GSSPs) and informal.

In an attempt to resolve the situation, in 2016 the ICS organized an informal vote of the three subcommissions of the Cenozoic. As reported in Finney and Bown (2017), the Subcommission on Quaternary Stratigraphy (SQS) voted strongly in favor of formalization, whereas the International Commission on Paleogene stratigraphy (ISPS) voted strongly against it. The Subcommission on Neogene Stratigraphy (SNS) was short of a required 60 % majority with 10 "yes" and 7 "no" votes. The ensuing procedural disharmony in Cenozoic chronostratigraphy became a reality when subseries/subepochs were formally ratified for the Holocene and Pleistocene (Walker et al., 2018, 2019; Head et al., 2021).

The formalization of six Quaternary subseries/subepochs implied, however, that the concept was now accepted by the International Subcommission on Stratigraphic Classification (ISSC) and the North American Commission on Stratigraphic Nomenclature (NACSN) (Aubry et al., 2020a, b), making it illogical for pre-Quaternary subseries to remain informal (Aubry and Piller, 2021). This led to a proposal ratified on 1 May 2021 by the IUGS Executive Committee for "formal adoption of chronostratigraphical/geochronological unit divisions Subseries/Subepoch within the *International Stratigraphic Guide*". With this ratification, subseries/subepoch became a formal rank in a six-tiered chronostratigraphic hierarchy of stage/age, subseries/subepoch, series/epoch, system/period, era/erathem and eonothem/eon.

Rationale for a Decision on the Status of the Neogene Subseries/Subepochs

After the 2016 vote, the Neogene subseries/subepochs continued to be treated as informal units by the SNS, regardless of historical precedent and their clearly hierarchical definition with boundaries set by the GSSPs of their incorporated stages/ages. This situation now requires reconsideration in view of the IUGS Executive Committee ratification of the proposal cited above, according to which subseries/subepoch are specifically identified as a formal rank immediately above stage/age. Formal rank implies that subseries/subepochs should no longer be used informally, i.e., subseries cannot be both informal and of global chronostratigraphic value (Aubry and Piller, 2021), and suitable action by relevant subcommissions has been requested by the ICS. On 30 January 2020, the explicitly defined subseries/subepochs for the Quaternary were *formally* ratified and incorporated in the International Chronostratigraphic Chart (ICC) (Head et al., 2021). Informally defined units of this scale should be seen at best as local terms with no global chronostratigraphic meaning. Consequently, the SNS bureau asked the SNS voting members to vote once more on the status of subseries/subepochs in Neogene chronostratigraphy. The question was formulated as follows:

Should the chronostratigraphic hierarchy for the Neogene include properly defined subseries/subepochs *as a formal rank, with Lower/Early Miocene (comprised of the Aquitanian and Burdigalian* stages/ages*), Middle Miocene (comprised of the Langhian and Serravallian* stages/ages*), Upper/Late Miocene (comprised of the Tortonian and Messinian* stages/ages*), Lower/Early Pliocene (corresponding to the*

Zanclean Stage/Age) and Upper/Late Pliocene (corresponding to the Piacenzian Stage/Age)?

A **yes vote** would recognize their formal status and incorporation in the ICC. Subseries would then be denoted by the positional adjectives *Lower*, *Middle* and *Upper*, and subepochs by the positional adjectives *Early*, *Middle* and *Late* (note the uppercase initial letter in these adjectives). A **no vote** was to say that SNS does not recognize subseries/subepochs as useful units in Neogene chronostratigraphy, accepting the loss of the chronostratigraphic meaning that is otherwise conveyed by formal status.

It is important to note that this vote was not merely an academic matter. The Earth Sciences community relies on the chronostratigraphic meaning of subseries/subepochs in disciplines as different as, inter alia, geophysics, paleoceanography and paleobiology. To cite only one example, Upper and Late Miocene have been cited 260,000 and 264,000 times each between 1 January 1996 and 8 January 2021 compared to 15,600 and 22,000 times for Tortonian and Messinian Stages, respectively (from Aubry and Piller, unpublished). In addition, from an editorial point of view, a stylistic editorial change from upper/late Pliocene in the Neogene to Lower/Early Pleistocene in the Quaternary is not only cumbersome but difficult to rationalize, particularly in view of the fact that the latter expression carries a global chronostratigraphic message which is no longer borne by the former expression. Finally, from a procedural point of view and considering that the subseries of the Quaternary are formal and not to be demoted in the foreseeable future, the vote of SNS was a de facto move towards or against the re-establishment of unity in Cenozoic chronostratigraphy.

