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Formal subdivision of the Quaternary System/Period: Present status and future directions

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ABSTRACT

The Quaternary System/Period and Pleistocene Series/Epoch were defined in 2009 by the Global boundary Stratotype Section and Point (GSSP) for the Gelasian Stage/Age (2.58 Ma), which aligns with Marine Isotope Stage (MIS) 103 and approximates the Gauss–Matuyama Chron boundary, contrary to earlier reports. The Vrica GSSP (1.80 Ma) was repurposed in 2011 to define the Calabrian Stage, effectively completing the Lower Pleistocene Subseries/Subepoch. The candidate for the Middle Pleistocene Subseries (and proposed Chibanian Stage) GSSP (~774 ka) is the Chiba section, Japan. It aligns with MIS 19 and approximates the Matuyama–Brunhes Chron boundary (~773 ka). The Upper Pleistocene Subseries, with a base traditionally marked by the onset of the Last Interglacial, is not yet defined by GSSP. The Holocene Series/Epoch was formally defined in 2008 by a GSSP in the NGRIP2 Greenland ice core with an age of 11,700 yr b2k (before 2000 CE) and in 2018 was subdivided, using climatic events at 8.2 and 4.2 ka, into the Greenlandian, Northgrippian and Meghalayan stages/ages and their corresponding Lower/Early, Middle, Upper/Late subseries/subepochs. The Northgrippian GSSP (8236 yr b2k) is defined in the NGRIP1 Greenland ice core, and the Meghalayan GSSP (4250 yr b2k) in a speleothem from Meghalaya, India. This subdivision formally introduces the rank of subseries/subepoch, and incorporates by far the briefest of all stages into the geological time scale. Using ice cores and a speleothem for GSSPs is unique to the Holocene. The presently undefined term Anthropocene is already used extensively and, like Holocene subdivisional terms, its functionality will be enhanced by formal definition. The Anthropocene should not be confused with anthropogenic: it reflects a tipping point in the Earth System response to the marked intensification of human impacts, not simply the fact of human impact. The geological Anthropocene, as currently envisioned, would start in the mid-twentieth century, holding the rank of series, and terminating the Holocene but not interfering with its subdivision other than to terminate the Meghalayan Stage.

1. Introduction

The term Quaternary stems from one of the earliest attempts at classifying rocks using (chrono-)lithostratigraphic criteria, with Giovani Arduino defining a "fourth order" (*quarto ordine*) in his subdivision of strata in the Venetian and Tuscan regions of Italy (Arduino, 1760; Vaccari, 2006). Much later, the Pliocene–Pleistocene boundary was the first to be discussed in the context of a boundary stratotype, rather than the hitherto customary practice of designating body stratotypes. Deliberations held during the 18th International Geological Congress in London, 1948, considered it "necessary to select a type-area where the Pliocene–Pleistocene (Tertiary–Quaternary) boundary can be drawn in accordance with stratigraphic principles" (King and Oakley, 1949, p. 213). This preceded the eventual protocols developed to establish a Global boundary Stratotype Section and Point (GSSP), with the Devonian System/Period being the first to be so defined, in 1972 (McLaren, 1977). The Pleistocene was not defined until 31 May 1985 (Bassett, 1985; Aguirre and Pasini, 1985; Pasini and Colalongo, 1997, p. 39), with a GSSP at Vrica, Calabria, Italy, and unfortunately without consideration of the Quaternary, or indeed the Tertiary (Head et al., 2008a, b). It would take 24 years for the consequences of this omission to be fully resolved (Head and Gibbard, 2015a). The Quaternary System was finally ratified in 2009 and the base of the Pleistocene lowered to share the same GSSP with an age of 2.58 Ma (Gibbard and Head, 2009, 2010; Gibbard et al., 2010). Although addressing deeply rooted and contentious issues, and notwithstanding limited objection (notably Hilgen et al., 2012), these definitions have been embraced widely by the scientific community.

The Subcommission on Quaternary Stratigraphy (SQS), as a constituent body of the International Commission on Stratigraphy (ICS), is responsible for the formal subdivision of the Quaternary interval of the International Chronostratigraphic Chart, which informs the Geological

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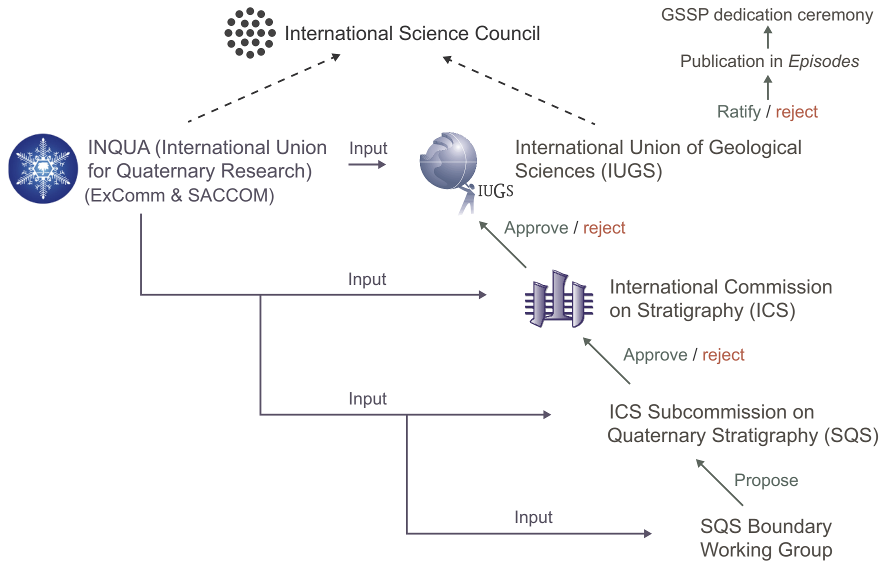

Fig. 1. The sequence of events leading to the ratification of a Global boundary Stratotype Section and Point (GSSP). For a Quaternary GSSP, the process may include input from INQUA both through its Stratigraphy and Chronology Commission (SACCOM) and directly via its Executive Committee.

Time Scale (GTS). The process usually begins at the level of an SQS boundary working group which, after much deliberation and the examination of and voting upon candidate sections, formulates a GSSP proposal. This proposal is submitted to the SQS for further discussion and voting. If approved, the SQS passes the proposal to the voting membership of ICS for its own deliberation and voting. All voting within ICS and its constituent bodies requires a statutory 60% or more to pass. If the proposal is approved by ICS, it is submitted to the Executive Committee of the International Union of Geological Sciences (IUGS) for ratification. At any point in this process, a proposal can be rejected and returned to the proponents for revision or withdrawal. The International Union for Quaternary Research (INQUA) can provide input to the process in an advisory and liaison capacity both through its Stratigraphy and Chronology Commission (SACCOM) and directly via its Executive Committee. Following ratification, the International Chronostratigraphic Chart is updated, and an announcement detailing the GSSP is then published in the IUGS journal *Episodes*. A dedication ceremony may also be held at the GSSP site. The sequence of events leading to GSSP ratification is shown on Fig. 1.

The work of the ICS and its subcommissions and working groups combines *descriptive* with *normative* science. The descriptive element includes the study and evaluation of potential boundary guides and candidate GSSPs, and is typically highly integrative and at the leading edge of stratigraphic research. The normative aspect involves the establishment of conventions, including the time scale itself, which is partly influenced by historical usage and partly by the practicalities of selecting boundaries that can be correlated globally. If the GTS were designed anew without such regard, it would look very different from our present historically rooted version. It would reflect more faithfully the narrative of Earth history as we now perceive it, but connections with the older literature would then be severed, and its practicability would be compromised. Any changes to the time scale must therefore reflect a delicate balance of considerations.

The Quaternary continues to serve as a testing ground for formal chronostratigraphy, bearing in mind that the difference between isochroneity and diachroneity is simply a matter of scale. Extensive and highly resolved sedimentary records constrained by precise geochronology have afforded an exceptionally fine subdivision of the Quaternary time scale. Rates of tectonic uplift are usually too slow to expose deeper marine Quaternary sediments on land. It has therefore been necessary, certainly for the latter part of the Quaternary, to use novel geological materials in establishing GSSPs. The Holocene Series GSSP defined in an ice core is one such innovation, now repeated for the Greenlandian Stage GSSP, and the Meghalayan Stage GSSP defined in a speleothem is another (Walker et al., 2018). The introduction of a new rank in the geological time scale through ratification of the Lower, Middle and Upper Holocene subseries/subepochs (Head et al., 2017; Walker et al., 2018, 2019), represents a further innovation. The Anthropocene as a prospective new series/epoch (e.g. Crutzen and Stoermer, 2000; Waters et al., 2016; Zalasiewicz et al., 2019a, b) and the only interval where historical, instrumental, and geological time overlap, meanwhile provides opportunities that challenge the conventional modalities for defining geological time.

This contribution summarizes the formal subdivision of the Quaternary System, and updates an earlier comprehensive overview and historical account by Head and Gibbard (2015a). The reader is referred to that publication for extensive details leading to the ratification of the Quaternary, and for a description of the technical requirements of a GSSP from a Quaternary perspective. The present account focuses on subsequent developments, including the relationship between the base of the Quaternary and the Gauss–Matuyama Chron boundary, a proposal by the SQS that the Chiba Section in Japan serve as the GSSP for the Middle Pleistocene Subseries (and proposed Chiba Stage), the introduction of subseries as a new rank for the Quaternary, the newly ratified subdivision of the Holocene, and progress towards the formalization of the Anthropocene (Fig. 2).

The dual terminology of chronostratigraphy and geochronology was formalized at the 2nd International Geological Congress in Bologna, in 1881 (Anonymous, 1882, p. 197), and further embraced with the introduction of the GSSP. The GSSP is the only point where time and the rock record intersect by definition – this point simultaneously defines both chronostratigraphic and geochronologic terms, notwithstanding the obvious conceptual difference between time and its stratal equivalent. To simplify the present account, chronostratigraphic rank terms (system, series, subseries, stage) are often cited alone, respecting the primacy of the "rock" record, although each term is understood to represent also its geochronological equivalent (period, epoch, subepoch, age).

2. The base of the Quaternary System and the Gauss–Matuyama boundary

The base of the Quaternary System and Pleistocene Series is defined by the GSSP for the Gelasian Stage at Monte San Nicola, Sicily, Italy

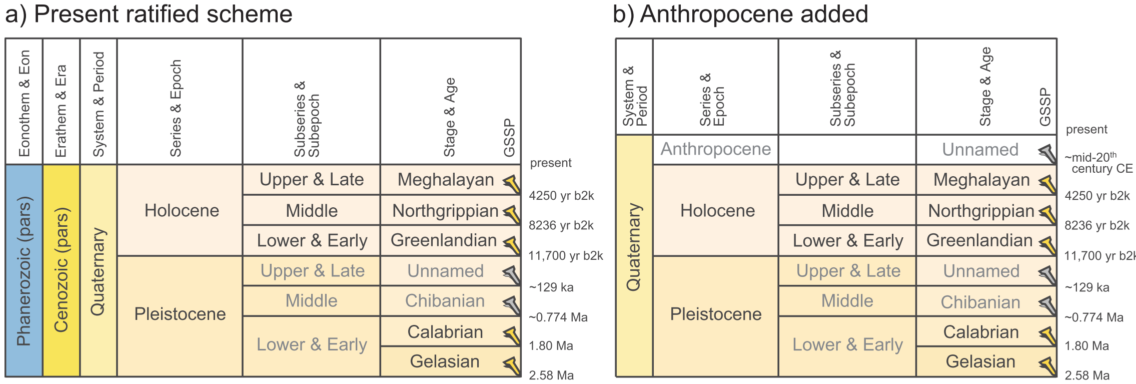

Fig. 2. Formal chronostratigraphic subdivision of the Quaternary System/Period showing: a) the current IUGS-ratified scheme as of May 2019, and b) the Anthropocene included according to the current preferences of the Anthropocene Working Group. Black type and yellow golden-spike symbols indicate ratified names and GSSPs; grey type and grey golden-spike symbols indicate proposed or suggested names and GSSPs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 3. The Monte San Nicola section, near Gela, in Sicily. The GSSP for the Gelasian Stage, Pleistocene Series, and Quaternary System is placed at the base of the marly layer conformably overlying the sapropelic Nicola bed. The level of the GSSP is indicated by an arrow. The GSSP has an age of 2.58 Ma. Photograph courtesy of John Clague.