Ratification of the Proposal for Formal Neogene Subseries and Definitions

Following an engaging discussion, the SNS voted on 20 July 2021 with a majority of 81.25 % (13 Yes, 3 No, and 1 Abstention) in favor of formal Neogene subseries/subepochs. The proposal for formal status of the Neogene subseries/subepochs was approved by the ICS on 24 September 2021 and forwarded to the IUGS EC which ratified it on 13 October 2021. The Neogene subseries/subepochs are now part of the ICC (https://stratigraphy.org/ICSchart/ChronostratChart2021-10.pdf).

The Neogene subseries/subepochs are defined by the GSSPs of the respective lowermost incorporated stages (Fig. 1). These GSSPs have been defined in the Mediterranean area where they are bracketed by bio-, magneto- and isotopic events that provide intra- and interregional means of correlations, that is, they provide the means to approximate GSSPs away from the global boundary stratotype sections. These events thus serve to approximate/correlate the base of the Neogene subseries/subepochs (Fig. 1). Magnetostratigraphic and chemostratigraphic events are global and superior means of delineating accurately and precisely the boundaries, but biostratigraphy offers more immediate means of correlation in addition to providing the necessary temporal context of faunal succession. Some biostratigraphic events are truly global (e.g., the extinction of the calcareous nannoplankton (CN) genus *Sphenolithus*) whereas others are applicable only *within* or *outside* the Mediterranean area. The biostratigraphic datum points given in Fig. 1 are those that afford maximum reliability across broad geographic areas.

The base/onset of the Lower/Early Miocene Subseries/Subepoch, which encompasses the Aquitanian and Burdigalian stages/ages, is defined by the base of the Aquitanian Stage which is marked by a prominent decrease in $CaCO_3$ content of the silty clays at level 35 m as measured from the top of the Lemme-Carrosio section in northern Italy (Steininger et al., 1997). The primary means of global correlation are the 1) Lowest Occurrence (LO) of calcareous nannoplankton (CN) *Sphenolithus capricornutus*, and 2) LO of the planktonic foraminifera (PF) *Paragloborotalia kugleri*. Secondary markers include, among others, the LO and HO of (CN) *Sphenolithus delphix* and the LO of (PF) *Globoquadrina dehiscens*. Although the reliability of the magnetostratigraphic record of the Lemme-Carrosio section is questionable, correlation with Deep Sea Drilling Project (DSDP) Site 522 implies that the GSSP lies very close to Subchron C6Cn.2n(o) (Shackleton et al., 2000).

Importantly, the base of the Aquitanian Stage at level 35 in the Lemme-Carrosio section defines the boundary between the Neogene and Paleogene systems/periods and that of the Oligocene/Miocene series/epochs. Because no formalized Paleogene subseries presently exist, there is no Upper Oligocene/Lower Miocene boundary and Late Oligocene/Early Miocene Epoch boundary while the expressions upper Oligocene/Lower Miocene and late Oligocene/Early Miocene should be discouraged (as well as upper Oligocene-Lower Miocene and late Oligocene-Early Miocene that designate a stratigraphic interval and a duration, respectively) for integrating stratigraphic units of different values.

The Middle Miocene Subseries/Subepoch encompasses the Langhian and Serravallian stages/ages. A proposal will be considered for the definition of the GSSP of the base of the Langhian Stage in the La Vedova section in Italy, at a level (17.84 m) very close to the top of Chron C5Cn (at 15.795 m) (Turco et al., in prep.). The forthcoming definition will simultaneously apply to the base of the Middle Miocene Subseries/Subepoch, and, if accepted, the Chron C5Cn/C5Br magnetic reversal will thus be the primary means of correlation of the base of the Middle Miocene (Hilgen et al., in prep.).