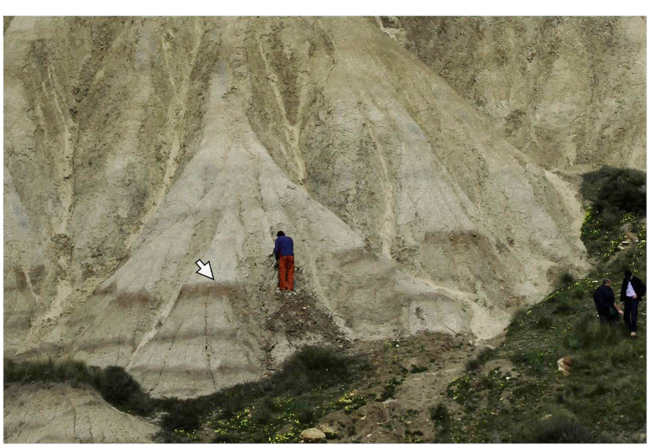

Fig. 4. Detail of the sapropelic Nicola bed at the Monte San Nicola section, near Gela, in Sicily. The level of the Gelasian GSSP is indicated by an arrow. The Gauss–Matuyama paleomagnetic reversal occurs within a ~3 m interval above the Nicola bed. Photograph courtesy of John Clague.

(37°8′45.64″N, 14°12′15.22′E), ratified for the Gelasian in August 1996 (Rio et al., 1998) and for the Pleistocene and Quaternary on 29 June 2009 (Gibbard and Head, 2010). The GSSP is placed at the base of the marly layer immediately overlying a prominent sapropelic bed known as the Nicola bed (Figs. 3 and 4). The boundary interval, occurring within marly-silty deposits of the Monte Narbone Formation, is interpreted to have been deposited within a slope-basin setting at a water depth of 500–1000 m (Rio et al., 1994). The sedimentation rate at the boundary is 6.1 cm/kyr (fig. 8 in Hilgen, 1991). The sediments at Monte San Nicola are deeply weathered and this may limit the usefulness of the section for geochemical (Herbert et al., 2015, p. 308) and palynological analysis.

The Gelasian Stage was initially proposed to coincide with the intensification of Northern Hemisphere glaciation (Rio et al., 1998), and represents a crucial phase in the evolution of the Earth's ocean–climate system owing to the appearance of major obliquity-paced climate cycles controlled by this glaciation (Ruddiman et al., 1986; Lourens et al., 2005). The precise horizon of the GSSP was chosen for two reasons: 1) the Nicola bed is very conspicuous in the field, permitting unambiguous local and regional correlation, and 2) the Gauss–Matuyama Chron boundary lying near to the GSSP serves as a close approximation of the boundary globally and in both marine and terrestrial deposits (Rio et al., 1994, 1998).

2.1. The Nicola bed

Sapropels correspond to precession 'minima' (where 'maxima' represent the present configuration during which perihelion falls in the northern winter), when summer insolation on the northern hemisphere is maximized and winter insolation is minimized. This configuration occurs when perihelion aligns with northern hemisphere summer, and is amplified by high eccentricity. The increased seasonal contrast and enhanced summer temperatures increase monsoon intensity. Therefore, sapropels predominantly represent precession-forced variations in the intensity of the monsoon system, and cluster over intervals of high eccentricity (Rohling et al., 2015). Obliquity, in contrast, aligns with global ice volume and hence with marine isotope stages. Obliquity cycles are essentially independent of precession cycles.

The Nicola bed (Fig. 4) is ~20 cm thick (Rio et al., 1994) and corresponds to small-scale cycle 119 at Monte San Nicola (= Rossello composite section cycle number 119), and to Mediterranean Precession-Related Cycle (MPRC) 250 (Hilgen, 1991). It is the highest in a cluster of six sapropels (cluster A) occurring at a time of maximum eccentricity (Rio et al., 1994). Each sapropel aligns with a precession minimum (insolation maximum). The Nicola bed corresponds to the precession minimum with the highest negative value (greatest summer insolation) in this eccentricity cluster, explaining its prominence.

All six sapropelic beds also occur at the Punta Piccola section in Sicily which is the highest segment of the Roselli composite section (fig. 3 in Hilgen, 1991; fig. 1 in Lourens et al., 1996a). Obliquity aligns with global ice volume and hence with marine isotope stages for this interval of the Plio-Pleistocene. An obliquity maximum, representing MIS 103, happens to coincide with the precession minimum represented by the Nicola bed. The sapropelic bed immediately underlying the Nicola bed belongs to small-scale cycle 118 (= Rossello composite section cycle number 118 = MPRC 252). It represents the next oldest precession minimum and aligns precisely with the obliquity minimum representing MIS 104. This sapropelic bed represents relatively weak summer insolation (Lourens et al., 2005) and is the only one of the six sapropelic beds in cluster A not represented at the well-studied Singa section in Calabria (Lourens et al., 1992).

The Monte San Nicola section lacks isotope stratigraphy but the Nicola bed correlates with the Singa Section which has isotope stratigraphy confirming MIS 103 for MPRC 250 (Lourens et al., 1992; Rio et al., 1994). Foraminiferal assemblage analysis of the Monte San Nicola section supports the correspondence of the Nicola bed with MIS 103 (Sprovieri, 1992, 1993). The sapropelic layer assigned to MPRC 252 immediately underlying the Nicola bed similarly corresponds to MIS 104. The Nicola bed (MPRC 250) and underlying sapropelic bed (MPRC 252) are therefore securely tied to MIS 103 and 104 respectively.

The Nicola bed (MPRC 250) at its midpoint has an astrochronological age of 2.588 Ma (Lourens et al., 1996a; Rio et al., 1998, p. 85). As Gibbard and Head (2009) have noted, the GSSP effectively lies at the top of the Nicola bed, and assuming both a duration of 7–10 kyr for the deposition of this sapropel and its full preservation at this location, the age of the GSSP is therefore about 3.5–5.0 kyr younger than the midpoint age, rounding down to 2.58 Ma. That age is currently accepted (Gibbard and Head, 2009, 2010; Gibbard et al., 2010; Cohen et al., 2013; Head and Gibbard, 2015a), although the precise position of the GSSP was not specified by Rio et al. (1998).

2.2. The Gauss–Matuyama reversal

The Gauss–Matuyama paleomagnetic boundary is a major geochronological guide in the late Cenozoic, but its precise position relative to both marine isotope stratigraphy and Mediterranean sapropel stratigraphy has been a source of uncertainty. The observed polarity reversal in deep ocean sediments varies between MIS 103 and 104 depending on the site. MIS 103 has a duration of 2.595–2.575 Ma (Lisiecki, 2005). For IODP Site U1314 on the Gardar Drift, Ohno et al. (2012) found the Gauss–Matuyama boundary to align with the early peak in MIS 103, giving an age of 2.590–2.585 Ma (duration of 5 kyr) and a midpoint of 2.587 ± ≥5 Ma when tuned to the benthic $\delta^{18}O$ stack of Lisiecki and Raymo (2005). Because sedimentation rates at the boundary are high (~20 cm/kyr), an expected lock-in depth of 20 cm makes little difference to this age (Ohno et al., 2012). The Gauss–Matuyama boundary also occurs at the base of MIS 103 at northern North Atlantic ODP Site 982 (Channell and Guyodo, 2004; Lawrence et al., 2013). The Gauss–Matuyama Chron boundary is therefore accepted as occurring within MIS 103 at ~2.587 Ma.

However, this boundary was attributed to MIS 104 by Lisiecki and Raymo (2005) presumably resulting from incorporating sites with low sedimentation rates where lock-in depth would be significant (Ohno et al., 2012). Unfortunately, this association with MIS 104 has been uncritically accepted in the literature.

No lava flows are known to record the Gauss–Matuyama boundary, and therefore direct $^{40}Ar/^{39}Ar$ constraints on its age are lacking, although interpolation using two $^{40}Ar/^{39}Ar$-dated tuffs in lake sediments from Kenya have yielded an age of 2.610 Ma (Deino et al., 2006; Singer, 2014) in contrast to the astronomically tuned 2.587 Ma estimate from IODP Site U1314. Ohno et al. (2012) suggested a calibration problem for the $^{40}Ar/^{39}Ar$-dated tuffs.

2.3. The Gauss–Matuyama Chron boundary in relation to the Nicola bed

At Monte San Nicola, the Gauss–Matuyama reversal was reported to occur approximately 1 m (20 kyr) below the Nicola bed, at the level of the sapropel labeled small-scale cycle 118 and MPRC 252 (Rio et al., 1994, 1998). The source for this placement was given as Channell et al. (1992). However, Channell et al. (1992, text fig. 16) delimited the reversal between two samples, one collected at ~62 m (normal polarity) and the next sample above at ~65 m (reversed polarity). The Nicola bed is located at 62 m (Rio et al., 1998) so the Gauss–Matuyama reversal is actually placed either at the Nicola bed itself or as much as ~3 m above it. Given that the Nicola bed has an astronomical age of 2.588 Ma and assuming a sedimentation rate of 6.1 cm/kyr, this would constrain the Gauss–Matuyama reversal at Monte San Nicola to somewhere between ~2.588 and ~2.539 Ma.

The sapropelic layer representing MPRC 250 (= the Nicola bed) is clearly represented in the Singa section in southern Calabria. Here the directional midpoint of the Gauss–Matuyama reversal was shown to occur above the top of the sapropel, and 85 cm above its midpoint, giving an extrapolated age of 2.581 Ma (Langereis et al., 1994). This is within the limit observed for the Monte San Nicola section by Channell et al. (1992) and close to the age of ~2.587 Ma as determined from the North Atlantic.

A reanalysis of the Monte San Nicola section at high temporal resolution is now needed to determine the precise position of the Gauss–Matuyama reversal relative to the GSSP. The acquisition of a beryllium-10 (^{10}Be) record should also be considered. This is used as a proxy for lows in the geomagnetic dipole moment associated with polarity reversals (Suganuma et al., 2011), and has the advantage of not being subject to the effects of lock-in depth or later remagnetization.

Miller and Wright (2017) favoured lowering the Gelasian GSSP to the ostensible level of the Gauss–Matuyama Chron boundary, and hence also to MIS 104 because this is a significant glacial cycle and more distinctive than MIS 103 for global correlation. But moving the GSSP down to the Gauss–Matuyama Chron boundary is moot: this boundary coincides with MIS 103, not MIS 104, at Monte San Nicola and elsewhere, as shown above. The GSSP is already essentially optimal relative to the position of the Gauss–Matuyama Chron boundary and sapropel chronology.

Symbolically, MIS 104 would indeed have been a better choice for a Quaternary GSSP, which is associated with the intensification of northern hemisphere glaciation (Head et al., 2008a). MIS 104 is a pronounced glacial (Bailey et al., 2013) and known to represent a major climatic reorganization across the middle and higher latitudes of the Northern Hemisphere (Hennissen et al., 2014), including a shift to increasing seasonality (Hennissen et al., 2015) and significant cooling in the Mediterranean (Versteegh, 1997; Herbert et al., 2015). However, the Quaternary GSSP is close enough to MIS 104 to capture some of this symbolism while benefitting from its near alignment with the Gauss–-Matuyama boundary.

A GSSP ideally should be placed at a lithological horizon that can be visibly traced throughout the type locality and beyond. Tephra beds and sapropels are suitable as they supplement rather than interrupt sedimentation. The Nicola bed is more effective for this purpose than the immediately underlying sapropelic bed assigned to MPRS 252 which has neither wide regional expression nor is observed at the Singa section in Calabria. Maintaining the GSSP at the Nicola bed (MIS 103) is therefore advocated here not only because of its regional distinctiveness as a marker bed, but because it aligns very closely with the Gauss–Matuyama Chron boundary, an objective that Miller and Wright (2017) were in fact promoting.

In summary, the Monte San Nicola GSSP is placed at the base of a marly layer immediately overlying the sapropelic Nicola bed which is assigned to MPRC 250 with a midpoint astronomical age of 2.588 Ma. The slightly younger GSSP itself then rounds to 2.58 Ma. The Gauss–Matuyama reversal boundary occurs between 0 and ~3 m *above* the Nicola bed, not ~1 m (20 kyr) below it as reported by Rio et al. (1994, 1998). The Nicola bed, GSSP, and Gauss–Matuyama boundary all occur within MIS 103. The most likely directional midpoint age for the Gauss–Matuyama reversal is between ~2.587 Ma (IODP Site U1314, Ohno et al., 2012) and 2.581 Ma (Singa section; Langereis et al., 1994), and so within the middle of MIS 103 using the boundary ages of Lisiecki (2005).

3. Subdivision of the Pleistocene Series/Epoch

The Pleistocene Series has long been subdivided into three parts. The terms Lower, Middle, and Upper Pleistocene were in use at the Second International Conference of the Association pour l'étude du Quaternaire européen (a precursor of INQUA and its congresses) held in Leningrad in 1932 (Woldstedt, 1953). These positional terms were later employed in a formal sense in English by Zeuner (1935, 1945) and Hopwood (1935), as noted by Pillans and Gibbard (2012). A somewhat different scheme arose in the former USSR and Russia, essentially beginning with the Leningrad Conference, with the Eopleistocene equivalent to the Gelasian and Calabrian, and the Neopleistocene equivalent to the Middle and Upper Pleistocene. The Neopleistocene itself has lower, middle and upper subdivisions, with the Upper Neopleistocene being exactly equivalent to the Upper Pleistocene (e.g. Tesakov et al., 2015; Head and Gibbard, 2015a and references therein). Importantly, as chronostratigraphic subdivisions of the Pleistocene, the terms Lower, Middle and Upper have long been used in the former USSR and Russia (Gromov, 1939; Nikiforova, 1987; Gaudenyi et al., 2014).

Although the terms Lower/Early, Middle, and Upper/Late Pleistocene have been used regularly for many decades in the Quaternary literature where they are treated as formal chronostratigraphic/geochronologic subdivisions, the rank of subseries/subepoch itself only became formalized in June 2018, specifically to allow subdivision of the Holocene (Walker et al., 2018). The Holocene is now officially subdivided into Greenlandian, Northgrippian, and Meghalayan stages/ages and their corresponding Lower/Early, Middle, and Upper/Late Holocene subseries/subepochs (Walker et al., 2018, 2019, Fig. 2). While a multifaceted case for adopting subseries/subepoch as a formal rank for the Cenozoic had been made by Aubry (2016) and Head et al. (2017), the rationale for Holocene subseries derives in part from the observation that geochronology is used universally in Holocene stratigraphy owing to an array of geochronometric techniques that are considerably more precise and reliable than traditional methods of stratigraphic correlation. Accordingly, it is natural to use the terms "Early", "Middle" and "Late" with respect to the Holocene, and stratigraphic records are commonly plotted against time rather than depth (Head et al., 2017; Walker et al., 2018, 2019).

Similar justification for the use of subepochs applies to the Pleistocene, where continuous sedimentation allows calibration to an orbitally derived, and hence numerically calculated, insolation curve. Such tuned Pleistocene records are shown routinely in years (or thousands of years) before present, and indeed facilitate the precise numerical dating of GSSPs for the Gelasian and Calabrian stages/ages.

Accordingly, on November 5, 2018, the SQS voted for the following three proposals, with votes being returned from 21 of the 22 voting members (no absentions):

1. Formalization of the Lower/Early Pleistocene Subseries/Subepoch, comprising the Gelasian Stage/Age and the superjacent Calabrian Stage/Age, with a GSSP corresponding to that of the Gelasian Stage, the Pleistocene Series, and the Quaternary System. Age: 2.58 Ma. Vote in favour 20/21 = 95% supermajority.
2. Formalization of the term Middle Pleistocene, at the rank of subseries/subepoch, with a base presently undefined but provisionally dated at ~773 ka. Vote in favour 20/21 = 95% supermajority.
3. Formalization of the terms Upper/Late Pleistocene, at the rank of subseries/subepoch, with a base presently undefined but provisionally dated at ~129 ka. Vote in favour 19/21 = 90% supermajority.

These proposals simply formalize terms already used widely within the Quaternary community. Whereas the Lower/Early Pleistocene already has an available GSSP (the Gelasian GSSP), the Middle and Upper/Late Pleistocene do not, with the Upper/Late Pleistocene several years away from being defined by GSSP. Yet because these are positional terms, all three must be defined in unison. These proposals will bring Pleistocene subseries/subepoch terminology officially in line with that of the Holocene. These three proposals have been submitted to the ICS for its approval, after which ratification by IUGS EC will be needed to complete formalization of these terms. Proposals to define the bases of the Middle and Upper/Late Pleistocene and their respective stages by GSSP will then follow in due course.

4. Lower/Early Pleistocene Subseries/Subepoch

The Lower Pleistocene Subseries comprises the Gelasian Stage followed by the Calabrian Stage (Cita et al., 2012).

4.1. Gelasian Stage/Age

The base of the Lower/Early Pleistocene Subseries/Subepoch is effectively that of the Gelasian Stage/Age, the Pleistocene Series/Epoch, and the Quaternary System/Period, and defined by the GSSP at Monte San Nicola, Sicily, Italy (see above), with a currently accepted age of 2.58 Ma (Gibbard and Head, 2009, 2010; Gibbard et al., 2010). The Gelasian GSSP is discussed above.

4.2. Calabrian Stage/Age

The Calabrian is the second stage of the Pleistocene Series and of the Lower Pleistocene Subseries, and its upper limit will be defined by the GSSP for the Middle Pleistocene Subseries/Subepoch (Cita et al., 2012). The Vrica GSSP had previously served as the GSSP for the Pleistocene Series (Aguirre and Pasini, 1985; Pasini and Colalongo, 1997), as discussed by Head and Gibbard (2015a), having been ratified on 31 May

Fig. 5. The Vrica section near Crotone, Calabria, southern Italy. The GSSP for the Calabrian Stage, and prospective Lower Pleistocene Suberies. The GSSP is placed at the base of the marine claystone conformably overlying sapropelic bed 'e', indicated by an arrow in the closeup of the section in (b). Photograph by Ilka Von Dalwigk (June 2000); supplied by Luca Capraro.

1985. Lowering the base of the Pleistocene to that of the Quaternary was to cause much consternation within the ICS Subcommission on Neogene Stratigraphy. Ultimately, however, because the choice of the Gelasian Stage GSSP to define the base of the Quaternary was relatively uncontentious, the hierarchical nature of the time scale itself then dictated the repositioning of the Pliocene–Pleistocene boundary to the same level.

The Calabrian is defined by the GSSP at the Vrica section (39°02′18.61″N, 17°08′05.79″E) in the Province of Crotone, Region of Calabria, Italy. The Vrica section represents a succession of silty marls that outcrop in badlands (*calanchi*) in this area, and was deposited at a water depth in excess of 500 m (Pasini and Colalongo, 1997). Full details are given in Cita et al. (2008, 2012). The GSSP was ratified on 5 December 2011. It is placed at the base of the marl bed immediately overlying sapropelic bed 'e' (Fig. 5), which is assigned to MPRS 176 (Lourens et al., 1996b) with a midpoint astronomical age of 1.806 Ma (Lourens et al., 2005). Allowing for the delay in deposition of the overlying claystone, the GSSP is dated to 1.80 Ma (Cita et al., 2012) and coincides with the transition from MIS 65 to 64.

The GSSP occurs ~8 m below the observed top of the Olduvai Subchron. The paleomagnetic record has been affected by diagenetic overprinting that prevents a more precise estimate of this polarity reversal (Roberts et al., 2010). Indeed, a brief interval of reversed polarity earlier recorded near the top of the Olduvai at Vrica (Zijderveld et al., 1991) has not been replicated either in high-resolution marine records (Channell et al., 2016) or from a high-resolution unweathered subsurface section in east Africa (Sier et al., 2017). This would appear to confirm later remagnetization in the Vrica record, caused perhaps by sulphidic fluids generated during tectonism along the Calabrian arc (Roberts et al., 2010). Elsewhere, the top of the Olduvai Subchron is consistently placed within MIS 63, and at North Atlantic IODP Site 1308 it has an age of 1.780 Ma on the Lisiecki and Raymo (2005) time scale (Channell et al., 2016). The Calabrian GSSP is therefore ~20 kyr older than the top of the Olduvai Subchron. This estimate is consistent with its observed position ~8 m above the GSSP, based on a sediment rate of 36 cm/kyr immediately below sapropelic bed 'e' using the sapropel chronology of Lourens et al. (1996b). Further paleomagnetic analysis of the Vrica section is probably not profitable (Roberts et al., 2010), but the acquisition of a ^{10}Be record as a proxy for the position of the top of the Olduvai should be considered given that ^{10}Be is not subject to remagnetization or to lock-in depth.

The GSSP was originally selected to mark the first appearance of "northern guests" in the Mediterranean, as recommended at the 1948 International Geological Congress in London (King and Oakley, 1949; Pasini and Colalongo, 1997). These northern immigrants have since been reported below the GSSP level (Pasini and Colalongo, 1997; Gibbard and Head, 2010), having entered the Mediterranean at different times. In any case, the paleoclimatic significance of northern immigrants in the bathyal depths represented by the Lower Pleistocene Italian successions was uncertain even when the Vrica section was being considered (Pasini and Colalongo, 1997). Nonetheless, new research has signalled an important climatic transition near the base of the Calabrian. Alkenone unsaturation analysis of several Pleistocene sections in Italy including the Vrica section has been used to reconstruct (what are effectively annual) sea-surface temperatures (SSTs) at high (~3 kyr) resolution between ~3.5 and 1.5 Ma. An intense cooling of ~5 °C at ~2.06 Ma (MIS 78) is registered, followed by a significant and sustained pattern in the amplitude of precession-driven SST cycles in which both warm and cool cycles are depressed along with a near doubling in the amplitude of these cycles at ~1.84 Ma (MIS 68) (Herbert et al., 2015). Cooling at ~1.8 Ma in Siberia and elsewhere indeed suggest an expansion of Eurasian glaciation from this time (Herbert et al., 2015), and the increased influence of obliquity on Mediterranean SST (Herbert et al., 2015) and African monsoon (Tiedemann et al., 1994) records is consistent with this interpretation. Stable isotope analyses on molluscs from a marine section in northern Italy by Crippa et al. (2016) show that increased seasonality and low winter temperatures at 1.8 Ma were most likely responsible for the immigration of cold-adapted "northern guests" into the Mediterranean.

5. Middle Pleistocene Subseries/Subepoch

The Early–Middle Pleistocene Transition (1.4–0.4 Ma) represents a fundamental change in Earth's climate state characterized by a progressive increase in the amplitude of climate oscillations, an evolving waveform, and a shift towards a quasi-100 ky frequency (Head and Gibbard, 2015b). The Matuyama–Brunhes paleomagnetic boundary, with an age of ~773 ka, occurs at the approximate midpoint of this transition and is therefore conveniently positioned to mark the Early–Middle Pleistocene boundary (Head and Gibbard, 2015a, b). In 2004, at the 32nd International Geological Congress in Florence, the SQS Early–Middle Pleistocene Boundary Working Group formally adopted this paleomagnetic reversal as the primary guide for the boundary (Head et al., 2008c). This followed an earlier recommendation by Butzer and Isaac (1975) which was supported by the INQUA Working Group on Major Subdivision of the Pleistocene at the 12th INQUA Congress in Ottawa in 1987 (Anonymous, 1988; Richmond, 1996). As a paleomagnetic boundary, its appeal is that it is essentially isochronous and can be recognized in both marine and continental deposits an even the ice core record (Head and Gibbard, 2015b).

5.1. Candidates for the Middle Pleistocene GSSP

Three candidate GSSPs had long been under consideration, the Ideale section of Montalbano Jonico in Basilicata (Marino et al., 2015; Maiorano et al., 2016; Simon et al., 2017; Nomade et al., 2019), the Valle di Manche in Calabria (Capraro et al., 2017; Macrì et al., 2018; Azzarone et al., 2018; Rossi et al., 2018), both in southern Italy, and the Chiba section on the Boso Peninsula, Japan (Nishida et al., 2016; Okada et al., 2017; Suganuma et al., 2018). Highly resolved benthic foraminiferal oxygen isotope records provide detailed and robust astronomical age control for each of the three sections: Montalbano Jonico (Simon et al., 2017; Nomade et al., 2019), the Valle di Manche (Capraro et al., 2017), and the Chiba section (Suganuma et al., 2018).