The base/onset of the Upper/Late Miocene Subseries/Subepoch, encompassing the Tortonian and Messinian stages/ages, is defined by the GSSP of the Tortonian Stage located in the Monte del Corvi section, near Ancona in Italy, at the mid-point of the sapropel of small-scale sedimentary cycle 76 (Hilgen et al., 2005). Primary markers for global correlations include the base of the short magnetic Subchron C5r.2n, and the Highest Common Occurrences of (CN) *Discoaster kugleri* and (PF) *Globigerinoides subquadratus*. Correlation with the Auxiliary Boundary Stratotype of Gibliscemi (Sicily) shows that the GSSP level slightly predates oxygen isotope event Mi-5 (Hilgen et al., 2005). In the terrestrial record, the GSSP level is ~0.5 Myr older than the First Appearance Datum (FAD) of *Hipparion* in Eurasia whereas it is essentially correlative with the Barstovian/Clarendonian boundary in the North American Land Mammal Age scheme.

The base/onset of the Lower/Early Pliocene Subseries/Subepoch is defined by the GSSP of the Zanclean Stage, at the base of the Trubi Formation in the Eraclea Minoa section on the southern Coast of Sicily in Italy (Van Couvering et al., 2000). This level lies in Chron C2Ar (Gilbert Subchron) and is identified as Insolation cycle 510 counted from the present which serves as a primary marker for global correlation together with the proximity of the base of Chron C3n.4n (Thvera

Ma (base)	System/ Period	Series/ Epoch	Subseries/ Subepoch	Stage/ Age	Definition	Main Means of Correlation: Biostratigraphy	Magneto-stratigraphy	Isotopic and Astronomical events
2.58	Quat.	Pleist.	L./E.	Gelasian	Monte San Nicola Section, Sicily, Italy. Base of marly layer overlying Sapropel MPRS 250 [~1 m above G/M reversal]		Gauss/ Matuyama [G/M]Reversal	MPRS 250; ~MIS 103
3.60	Neogene	Pliocene	Upper/ Late	Piacenzian	Marly bed of the small scale carbonate cycle 77, in Punta Piccola Section, Sicily, Italy	HOs *Sphenolithus* spp., HOs *G. margaritae*, and *P. primalis*	Gilbert/Gauss Reversal	Precessional excursion 347
5.33	Neogene	Pliocene	Lower/ Early	Zanclean	Base of the Trubi Formation in Eraclea Minoa Section, Sicily, Italy	HOs *T. rugosus* and *D. quinqueramus;* LO *C. acutus;* LOs *G. tumida and G. sphericomiozea*	Base Subchron C3n.4n (Thvera)	Insolation cycle 510
	Neogene	Miocene	Upper/ Late	Messinian				
11.63	Neogene	Miocene	Upper/ Late	Tortonian	Mid-point of sapropel of small scale sedimentary cycle 76 in Monte dei Corvi Beach Section, Italy	HCOs *D. kugleri* and *G. subquadratus*; predates FAD *Hipparion*; equates NALMA Barstovian/ Clarendonian	Base Subchron C5r.2n	$\delta^{18}O$ Mi-5 Event
	Neogene	Miocene	Middle	Serravallian				
[15.97]	Neogene	Miocene	Middle	Langhian	[Level 15.795 m in La Vedova Section, Italy, near top of Chron C5Cn]		[Chron C5Cn/C5Br reversal]	
	Neogene	Miocene	Lower/ Early	Burdigalian				
23.03	Neogene	Miocene	Lower/ Early	Aquitanian	35 m from the top of the Lemme-Carrioso Section, Italy, marked by a sharp decrease in $CaCO_3$ content	LO and HO *S. capricornutus* within 1 m of GSSP; LO *P. kugleri* 3 m above GSSP	Subchron C6Cn.2n	$\delta^{18}O$ Mi-1 Event
	Pal.	Olig.		Chattian				

Figure 1. Chronostratigraphic subdivisions of the Neogene System/Period, and definitions of the Miocene and Pliocene subseries/subepochs. The bases of the Neogene subseries/subepochs are defined by the GSSPs of their lower stage. Definitions of the GSSPs are given here together with the means of correlation. Numerical ages of the relevant stage GSSPs (and thus numerical ages of subseries/subepoch boundaries) are those in the ICC. Full names of taxa: Planktonic foraminifera*: Globigerinoides subquadratus, Globorotalia margaritae, G. tumida, G. sphericomiozea, Paragloborotalia kugleri, Pulleniatina primalis. *Calcareous nannoplankton*: Ceratolithus acutus, Discoaster kugleri, Discoaster quinqueramus, Sphenolithus capricornutus, Triquetrorhabdulus rugosus. *(Taxonomy as used in original definitions of relevant chronostratigraphic units): FAD: First Appearance Datum; HO: Highest Occurrence; HCO: Highest Common Occurrence; MPRS: Mediterranean Precession Related Sapropels; NALMA: North American Land Mammal Age. Gauss/Matuyama = Chron C2An/C2n magnetic reversal; Gilbert/Gauss = C2Ar/C2An magnetic reversal. Note: preferred terminology varies among authors so that 'calcareous nannoplankton', 'calcareous nannofossils' and 'coccolithophores' are alternate terms. Terminology also varies with regard to the description of the ranges of taxa, with some authors using strictly stratigraphic terms (i.e., LO, HO; HCO [see above]) while other authors use terms with dual stratigraphic and temporal connotation (respectively: First and Last Occurrences: FO and LO; Last Common Occurrence: LCO; see discussion in Aubry, 2015). To avoid the confusion resulting from the same acronyms for different concepts only strictly stratigraphic terms are used herein.

magnetic event) only five precessional cycles younger. Biostratigraphic markers for long distance correlation include the HO of (CN) *Triquetrorhabdulus rugosus* and the LO of (CN) *Ceratolithus acutus* and, outside the Mediterranean area, the HO of (CN) *Discoaster quinqueramus* and LOs of (PF) *Globorotalia tumida* and *G. sphericomiozea* (the latter being considered unreliable, Wade et al., 2011, p. 121).

The base/onset of the Upper/Late Pliocene Subseries/Subepoch corresponds to the base of the Piacenzian Stage, defined in the Punta Piccola section of the composite Capo Rossello section by the base of a beige marl bed of the small-scale carbonate cycle 77, which corresponds to precessional excursion 347 counted from the present, and is correlatable on the basis of the Chron C2Ar/C2An (Gilbert/Gauss) magnetic reversal which occurs just above the GSSP (Castradori et al., 1996). The HO of (CN) *Sphenolithus* spp. is a reliable biostratigraphic event for global correlation while those of (PF) *Globorotalia margaritae* and *Pulleniatina primalis* constitute two good proxies for the GSSP level outside the Mediterranean area.

The Upper Pliocene/Lower Pleistocene Subseries and Late Pliocene/Early Pleistocene Subepoch (= Neogene/Quaternary Systems/Periods) boundaries are defined by the GSSP of the Gelasian Stage in the Monte San Nicola section near Gela in Sicily (Rio et al., 1998). The GSSP is the base of a marly layer overlying sapropel MPRS (Mediterranean Precession Related Sapropels) 250 located at 62 m in the section, easily approximated in global correlations by the Chron C2An/C2r (Gauss/Matuyama) reversal (which occurs between 0 and 3 m above the GSSP; Head, 2019) and by Marine Isotope Stage (MIS) 103 (Head, 2019). As indicated above, the Gelasian was initially introduced as a stage/age of the Upper/Late Pliocene Subseries/Subepoch with the Piacenzian being "Middle" Pliocene. Instatement of the Quaternary System/Period has led to a reassignment of these two stratigraphic intervals to reflect the new nomenclature (Gibbard and Head, 2010).

Color Coding of New Units

The Commission for the Geological Map of the Word (CGMW) has developed a color scheme which is used in the ICC (Cohen et al., 2013) such that each chronostratigraphic unit is characterized by a unique color. The CGMW uses color codes in CMKY and RGB (see www.ccgm.org). The use of these codes in publishing and their compatibility are discussed in Head et al. (2021). In this paper (Fig. 1), we follow the CGMW scheme which was updated in February 2022 to provide colors for the recently ratified Neogene subseries (Fig. 2; B. Vrielynck, written communication to MPA, 9 February 2022).