Field trips to all three sections had been conducted earlier (Ciaranfi et al., 2015; Okada and Suganuma, 2018). Proposals were assessed by the SQS Working Group during the summer of 2017. The Working Group fully recognized the importance of an array of markers for assisting global correlation, but discussions ultimately focused on the expression and reliability of the Matuyama–Brunhes boundary as recorded at each site. It was noted that the Valle di Manche and Chiba sections have magnetostratigraphy, whereas Montalbano Jonico does not. All three candidates have a ^{10}Be record, but only the Chiba section has the full combination of paleomagnetic polarity reversal, geomagnetic field paleointensity, and ^{10}Be records. Although the Chiba paleomagnetic record does not extend sufficiently far below the Matuyama–Brunhes boundary to detect an occasionally recorded "precursor" event (Singer, 2014), this feature does not appear to be a general feature of the Matuyama–Brunhes transition judging from numerous North Atlantic cores (Channell, 2017).

In deliberating the proposals it was remarked that the Chiba section has the best-defined Brunhes–Matuyama reversal boundary of the three candidate sections. It was also noted that the Brunhes–Matuyama boundary at the Chiba section occurs in the upper part of MIS 19c and is dated astronomically at ~773 ka, in agreement with numerous high-sedimentation-rate records across the North Atlantic (Channell et al., 2010; Head and Gibbard, 2015b; Channell, 2017). The boundary at the Valle di Manche section occurs below the peak of MIS 19 with an astronomically dated age of 786.9 ± 5 ka including the error in orbital tuning (Macrì et al., 2018) which is anomalously old compared with most global records. In addition, the polarity transition was found to have a duration of ~100 years or less at the Valle di Manche section (Macrì et al., 2018) compared with several thousands of years at most other sites (Head and Gibbard, 2015b) and 1.9 kyr at the Chiba section (Suganuma et al., 2018). It may be significant that the Sulmona Basin record in central Italy, which has yielded a polarity reversal age claimed to exceed ~781 ka and with a duration of transit much less than a century (Sagnotti et al., 2014, 2016), has been reexamined and determined not to carry a reliable high-resolution signal of the geomagnetic field (Evans and Muxworthy, 2018). Similarly, claims of a Brunhes–Matuyama transition age of 783.4 ± 0.6 ka at ODP Site 758 in the Indian Ocean by Mark et al. (2017) have been challenged on grounds that the sedimentation rates and the resolution of the isotope and magnetic stratigraphies are all too low for a precise age determination to be made (Channell and Hodell, 2017).

Macrì et al. (2018) maintained that the Valle di Manche section indeed preserves a primary paleomagnetic signal. However, the Montalbano Jonico section has a ^{10}Be record that peaks between ~776.0 and 768.5 ka, with a duration of 7.5 kyr and a geometric midpoint at ~772.5 ka. The V4 tephra occurs within this peak and is independently dated at 773.9 ± 1.3 ka (Simon et al., 2017). This peak serves as a proxy for the Matuyama–Brunhes polarity reversal. Both its timing and duration compare strongly with the North Atlantic records and the Chiba section, which is significant because ^{10}Be is not subject to lock-in or overprinting that often account for spurious paleomagnetic boundary positions. Studies of the ^{10}Be record spanning the Matuyama–Brunhes transition globally have yielded minimum values in the geomagnetic dipole moment dated astronomically at between 776 and 771 ka, in accord with highly resolved North Atlantic paleomagnetic records (Simon et al., 2018). There is no obvious reason why the Valle di Manche section should have a Matuyama–Brunhes boundary age of 786.9 ± 5 ka when the Montalbano Jonico section just 135 km to the north has a more representative age of ~772.5 ka.

A recently published ^{10}Be record at the Valle di Manche section (Capraro et al., 2018) provides important insights into this conundrum. A peak in ^{10}Be concentration occurs ~3.5 m above the reported Matuyama–Brunhes boundary, which translates to a difference of ~12 kyr (Capraro et al., 2018). This age discrepancy cannot be attributed to lock-in depth because of the high sedimentation rates (~27 cm/kyr; Macri et al., 2018). Capraro et al. (2018) has suggested that complex interacting dynamics between ocean currents, sedimentology, and climate account for the ~12 kyr offset, but a simpler and more plausible explanation is that the ^{10}Be peak represents the Matuyama–Brunhes boundary and the paleomagnetic reversal ~3.5 m below it reflects diagenetic overprinting and remagnetization.

Voting by the SQS Working Group concluded on November 10, 2017 by supermajority to recommend the Chiba Section, Japan as the GSSP for the Middle Pleistocene Subseries, with the Chibanian Stage as its basal (and prospectively sole) stage. Votes were as follows: Chiba = 11, Montalbano Jonico = 2, Valle di Manche = 2; with no abstentions, and 15 out of 16 votes returned. The Chiba proposal therefore gained 73% of the total votes cast. This result represents the culmination of 15 years of focused effort by three research groups including the organization of field trips (Ciaranfi et al., 2015; Okada and Suganuma, 2018) allowing Working Group members to inspect each section.

The revised Chiba proposal was submitted to the SQS voting membership for discussion and then voting, and this concluded on 16 November 2018. The proposal received the following votes: 19 in favour, 2 against, 1 abstain. Having attained a supermajority of 86%, the Chiba proposal will be submitted to ICS for its approval in 2019 after minor revision. If the Chiba section is ratified, it will be the first GSSP to be located in Japan.

5.2. The Chiba section, Japan

The Chiba section (35°17.41′N, 140°8.48′E; known as the Tabuchi section in Kazaoka et al., 2015 and Nishida et al., 2016) is exposed along the Yoro River at the point where the Matuyama–Brunhes boundary outcrops (Fig. 6). It is one of five sections along the deeply incised valleys of the Boso Peninsula, east-central Japan, that form the Chiba composite section. These sections, from east to west the Urajiro, Yanagawa, Yoro River (including Chiba), Yoro-Tabuchi, and Kokusabata, represent continuous deposition extending along strike for ~7 km, and are tied by means of numerous isochronous tephra beds.

The boundary interval occurs in the middle part of the Kokomoto Formation within the Kazusa Group (Kazaoka et al., 2015). The deposits here are predominantly silty and intensely bioturbated but lack any evidence of episodic deposition. The silts are interpreted as representing continuous hemipelagic deposition under stable and quiescent bottom-water conditions on the continental slope in waters deeper than 200 m. Minor sandy beds below the boundary interval are interpreted as sediment gravity flow deposits (Nishida et al., 2016).

The Chiba composite section is constrained by a detailed benthic foraminiferal δ^{18}O record, and has a highly resolved pollen stratigraphy (Suganuma et al., 2018). A distinctive marker within the boundary interval is the regionally widespread Ontake-Byakubi tephra bed (also known as the Byakubi-E tephra bed or simply Byk-E; Fig. 7) which is U–Pb zircon dated to 772.7 ± 7.2 ka (Suganuma et al., 2015). The Matuyama–Brunhes boundary has been studied in detail (Okada et al.,

Fig. 6. Chiba section, Japan. Candidate GSSP for the Chibanian Stage and Middle Pleistocene Subseries. The marker bed for the proposed GSSP is the Byakubi-E (Byk-E) ash bed which is 1.1 m below the directional midpoint of the Matuyama–Gauss boundary which serves as the primary guide. An arrow marks the position of the Byakubi-E bed. Photograph by MJH taken at the INQUA Post-Congress field trip, August 2015.

Fig. 7. Detail of the regionally widespread Ontake-Byakubi tephra bed (Byakubi-E or Byk-E) at the Chiba section, Japan. The base of this tephra bed is proposed for the Chibanian Stage GSSP and has an astronomical age of 774.1 ka. Moderate bioturbation is visible. The scale is in cm. Photograph by MJH taken at the INQUA Post-Congress field trip, August 2015.

2017), and has an astronomical age of 772.9 ka, with a duration of 1.9 kyr for the directional transition. The mid-horizon of its directional transition zone, taken as the paleomagnetic boundary itself, is 1.1 m above the Byk-E tephra. The base of the Byk-E tephra is proposed for the GSSP. The sedimentation rate across the boundary interval is 89 cm/kyr as determined by δ^{18}O stratigraphy (Suganuma et al., 2018). The astronomical age of the Byk-E tephra bed, and hence the base of the Chibanian Stage and Middle Pleistocene Subseries if approved by ICS and ratified, is therefore 774.1 ka. The proposed GSSP level occurs just after the termination of full glacial conditions at ~775 ka as reflected by pollen analysis, just before a major turnover in the dinoflagellate cyst record at ~773 ka (Balota, 2018), and just before the end of MIS 19c at 771.7 ka as determined by the benthic δ^{18}O stratigraphy (Suganuma et al., 2018).

6. Upper/Late Pleistocene Subseries/Subepoch

Coupling the base of the Upper Pleistocene with that of the Last Interglacial was first agreed in 1932 during the Leningrad Conference; and later at the 12th INQUA Congress in Ottawa in 1987, a proposal was approved to use the base of MIS 5 (Termination II) as its primary guide (Anonymous, 1988). The base of the Eemian regional Stage had long been taken to represent the base of the Last Interglacial in Europe (Gibbard, 2003). However, subsequent studies have shown that the base of MIS 5 is about 6 kyr older than the base of the Eemian pollen stage (Shackleton et al., 2003). The onset of the Eemian represents a regional climatic response. It was defined at Amersfoort, the Netherlands, and characterized by a warm-temperate marine mollusc fauna (Harting, 1874, 1875; Bosch et al., 2000). Only later was the term Eemian applied across NW Europe to identify the interval of forest cover as determined by pollen records. The presence of leads and lags in the climate–ocean system has therefore complicated efforts to define a GSSP for the Upper Pleistocene, as detailed by Head and Gibbard (2015a) and summarized here. Defining the Upper Pleistocene, and its corresponding stage or stages, is now a priority for the SQS.

An initial attempt to define the boundary by GSSP utilized the Amsterdam Terminal borehole in the Netherlands, which penetrates a non-marine to marginal marine succession yielding an excellent pollen record and many other paleoenvironmental proxies (Gibbard, 2003; Litt and Gibbard, 2008). The proposed GSSP was placed at the base of the Eemian Stage. This proposal passed SQS and ICS voting but failed to achieve ratification by the IUGS EC. One difficulty is that the proposed GSSP interval was in non-marine to marginal marine sediment, hindering efforts to tie its terrestrial biostratigraphies with the marine isotopic record. Another relates to the ~6 kyr delayed start of the Eemian relative to that of MIS 5. There are no plans to resubmit this proposal.

More recently an ongoing study of the Fronte Section in Taranto, Italy (Fig. 8), has yielded an excellent Last Interglacial marine record (Negri et al., 2015) but is also limited in potential. Termination II marking the base of MIS 5 is not captured by the δ^{18}O record. Moreover, the position of the suggested GSSP, which is placed at the beginning of the maximum flooding zone, occurs well within the plateau of MIS 5e, and it remains to be seen whether it can be correlated unequivocally to the global δ^{18}O record.

Any future proposal for the Upper Pleistocene GSSP should allow for Atlantic over Pacific leads in respective isotope stratigraphies of several thousands of years for the past six terminations (Lisiecki and Raymo, 2009), and that peak temperatures may be globally asynchronous, with North Atlantic high-latitude temperatures lagging southern hemisphere records by several thousand years (Capron et al., 2014). A further limitation is that Greenland ice core records do not extend beyond 129 ka (NEEM Community Members, 2013). While sea level rise at the beginning of the Last Interglacial inevitably had globally synchronous effects, modeled rates of rise (Kopp et al., 2009; Goelzer et al., 2016) are insufficiently high to be useful for narrow definitional purposes.

Fig. 8. The Fronte section, in the vicinity of Taranto, Apulia, southern Italy, a suggested GSSP for the Upper Pleistocene. Last Interglacial marine deposits unconformably overlie Middle Pleistocene (MIS 13, ~500 ka) blue clay. The suggested GSSP level (marked by an arrow) is in a mud unit and occurs about 80 cm above the top of a 2 m-thick calcarenite bed. Photograph by MJH, taken October 2014.