Conclusions

The Neogene System/Period now encompasses two series/epochs, five subseries/subepochs and eight stages/ages, all but two stages and

System / Period	Series / Epoch	Subseries / Subepoch	Stage / Age	CMYK System	CMYK Series	CMYK Subseries	CMYK Stage	RGB System	RGB Series	RGB Subseries	RGB Stage
Neogene	Pliocene	Upper/Late	Piacenzian	0/10/90/0	0/0/40/0	0/5/25/0	0/0/25/0	255/230/25	255/255/153	255/242/205	255/255/191
		Lower/Early	Zanclean			0/5/30/0	0/0/30/0			255/242/195	255/255/179
	Miocene	Upper/Late	Messinian		0/0/100/0	0/5/55/0	0/0/55/0		255/255/0	255/236/140	255/255/115
			Tortonian				0/0/60/0				255/255/102
		Middle	Serravallian			0/5/65/0	0/0/65/0			255/236/115	255/255/89
			Langhian				0/0/70/0				255/255/77
		Lower/Early	Burdigalian			0/5/75/0	0/0/75/0			255/236/85	255/255/65
			Aquitanian				0/0/80/0				255/255/51

Bruno VRIELYNCK
9/02/2022

Figure 2. CMYK and RGB color codes for the Neogene subseries/subepochs as adopted by the Commission for the Geological Map of the World (CGMW). The CGMW defines its colors by CMYK codes; their RGB equivalents are for information only (courtesy of B. Vrielynck).

one subseries tied to the GSSPs of the intervening stages and calibrated through orbital tuning for chronostratigraphic stability. The definitions of the last two GSSPs will follow in due course to complete a comprehensive chronostratigraphic treatment of the Neogene System/ Period. One of the main pre-GSSP successes of the subseries/subepochs has been their convenient duration between the shorter stages/ ages and longer series/epochs, making them particularly useful for straightforward narratives in appropriate fields of Earth Sciences. This is reflected in the discussion of climatic events in terms of subseries, such as the "Early Miocene Climate Optimum" and the "Middle Miocene Climate Transition". The formalization of the subseries of the Neogene fulfills a need in the Earth Sciences community for chronostratigraphic practicality and clarity combined. Their boundaries are correlatable through magnetostratigraphy, isotope stratigraphy and biostratigraphy, ensuring firm global correlation not only in the marine realm, but between the marine and terrestrial realms, although a sustained effort is needed to expand the recognition of chronostratigraphic boundaries in terrestrial records.

The formalization of the Neogene subseries/subepochs goes a long way towards the integration of pre-GSSP chronostratigraphy into current chronostratigraphic philosophy and practice, thus eliminating an unnecessary historical barrier between past and present. It also represents the first step towards re-unification of Cenozoic chronostratigraphy following the controversial inclusion of the Quaternary System/ Period at the expense of the Neogene. The Subcommission on Neogene Stratigraphy thus invites the Subcommission on Paleogene Stratigraphy to consider joining in an effort that can only serve best the Earth Sciences community. Finally, the SNS encourages all interested parties to inform colleagues, students, authors, editors and publishers of the new formal status of the Neogene subseries/subepochs.

Appendix

References to divisions of the Neogene into subseries associated with summaries of ICS subcommissions and ratification of the GSSPs of Neogene stages. Quotes are taken verbatim from the descriptions of GSSPs as published in Episodes, although emphasis (bold initial letter in positional adjectives and their underlining) is ours (although the uppercased initial letters are original). In all instances the names of subserial divisions were printed using an initial uppercase letter, implying intended formal status. If there is any doubt that formalized status was intentional, compare the titles of the papers by Hilgen et al. (2000a) and Hilgen et al. (2005) in describing the GSSPs for the Messinian and the Tortonian Stages, respectively. The titles of the two papers are essentially the same "The Global Boundary Stratotype Section and Point (GSSP) of the …" continuing "Messinian Stage (uppermost Miocene)" in Hilgen et al. (2000a, p. 172) but "Tortonian Stage (Upper Miocene) …" in Hilgen et al. (2005, p. 6). Upper Miocene refers to a chronostratigraphic interval, uppermost does not.

Reproduced from Table 2 (partim) in Aubry (2016).

Miocene Series

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

Middle Miocene: This division comprises the Langhian and Serravallian.

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

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

Langhian Stage: definition of GSSP in progress.