Given these limitations, an Antarctic ice core has been suggested for the GSSP, with the abrupt methane rise seen in Antarctic ice cores at Termination II (e.g. fig. 6 in Govin et al., 2015) potentially serving, along with related stratigraphic signals, as the primary guide to the boundary (Head and Gibbard, 2015a; Head, 2016, Fig. 9). This methane rise is a distinctive event (fig. 7 in Bazin et al., 2013; Capron et al., 2014), aligns with maxima for CO_2 and δD in the EPICA Dome C ice core (Pol et al., 2014), and is closely related to rising temperatures in the higher northern latitudes. For the last glacial interval in Greenland, methane lagged temperature rise by less than 30–70 years (Wolff and Spahni, 2007; Wolff, 2011), and its abrupt increase during Termination II in Antarctica is thought to reflect more-or-less synchronous abrupt warming of the air above Greenland (Capron et al., 2014). Termination II has a gas orbital age of 132.4 ka at its midpoint, with a subsequent steep methane increase at 128.51 ± 1.72 ka in the EPICA Dome C core (Bazin et al., 2013). The timing of this methane rise compares favourably with mean eustatic highstand conditions being reached at 129.0 ± 1.0 ka, European speleothem $\delta^{18}O$ values reaching a minimum at 128.0–128.5 ± 0.9 ka, Asian speleothem $\delta^{18}O$ values reaching a minimum at 128.2 ± 0.5 ka, CO_2 values at EPICA Dome C reaching a maximum at 128.0 ± 1.8 ka, and Mediterranean sclerophyll pollen reaching maximum values in Greece at 127.5 ± 2.3 ka (Govin et al., 2015). The percentages of warm foraminifera at IODP Site 1063 within the North Atlantic subtropical gyre also rise steeply at this time (Deaney et al., 2017), and highest temperatures on the Greenland Ice Sheet are registered from ~127 ka (NEEM Community Members, 2013). To construct a time scale independent of orbital forcing for the Last Interglacial, Tzedakis et al. (2018) assembled a stack of four $\delta^{18}O_{speleothem}$ records, constrained by 87 U–Th dates, from the Corchia Cave system in northern Italy. Given that this cave system receives precipitation from the North Atlantic via westerly air masses, the Corchia stack provides a plausible template for North Atlantic paleoclimate records. Tzedakis et al. (2018) accordingly placed a selection of such records on the Corchia time scale for comparison. Several of these are reproduced in Fig. 9 alongside the EPICA Dome C methane and deuterium excess records which are tuned on an orbital timescale (Bazin et al., 2013) and hence dated independently of these other records. The steep methane rise at 128.51 ka aligns closely with sharp decreases in ice-rafted debris and increases in sea-surface temperature in core MD03-2664 south of Greenland, with abrupt changes in foraminiferal species percentages at ODP Site 984 south of Iceland, a steep rise both in ligher planktonic foraminiferal oxygen isotopes and in temperate tree pollen in core MD01-2444 on the Portuguese margin, and a small but steep shift in the $\delta^{18}O_{speleothem}$ Corchia stack. These shifts at ~128.5 ka are accentuated by the preceding North Atlantic cold event C28 (see Section 9.1 below). Such North Atlantic responses suggest that the abrupt northern hemisphere warming signalled by the methane rise in Antarctica at 128.5 ka has left stratigraphic markers that would allow recognition of the base of the Upper Pleistocene on both hemispheres and in both marine and terrestrial records.

The EPICA Dome C and other Antarctic ice records show low depositional rates compared with those of Greenland, but no Greenland ice cores extend sufficiently far back in time to capture Termination II. Because annual layer counting chronologies extend only to ~60 ka (for Greenland ice cores), orbital tuning is central to all older ice core records (Bazin et al., 2016). Nonetheless, the gas orbital chronology of the Antarctic ice cores is supported by radiometrically dated speleothem records where available (Bazin et al., 2013). Although an ice core is an unconventional choice for a GSSP, precedence has been established: both the Holocene Series and the Northgrippian Stage GSSPs are defined in Greenland ice cores.

7. The Holocene Series/Epoch

The term 'holocène', from the Ancient Greek *holos* and *kainos* meaning 'entirely (wholly) recent', was introduced by the French zoologist and paleontologist Paul Gervais (1867–1869, p. 32) for the warm episode that followed the last glacial period. It entered the international lexicon as 'holocènes' during the Second International Geological Congress (IGC) held in Bologna in 1882, and a 'Holocenian' Stage was proposed by the Portuguese Committee for the Third IGC in Berlin in 1885. The term replaced 'Recent' (Lyell, 1833, p. 52) which is not an official chronostratigraphic term.

The Holocene Series/Epoch was officially defined on 8 May 2008, using for the first time an ice core for the GSSP. Its base is located at 1492.45 m depth in the NGRIP2 Greenland ice core (75.10°N, 42.32°W), and dated at 11,700 yr b2k (before 2000 CE) using multiparameter annual layer counting with a maximum counting error of 99 yr (equivalent to 2σ) (Walker et al., 2008, 2009; Head and Gibbard, 2015a). The GSSP itself represents climatic warming at the end of the Younger Dryas/Greenland Stadial 1 cold phase. It is marked by an abrupt decline in deuterium excess values as the primary guide and which corresponds counter-intuitively to an ocean surface temperature drop of 2–4 °C (Fig. 10). This cooling seems to reflect a northward shift in the source of precipitation from the mid-Atlantic Ocean to colder higher latitudes in the Early Holocene as the polar front moved rapidly

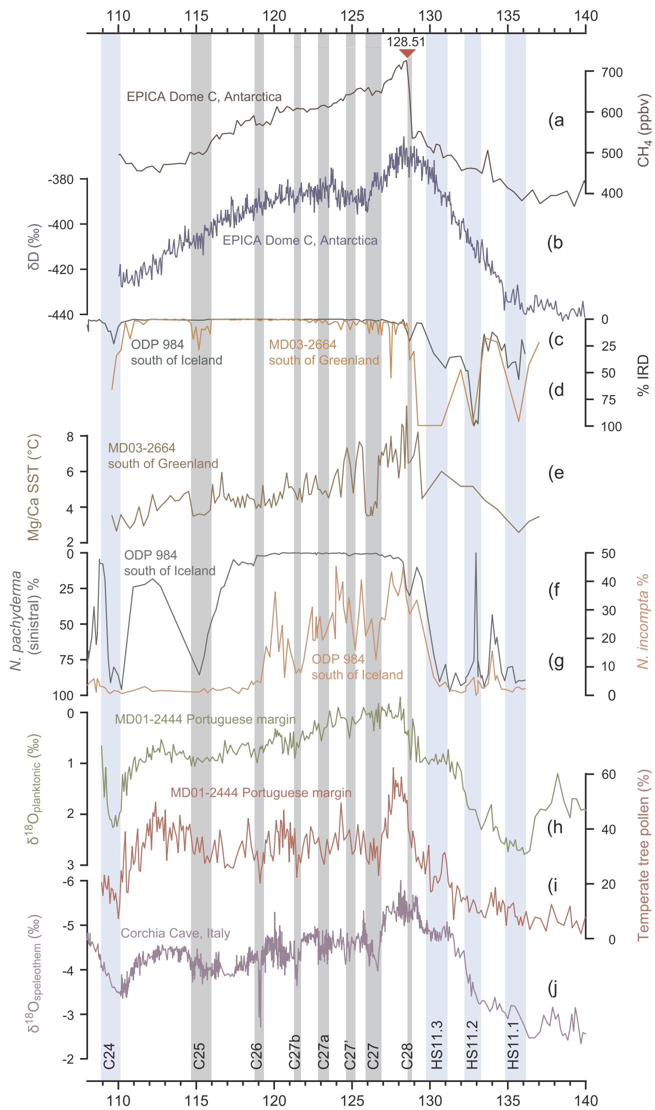

Fig. 9. Suggested lower boundary of the Upper Pleistocene Subseries (red triangle at top of figure) based on the rapid methane rise seen in the Antarctic ice core record (a, b), with selected Last Interglacial paleoclimate records from the northern hemisphere (fig. 3 of Tzedakis et al., 2018) included for comparison (c–j). a, b) Antarctic EPICA Dome C ice core, with a) methane levels showing an abrupt rise at 128.51 ± 1.72 ka, and b) deuterium excess values (δD) reflecting a simultaneous temperature peak in the moisture source area (fig. 7 of Bazin et al., 2013). c, d) ice-rafted debris (IRD) % from ODP Site 984 and MD03-2664; e) Mg/Ca sea-surface temperature (SST) reconstruction for MD03-2664; f, g) percentages of the planktonic foraminifers *Neogloboquadrina pachyderma* (sinistral) and *N. incompta*; h, i) $\delta^{18}O_{planktonic}$ and temperate tree pollen % for MD01-2444; j) stacked speleothem record for Corchia Cave, northern Italy. Light blue vertical bars indicate Heinrich events HS11.1, HS11.2, HS11.3 and C24; grey bars denote marine cold events as discussed in the text. Northern hemisphere records (c–j) are plotted on the Corchia Cave timescale based on U–Th dating (Tzedakis et al., 2018) whereas the EPICA Dome C records (a, b) are astronchronologically tuned and hence reside on an independent timescale (Bazin et al., 2013). Adapted from fig. 3 of Tzedakis et al. (2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

northward in response to warming. The sharp decline in deuterium excess represents an interval of just 1–3 years. A short-term shift to heavier $\delta^{18}O$ values (but longer-term shift to lighter $\delta^{18}O$), shifts in other chemical proxies, a trend towards lower dust concentrations, and a sharp increase annual ice-layer thickness, all constitute additional signals at the base of the Holocene. Global auxiliary stratotypes (Remane et al., 1996), which do not require official approval or ratification, have been designated in lacustrine deposits from eastern Canada, Germany, Japan, and New Zealand, and a deep marine core from the Cariaco Basin, Venezuela (Walker et al., 2009). The NGRIP2 core containing the GSSP is curated at the Centre for Ice and Climate, The Niels Bohr Institute, University of Copenhagen, Denmark.

7.1. Subdivision of the Holocene Series

The Holocene Series/Epoch is subdivided into the Greenlandian, Northgrippian and Meghalayan stages/ages and their corresponding Lower/Early, Middle, Upper/Late subseries/subepochs (Walker et al., 2018, 2019). This subdivision was ratified on June 14, 2018, the date when voting was finalized within the IUGS EC. The formalization process was long, rigorous and consultative, beginning with the publication of a discussion paper (Walker et al., 2012), further deliberation and voting within the SQS in 2015, and approval by the International Commission on Stratigraphy in June 2018, prior to ratification. The process was in fact delayed because the rank of subseries did not then have official status within the time scale, as noted above (see also Head et al., 2017), the impasse being ultimately resolved only by ratification of the Holocene subdivisional proposal itself.

Contrary to some popular reports (e.g. Voosen, 2018), the Quaternary community overwhelmingly supported these new definitions, with the president of INQUA thanking the IUGS president for bringing about the long desired nomenclatural clarification afforded by these subdivisions (Ashworth, 2018). Other popular reports have regrettably confused the ratification of the Meghalayan with the supposed ratification of the Anthropocene. The following descriptions are largely summarized from Walker et al. (2018, 2019).

7.2. Greenlandian Stage/Age and Lower/Early Holocene Subseries/Subepoch

The stage/age is the fundamental unit of the international chronostratigraphic chart, and the Holocene was ratified in 2008 in anticipation that its accompanying basal stage would subsequently be defined. The Greenlandian Stage/Age and Lower/Early Holocene Subseries/Subepoch were eventually ratified on June 14, 2018, as already noted. The GSSP for the Greenlandian Stage/Age and Lower/Early Holocene Subseries/Subepoch is by definition that of the Holocene, placed at 1492.45 m depth in the NGRIP2 Greenland ice core, and dated at 11,700 yr b2k (before 2000 CE). Details of this GSSP are given above.

7.3. Northgrippian Stage/Age and Middle Holocene Subseries/Subepoch

The GSSP for the Northgrippian Stage/Age and Middle Holocene Subseries/Subepoch is located at 1228.67 m depth in the NGRIP1 Greenland ice core (75.10°N, 42.32°W), and dated at 8236 yr b2k (Walker et al., 2018, 2019). It represents a brief global cooling episode known as the "8.2 ka climatic event" that seems to have been triggered by catastrophic release from glacial lakes Agassiz and Ojibway and perhaps other meltwater accumulations into the North Atlantic, thereby disrupting North Atlantic Deep Water formation and thermohaline circulation. In the NGRIP1 core, the event is registered by a conspicuous shift to more negative $\delta^{18}O$ and δD values, signaling abrupt cooling, and by reduced ice-core annual layer thickness and deuterium excess. The $\delta^{18}O$ minimum contains a double acidity peak probably representing fallout from an Icelandic volcano, and this allows the boundary level to be recognized precisely within the Greenland ice core record (Fig. 11). The 8.2 ka event is near-global in extent, being recognized widely in an array of climate proxies (Walker et al., 2012, 2018, 2019). The GSSP has been dated by correlating to the DYE-3 ice core in southeastern Greenland where high ice accumulation rates have yielded the best resolved of all the Greenland ice-core time scales. Using

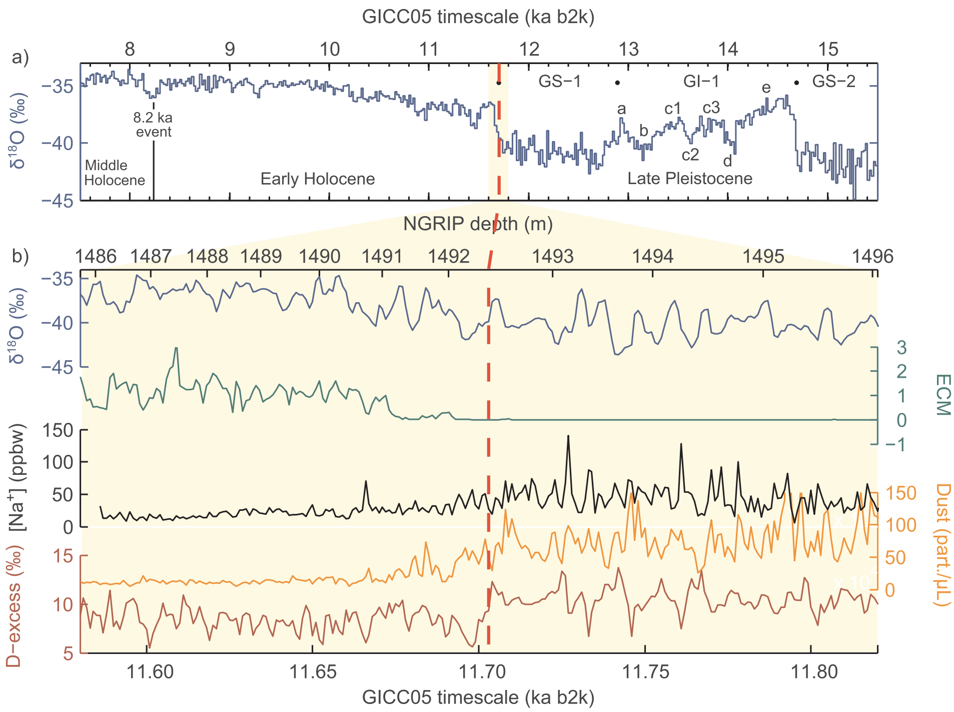

Fig. 10. Record of the GSSP for the Greenlandian Stage, Lower Holocene Subseries, and Holocene Series in the Greenland NGRIP core: a) The $\delta^{18}O$ record, and b) boundary interval showing multi-parameter record of $\delta^{18}O$, electrical conductivity (ECM), Na^{+} concentration, dust content, and deuterium excess; the last of these serving as the primary guide. Adapted from fig. 5 of Walker et al. (2009).

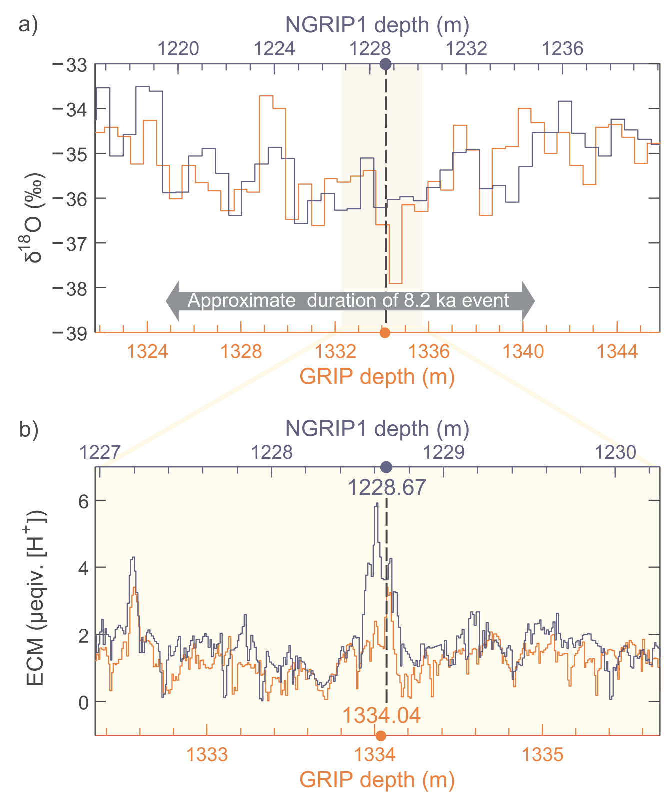

Fig. 11. The position of the GSSP for the Northgrippian Stage and Middle Holocene Subseries based on the 8.2 ka event in records of the GRIP and NGRIP1 ice cores. The GSSP is located in the NGRIP1 ice core. a) shows $\delta^{18}O$ water stable isotope ratios for the two cores with the approximate duration of the 8.2 ka event indicated for the NGRIP1 core. b) shows a marked acidity double peak reflected in electrical conductivity measurements (ECM) that most likely represents fallout from an Icelandic volcano. It serves as the primary marker for the GSSP, which has a depth of 1228.67 m in the NGRIP1 core and an age of 8236 b2k. Adapted from fig. 3 of Walker et al. (2019).

annual ice-layer counting with a range of physical and chemical parameters, the annual layer between the two acidity peaks in the DYE-3 ice core has an age of 8236 ± 47 yr b2k (Vinther et al., 2006). This is the age presently assigned to the GSSP (Walker et al., 2018). The NGRIP1 core containing the GSSP is curated at the Centre for Ice and Climate, The Niels Bohr Institute, University of Copenhagen, Denmark. This is the second GSSP to have been defined in an ice core (Walker et al., 2019).

A speleothem from the Gruta do Padre ("the Priest's Cave"; 13°13′S, 44°03′W) in Bahia State, Brazil has been designated as a global auxiliary stratotype for this boundary (Walker et al., 2019). The boundary is identified from the $\delta^{18}O$ values which reflect changes in the intensity of the South American monsoon. The 8.2 ka event is clearly marked by a shift to lighter isotopic values, signifying a significant increase in rainfall. This auxiliary stratotype, designated and described in Walker et al. (2019), therefore serves as a useful low-latitude expression of the 8.2 ka event. This event is similarly observed in the $\delta^{18}O$ record of the KM-A speleothem from Meghalaya, northeast India, which serves as the GSSP for the Meghalayan Stage (Walker et al., 2018, 2019).

7.4. Meghalayan Stage/Age and Upper/Late Holocene Subseries/Subepoch

The Meghalayan GSSP is located within the speleothem KM-A, a stalagmite from the Mawmluh Cave (entrance 25°15′44″N, 91°42′54″E) near the town of Sohra (Cherrapunji), State of Meghalaya, northeast India. The GSSP is located at a depth of 7.45 mm in this speleothem (Fig. 12). The primary guide is the "4.2 ka event", seen as a brief but significant shift to heavier $\delta^{18}O$ values in the speleothem record, reflecting an abrupt reduction in precipitation due to a weakening of the monsoon across India and southeast Asia. The 4.2 ka event, lasting for two or three centuries, has been linked to many low- and mid-latitude regions as an aridification episode, and explains profound human cultural and societal changes at this time. Some records, however, register wetter conditions, and the event is expressed in high northern latitudes by colder conditions and the advance of glaciers (Walker et al., 2012, 2018; Railsback et al., 2018). These responses reflect not simply aridification but a complex temporary readjustment of the ocean–atmosphere system (Rousseau et al., 2019). The 4.2 ka event as recorded in the $\delta^{18}O$ record of the KM-A speleothem (Fig. 12) shows an onset at

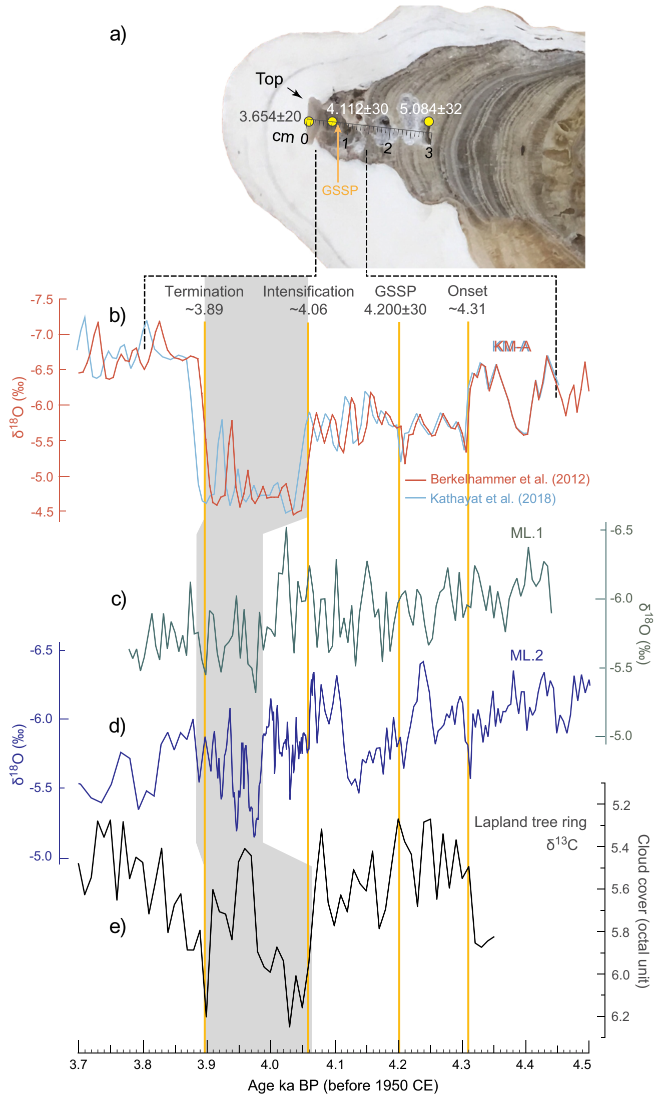

Fig. 12. The $\delta^{18}O$ record for speleothem KM-A, Mawmluh Cave, Meghalaya, in which the GSSP for the Meghalayan Stage and Upper Holocene Subseries is located (a, b), and for speleothems ML.1 (c) and ML.2 (d) also from the Mawmluh Cave. A high-latitude (Finnish Lapland) $\delta^{13}C$ tree-ring record is shown for comparison (e). The GSSP is placed in KM-A at the midpoint between the onset and intensification of the 4.2 ka event, which serves at the primary guide for this GSSP. a) uppermost ~9 cm of speleothem KM-A showing the position of the three ^{230}Th dates used to constrain the 4.2 ka interval. b) $\delta^{18}O$ record for speleothem KM-A based on the separate age models of Berkelhammer et al. (2012) and Kathayat et al. (2018). Key events of the 4.2 ka interval are based on speleothem KM-A using the age model of Berkelhammer et al. (2012) with modeled errors (see Walker et al., 2018, 2019 and text for discussion). c, d) $\delta^{18}O$ records for speleothems ML.1 and ML.2 using the highly constrained ^{230}Th age model of Kathayat et al. (2018). e) an inverted $\delta^{13}C$ tree ring record from Lapland, northern Finland as a proxy for cloudines (wetter conditions) and the most northerly expression yet documented for the 4.2 ka event (from fig. 1 of Helama and Oinonen, 2019). The grey vertical bar indicates the most intense phase of the 4.2 ka event, which might be synchronous at least for the KM-A and Lapland records given the reported uncertainties in dating. The GSSP is at a depth of 7.45 mm and has a modeled age of 4200 ± 30 yr BP (where BP = 1950 CE) and 4250 ± 30 yr b2k, based on the Berkelhammer et al. (2012) time scale. Adapted from fig. 7 of Kathayat et al. (2018).

~4.31 ka, intensification at ~4.06 ka, and a termination at ~3.89 ka. The GSSP is placed midway between onset and intensification, with a modeled age of 4.200 ± 30 ka. Ages are based on U–Th dating and expressed relative to the baseline date of 1950 CE, but to compare directly with the earlier Holocene GSSPs, an age of 4250 yr b2k is preferred (Walker et al., 2018). The KM-A speleothem has been curated at the Birbal Sahni Institute of Palaeosciences, Lucknow, India. Defining the Meghalayan GSSP in a speleothem is another innovation, and offers the only GSSP that can be displayed in a museum without refrigeration.