Serravallian Stage

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

"... I place the lower limit of the third subdivision of the Miocene terrains, which is that of the Upper Miocene and which I name the Serravallian stage …" (Pareto placed the Serravallian in the Upper Miocene).

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

"The Global Stratotype section and Point (GSSP) for the base of the Serravallian Stage (Middle Miocene) is defined in the Ras il Pellegrin…"

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

"Formal definition of Middle Miocene global chronostratigraphic units via their GSSPs is also…"

"One of the major changes in the climate system is termed the Middle Miocene climate transition..."

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

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

Tortonian Stage

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

"The GSSP of the Tortonian Stage, which per definition marks the base of the Tortonian and, hence, the boundary between the Serravallian and Tortonian Stages of the Middle and Upper Miocene Subseries, has recently been defined and ratified by the IUGS." (Note the use of 'subseries').

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

2003) and in the open ocean (Shackleton and Crowhurst, 1997; Shackleton et al., 1999)."

Messinian Stage

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

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

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

"... high quality magnetostratigraphic records from Upper Miocene sections on Crete…" (op. cit., p. 173).

Pliocene Series

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

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

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

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

"The base of the Piacenzian Stage, representing the Lower Pliocene-Middle Pliocene boundary, has been recently defined and ratified by IUGS."

Note: the Piacenzian Stage is now assigned to the Upper Pliocene following the transfer of the (ex Upper Piocene) Gelasian Stage to the Lower Pleistocene Subseries.

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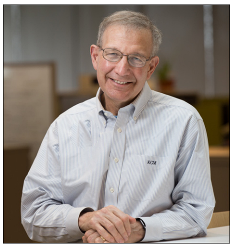
Marie-Pierre Aubry is a Distinguished Professor of Earth Sciences at Rutgers University, USA. She is the Secretary of the International Subcommission on Neogene Stratigraphy (SNS), a voting member of the International Subcommission on Stratigraphic Classification (ISSC) and a Commissioner on the North American Commission on Stratigraphic Nomenclature (NACSN). She was Chair of UNESCO/IUGS IGCP Project 308 (Paleocene/Eocene Boundary Events in Space and Time, 1990–1995) and the ICS Working Group on the Paleocene/Eocene Boundary (1989–2004). Her scientific interests include Earth Cenozoic history as well as the evolutionary dynamics of the marine plankton. She has edited and contributed to several books in Earth Sciences and she is the author of a multi-volume series on Cenozoic coccolithophores. She is a Fellow of the AAAS.



Kenneth G. Miller is a Distinguished Professor in the Department of Earth and Planetary Sciences at Rutgers University. He received an A.B. from Rutgers College (1978) and a Ph.D. from the Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program in Oceanography (1982). A veteran of 8 scientific cruises and numerous onshore drilling projects, he has integrated offshore seismic and drilling with onshore drilling. Author of over 150 peer-reviewed scientific papers, his most significant publications include widely cited synthesis of Cenozoic oxygen isotopes (Miller et al., 1987, 1991; Cramer et al., 2009) and syntheses of global sea-level change (Miller et al., 1998, 2005, 2011, 2020). He was awarded the 2003 Rosenstiel Award from the University of Miami, the Lawrence Sloss Medal from the Geological Society of America, a Fellow of the American Geophysical Union, a Fellow of the Geological Society of America. He is a two-time JOI/USSAC Distinguished Lecturer and an AAPG Distinguished Lecturer, Chair of the Subcommission on Neogene Stratigraphy of ICS, and member of the JOIDES Resolution Facility Board.

Elena Turco is Associate Professor of Micropaleontology and Paleoecology at the University of Parma (Italy). She is Vice-Chair of the Subcommission on Neogene Stratigraphy (SNS) and member of the SNS Working Groups for the definitions of the Global Stratotype Sections and Points (GSSPs) of the Langhian and Burdigalian stages. She formerly was SNS Secretary and a member of the SNS Working Groups for the definition of the GSSPs of the Tortonian and Serravallian Stages. Her main research interests focus on high resolution planktonic foraminiferal biostratigraphy and biochronology, integrated stratigraphy, and paleoecology and paleoclimatology of Neogene successions from the Mediterranean and open-ocean areas.