Analysis of two additional stalagmites ML.1 and ML.2 from Mawmluh Cave (Kathayat et al., 2018) has provided further insights into the 4.2 ka event at the type locality. All three speleothem records (Fig. 12) show considerable differences that reflect the complexities of cave hydrology, although an intensified weakening of the Indian summer monsoon beginning at ~4.06–3.99 ka seems to be reflected in all three speleothems. This phase of intensification is strikingly registered also in a tree ring isotope study of Lapland, arctic Finland (Fig. 12) where elevated $\delta^{13}C$ values are used as a proxy for cloudiness and hence wetter conditions (Helama and Oinonen, 2019). The beginning of intensification in the Lapland record has a midpoint age of 4064 years whereas for the KM-A speleothem it is 4058 ± 30 years. The Finnish study is based on dendrochronology and is theoretically accurate to a single year, although the $\delta^{13}C$ values for technical reasons are resolved at the decadal scale. Therefore, the beginning of intensification in the Lapland and KM-A (Indian) records is synchronous within a narrow range of uncertainty. This synchroneity implies a tight connection between North Atlantic forcing and a weakening of the Indian summer monsoon. It also demonstrates that rapid climate shifts may have synchronous impacts around the world, even though the impacts themselves may be regionally variable or indeed contrasting. These shifts can therefore be effective tools for chronstratigraphic subdivision so long as their context is understood.

The abrupt isotopic shift at ~3.89 ka in the KM-A record of Mawmluh Cave appears to mark the end of the 4.2 ka event. This shift is not reflected in the ML.1 and ML.2 records, and Kathayat et al. (2018) attributed the discrepancy to possible diagenesis of the KM-A speleothem near its top, influencing either the $\delta^{18}O$ record or the age of the uppermost date. Dissolution has indeed affected the top of KM-A, as seen by a thick white outer layer of replacement calcite (Fig. 12), but the differences in $\delta^{18}O$ signal between ML.1, ML.2, and KM-A suggest that localized hydrological variability within the Mawmluh Cave system is a significant factor.

The plateau ice field on Mount Logan in the Yukon has been designated as a global auxiliary stratotype for the base of the Meghalayan Stage (Walker et al., 2019). The Prospector Russell Col (PRCol) ice core recovered from this site (60°59′N, 140°50′W) has yielded a detailed signature of the 4.2 ka event including lowered $\delta^{18}O$ values and higher deuterium excess and calcium values between 4250 and 3950 yr b2k. This isotopic signal is thought to represent enhanced moisture transport from the tropical Pacific during pronounced El Niño events (Fisher et al., 2008; Fisher, 2011; Walker et al., 2019). The high-latitude Mount Logan record therefore complements the low-latitude GSSP from Mawmluh Cave. The PRCol ice core unfortunately melted in 2017 during a freezer failure, but there are plans to collect new core from the original drill site (Walker et al., 2019).

8. The Anthropocene as a formal series/epoch

The term Anthropocene was introduced by Crutzen and Stoermer (2000) and reiterated by Crutzen (2002) for a proposed formal unit of geological time at the rank of epoch. It would therefore terminate the Holocene. These authors suggested a start in the latter part of the eighteenth century to broadly coincide with the industrial revolution in NW Europe and its global effects as registered in ice cores and lake sediments. A subsequent major analysis of trends identified the "Great Acceleration" (Steffen et al., 2004; and by the name "Great Acceleration" in Hibbard et al., 2006; Steffen et al., 2007, 2011, 2015), occurring just after World War Two, as a more significant deflection of the Earth System trajectory. The Great Acceleration marks a rapid escalation in global industrialization, techno-scientific development,

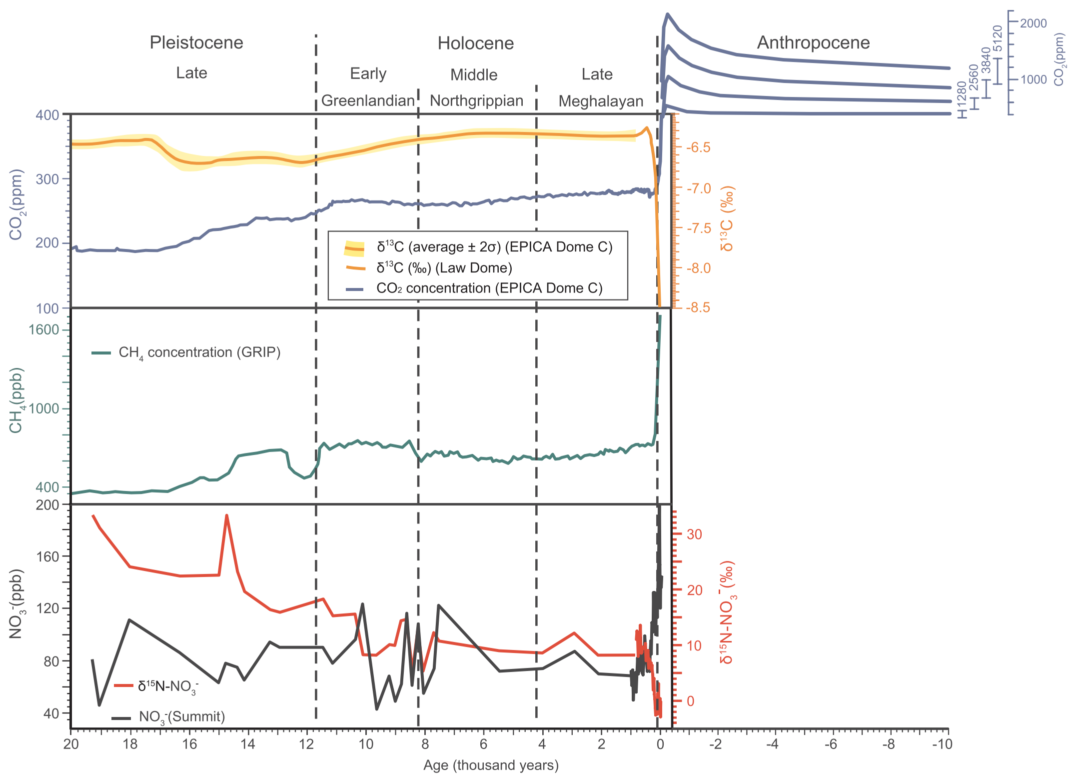

Fig. 13. Key trends for the Anthropocene from the Late Pleistocene to the present time, based on ice core records from Greenland (GRIP, Summit) and Antarctic (EPICA Dome C, Law Dome) and modern instrumental data. Note relative stability through the Holocene, and sharp deflections at the start of the Anthropocene in the mid-20th century contrasting with the relatively gradual changes, at this scale, across the Pleistocene–Holocene boundary. Projected atmospheric CO^2 concentrations are from Clark et al. (2016). Adapted from figs. 1 and 2 respectively of Zalasiewicz et al. (2018, 2019b).

economic growth, primary energy consumption, and population size (Steffen et al., 2011).

8.1. Progress towards formalization

In 2009, the Anthropocene Working Group (AWG) was established by the SQS to explore the validity of a chronostratigraphic Anthropocene, and if warranted to propose its formal definition. The case for a geological Anthropocene was analysed over the following years and presented in a series of publications (e.g., Zalasiewicz et al., 2015, 2019a, b; Waters et al., 2016). Based on a series of indicative (nonbinding) votes within its membership, the AWG then announced its interim findings and recommendations at the 35th International Geological Congress in Cape Town, South Africa on 29th August 2016. These were that the Anthropocene is stratigraphically substantiated, and that it should be formalized at the rank of epoch with an inception at ~1950 and defined by GSSP rather than a Global Standard Stratigraphic Age (Zalasiewicz et al., 2017a). A subsequent binding vote held by the AWG in April–May 2019 confirmed by supermajority that the Anthropocene should be treated as formal chronostratigraphic unit defined by GSSP, and that the primary guide should be one of the stratigraphic signals around the mid-twentieth century.

These recommendations rest on a number of assertions and requirements. The main assertion is that the international geological time scale reflects to varying degree the narrative of Earth history. This is not evident in the protocols and guidelines for defining a GSSP (Remane et al., 1996), the primary function of which is global correlation, but such a narrative is embedded within the time scale we have largely inherited from the nineteenth century (see for example Lyell, 1833, chapter 5, for subdivision of the Tertiary). The hierarchical nature of the geological time scale usually reflects the magnitude of change reflected in the boundaries of the time scale, again with varying degrees of fidelity. Indeed, if we were to redesign the geological time scale to reflect present understanding of Earth history (and this might be an interesting academic exercise), the time scale would look very different from the one we have; but stability in the definition of terms is needed to avoid a disconnect with the older literature.

Most units of the geological time scale have long been established, and their alignment to perceived changes in Earth history have been explored and tested. The base Gelasian Stage for example was selected to coincide with "a critical point of the evolution of Earth climatic system (i.e. close to the final build-up of the Northern Hemisphere Glaciation), which is characterized by plenty of signals … with a worldwide correlation potential." (Rio et al., 1998, p. 82). It therefore met the requirements of isochronous global correlation, but also connected to a significant change in Earth history.

In contrast, there was no existing critically analysed narrative when the AWG set out to evaluate the Anthropocene, and the initial activities of this working group were understandably focussed on this task. Indeed, the principle of "correlation precedes definition" (Remane et al., 1996) requires that an event under normal circumstances (see Cowie, 1986 for exceptions) be sought and tested for its correlation potential before being adopted as primary guide in a GSSP definition. The "Great Acceleration" has now emerged as the preferred event at which to place the start of the Anthropocene, as it provides an important shift in Earth's narrative and yields a wider range of synchronous correlatable signals than earlier historical events can provide. It also coincides with the beginning of above-ground thermonuclear (fusion) bomb testing in 1952, and the associated plutonium-238 fallout (Waters et al., 2015) is currently the favoured as the primary marker (Zalasiewicz et al., 2017a) because of its potentially global and rapid dissemination. The search is now underway for candidate GSSPs that have captured this and other signals (Waters et al., 2018a, 2018b).

The Anthropocene as currently envisioned, with a start in the mid-twentieth century CE, uniquely overlaps with instrumental and historical time, allowing geological events and processes to be interpreted and calibrated with unmatched temporal resolution. The Great Acceleration identifies many parameters of the Earth System that have shifted far beyond the variability documented earlier in the Holocene Series (Fig. 13). Indeed, modeling studies suggest that CO^2 concentrations are higher now than they have ever been during the past three million years, and that global temperatures have never exceeded pre-industrial values by more that 2 °C during the Quaternary (Willeit et al., 2019). Based at least on this narrative of Earth history, the lowest possible logical rank for the Anthropocene would therefore be at the series/epoch level. Assignation at this rank has been endorsed overwhelmingly by the AWG (Zalasiewicz et al., 2017a), although it is fair to assert that no other rank would be possible because the custom of naming series for the Cenozoic with the suffix "-cene" (Paleocene, Eocene, Oligocene etc.) effectively excludes the Anthropocene from holding any other rank, including that of subseries, as Walker et al. (2015) have noted.

Units of the time scale are defined only by their base, so an Anthropocene defined at the rank of series/epoch does not interfere with the definition of the Holocene or its highest stage, the Meghalayan, other than to terminate them (Walker et al., 2019).

8.2. Potential candidate stratotypes

Potential candidate GSSPs and global auxiliary stratotypes are presently being researched within a framework of previously identified promising natural archives (Waters et al., 2018a, b). Nine locations/deposits are presently undergoing investigation: the anoxic Gotland Basin of the Baltic Sea; coral reefs potentially from the Caribbean Sea and Great Barrier Reef; an estuary setting in San Francisco Bay; the meromictic Crawford Lake, Ontario; Huguangyan maar lake, China; an artificial reservoir at Jasper Ridge, California; a peat bog, Etang de la Gruère, Switzerland; firn/ice layers from the Antarctic Peninsula; and a speleothem from Ernesto Cave, northeastern Italy. Most records have annually resolved laminations that can be independently dated radiometrically to confirm their completeness (Waters et al., 2019). Any proposed GSSP will need to meet normal requirements, and must define a new stage along with an Anthropocene Series (Remane et al., 1996). Annually laminated sediments from Crawford Lake, Ontario (Fig. 14) are just one example of the fine detail available for stratigraphic analysis of the Anthropocene.

8.3. Concerns and objections to formalization

Concerns or objections to a formal Anthropocene, or to starting point earlier than the mid-twentieth century, have nonetheless been advanced (e.g. Autin and Holbrook, 2012; Finney, 2014; Gibbard and Walker, 2014; Visconti, 2014; Edwards, 2015; Smil, 2015; Walker et al., 2015; Braje, 2016; Finney and Edwards, 2016; Koch et al., 2019). They have been largely addressed by Zalasiewicz et al. (2017a).

The nature of the geological Anthropocene and its connection to anthropogenic activities have caused particular confusion and some disagreement. This has led for example to suggestions that the Anthropocene should somehow reflect the long, progressive and diachronous spread of human influence over the planet (e.g. Ellis et al., 2016; Bauer and Ellis, 2018; Ruddiman, 2018; Edgeworth et al., 2019). While such a holistic approach may well have a useful place in the social sciences and humanities, it would not then qualify the Anthropocene as a formal chronostratigraphic term (Zalasiewicz et al., 2017b, 2018, 2019b). The Anthropocene was indeed initially proposed to start with the Industrial Revolution in Europe and intended to "emphasize the central role of mankind in geology and ecology" (Crutzen and Stoermer, 2000, p. 17). Conceptually, however, a formal Anthropocene timed to begin with the Great Acceleration can now be seen as the Earth System response to the marked intensification of human impacts, not the impacts themselves, reflecting a tipping point reached in the mid-twentieth century and not before. This places the Earth itself as a functioning and responsive system (not simply a passive recorder of human impact) at the centre of a formal, geologically defined Anthropocene. Moreover, the Great Acceleration has left a cluster of near-synchronous signals capable of being preserved in the stratigraphic record, along with a synchronous radiogenic fallout spike at the inception of the geological Anthropocene as it is now understood.

8.4. Wide usage of the term Anthropocene

The Anthropocene is unusual in that it began within the Earth System community, and was only later conceptualized and tested as geological unit. Even so, as a term it is now widely used in the Earth sciences, and appears in the title of two scholarly international journals: *Anthropocene* (Elsevier) and *The Anthropocene Review* (Sage). On Clarivate Analytics' Web of Science Core Collection, "Anthropocene" was cited in 747 publications in 2018, compared with 2921 for "Holocene", 2753 for "Pleistocene", 877 for "Pliocene", 584 for "Neogene", and 423 for "Silurian" (on 11 February 2018). Perhaps more significantly, the number of publications citing "Anthropocene" has been rising rapidly since 2012 when only 65 publications were cited. These figures would be even greater were the Anthropocene defined as an official unit of geological time, but regardless they are large enough to imply that the term conveys a useful concept.

Given the now wide use of the term Anthropocene, in geological contexts but also within the social sciences and beyond, there is a growing imperative to define this term promptly and reduce further confusion. Unlike the Holocene GSSPs which were selected on the basis of already published data, most or all potential Anthropocene GSSP

Fig. 14. Retrieving sediment core from meromictic Crawford Lake, Ontario, Canada; a potential candidate GSSP site for the Anthropocene (Photo courtesy of R.T. Patterson, August 2018). Inset shows annual layering across the prospective Holocene–Anthropocene boundary. Stratigraphic detail and content are evident. One of the stratigrapic signals around the mid-twentieth century will be used to serve as the primary guide for the base of the Anthropocene. The year 1950 CE is indicated. (Photo courtesy of J.H. McAndrews, scale in cm).

candidate sections will need to be analysed specifically for this purpose. Analyzing sediment at annual or subannual resolution is time consuming, and it will be several years before GSSP proposals are ready for the AWG to assess.

The recent subdivision of the Holocene answers the fair question of whether defining a formal Anthropocene serves any real use. The rationale for formally subdividing the Holocene was that the terms, early, middle and late, were already widely used and that formal definition would simply increase their utility (Walker et al., 2018, 2019). The same justification clearly applies also to the Anthropocene.

8.5. GSSP or GSSA, or an augmented GSSP approach?

The option of using a Global Standard Stratigraphic Age (GSSA) rather than a GSSP to define the Anthopocene had been considered earlier by the AWG (Zalasiewicz et al., 2011, 2015) and by Gibbard and Walker (2014). However, GSSAs were initially intended to subdivide Precambrian time in the absence of an adequate fossil record (Remane et al., 1996). Even for the Precambrian the preference now is to use GSSPs for its formal subdivision (Van Kranendonk et al., 2012). Regarding the Anthropocene, the advantage of using a GSSP to define its base in a chronostratigraphic sense is that this emphasizes the stratigraphic content and nature of the Anthropocene. This helps to distinguish it from the non-chronostratigraphic concepts of the Anthropocene that have emerged particularly within the social sciences and humanities. Nonetheless, an Anthropocene GSSP in annually laminated sediments even under optimal circumstances would not achieve temporal resolution greater than a few months. While this would give unparalleled precision from a stratigraphic perspective, it would not provide the level of exactitude helpful for other purposes such as legal definitions and integration with historical time. It may therefore be pragmatic to augment the GSSP with an agreed age that is precise to the day, hour and minute. This could be approved by the ICS as a matter of convention, enhancing the utility of the GSSP without actually replacing it.

9. Fine-scale subdivision of the Quaternary System

GSSPs are required for all Phanerozoic units of the International Chronostratigraphic Chart, hence from the rank of stage upwards. Finer subdivision is nonetheless greatly needed in the Quaternary, and two examples employing slightly differing approaches are summarized, one based on event stratigraphy and the other on marine isotope stratigraphy.

9.1. Event stratigraphy

In a geological context, events are episodes of relatively brief duration lasting from an instant to thousands of years, and may be local, regional or even global in extent (Rawson et al., 2002). Although some events can span more than a million years (e.g. Oceanic Anoxic Event 1a in the Cretaceous), in the Quaternary they typically represent a fraction of a Milankovitch cycle. Neither the onset nor termination need to be isochronous, but events have been used as a guide when defining GSSPs, as with the 8.2 and 4.2 ka events used in formally subdividing the Holocene (see above). It is notable here that the event iteslf, representing a climatic perturbation of regionally varying (even contrasting) expression and recognized by an array of signals placed within a global context, that is used for global recognition of the boundary.

Event stratigraphy for the Quaternary was explored by Björck et al. (1998) and Walker et al. (1999) who focused on a ~18.0–11.5 k cal yr BP interval of the Last Glacial (latest Pleistocene). This episode had initially been subdivided, from oldest to youngest, into the Bølling Interstadial, Older Dryas Stadial, Allerød Interstadial, and Younger Dryas Stadial on the basis of lithological and paleobotanical evidence from lake successions in northwest Europe. This scheme was subsequently equated with pollen stratigraphy which transformed it into a biostratigraphic/climatostratigraphic subdivision. With the availability of radiocarbon dating, Mangerud et al. (1974) redefined these climatostratigraphic subdivisions into chronozones, as follows: the Bølling Chronozone including the "Oldest Dryas" (13.0–12.0 k^{14}C yr BP), Older Dryas Chronozone (12.0–11.8 k^{14}C yr BP), Allerød Chronozone (11.8–11.0 k^{14}C yr BP) and Younger Dryas Chronozone (11.0–10.0 k^{14}C yr BP). As Walker et al. (1999) remarked, treating these terms as chronozones risked confusion with their previous useful identity as regional and time-transgressive climatostratigraphic units.

Hence, as an alternative approach, Björck et al. (1998) and Walker et al. (1999) constructed an event stratigraphy for this Last Glacial interval based on a δ^{18}O record from the GRIP Greenland ice core. The events represent high-amplitude cold (Greenland Stadial, GS) and warmer (Greenland Interstadial, GI) episodes and are labeled from the top down as GS-1, GI-1, GS-2 and GI-2, with lower-amplitude sub-(inter)stadials being labeled GI-1a, GS-2b etc. The terms cannot be confused with earlier schemes, and because the approach is based on events – namely short-lived episodes – rather than the sharp boundaries separating them, they are more flexible to use. Because these events are climate-driven they are not strictly chronostratigraphic, but the approach has utility for long-distance correlation and can be applied to marine and terrestrial records.

This event-stratigraphic approach has since been extended through the synchronization of δ^{18}O and calcium ion concentration records of three Greenland ice cores, NGRIP, GRIP, and GISP2, resulting in a numbering scheme from GS-1 to GS-26 that now covers the latest Pleistocene interval from 119,140 to 12,896 yr b2k (Rasmussen et al., 2014). This scheme corresponds to the Dansgaard–Oeschger (D–O) events discovered earlier in Greenland ice cores and which represent decadal-scale warming episodes over Greenland (Dansgaard et al., 1993; Landais et al., 2015; Erhardt et al., 2019). These Greenland events can be traced though various climate archives in the North Atlantic region (e.g. McManus et al., 1994; Oppo et al., 2001, 2006). Comparable Bond events (Wanner et al., 2015) have been documented for the Holocene, and represent ice-rafting episodes in the North Atlantic. The 8.2 and 4.2 kyr events have been used to subdivide the Holocene into subseries and stages, as discussed above, and are widely recognized. However, it is unclear whether other short-lived Holocene events can be correlated globally.

Short-lived climatic events, although not strictly chronostratigraphic in nature, have great potential for fine-scale subdivision of the Quaternary at least as far back as the Last Interglacial which is where the Greenland ice core record ends (NEEM Community Members, 2013). McManus et al. (1994) identified from two sediment cores in the North Atlantic eight discrete episodes representing the southward expansion of polar watermasses between MIS 5d and MIS 4, labeling them C24–C17. The numbering of these cold events reflected the scheme then used to label stadials in the Greenland ice core record. More cold events were later recognized, with Chapman and Shackleton (1999) introducing C26 (within MIS 5e) and C25, Oppo et al. (2001) introducing C29–C27, Oppo et al. (2006) introducing the subevents C27a, C27b, and C21a, and Tzedakis et al. (2018) contributing subevent C27'. Cold events C27–C26 and subevents C27a, C27b, and C27′ now extend this event stratigraphy into the Last Interglacial MIS 5e (e.g. Mokeddem et al., 2014; Mokeddem and McManus, 2016, and references above; Fig. 9). Although these marine cold events can be correlated to Greenland stadial (GS) episodes back to GS-26, they are numbered slightly differently from the now widely used scheme of Rasmussen et al. (2014, see p. 21 for discussion) for the Greenland ice core record. There is an added difference in that marine cold subevents are labeled in ascending order (e.g. C27a, C27b with decreasing age) although the events themselves are numbered in descending order (C23, C24, C25 etc. with increasing age: Fig. 9). This differs from the Rasmussen et al. (2014) scheme where events and subevents are all labeled in descending order, which is derived consistently from a 'count from the top' approach. Quite apart from labeling differences, it would appear at least for the Last Glacial period that Greenland became decoupled from the North Atlantic climate system, and may not always serve as a reliable record for the timing of climatic changes in the North Atlantic (Landais et al., 2015). Furthermore, sub-millennial features seen in the Antarctic record may have no counterparts in the Greenland ice cores (Landais et al., 2015).

There is evidence from Antarctic ice core records that an event stratigraphic approach can be applied to earlier glacial phases extending through the Middle Pleistocene (Barker et al., 2011), although the events are controlled by bipolar seesaw oscillations and again are not strictly chronostratigraphic.

9.2. Marine isotope stages

The classification of marine isotope stages has followed a somewhat different approach in that glacial and interglacial intervals in the $\delta^{18}O$ record are generally labeled as stages rather than events (see Railsback et al., 2015 for discussion), with their boundaries sharply delimited. A total of 103 marine isotope stages have been defined for the Quaternary (Lisiecki and Raymo, 2005), and with the addition of substages (Railsback et al., 2015) a total of 95 subdivisions are available for the last million years alone.

Because boundaries between adjacent marine isotope stages are inevitably sharply defined, some diachroneity is almost assured. Nonetheless, Miller and Wright (2017) treated marine isotope stages as chrons, in part because the term "stage" is already used as a chronostratigraphic unit equivalent to "age", but also because "the time significance and duration of $\delta^{18}O$ events warrants the use of the term 'chron' (Miller and Wright, 2017, p. 15). Within a Quaternary context, however, marine isotope stages are treated as geochemical zones genetically linked to global ice volume changes, and hence can be treated as paleoclimatic zones with boundaries that may not be precisely isochronous (Railsback et al., 2015). For example, Skinner and Shackleton (2005) noted an Atlantic lead of 3.9 kyr over the Pacific for the last termination, and Lisiecki and Raymo (2009) estimated an average Atlantic lead of 1.6 kyr for the last six terminations but with leads of ~4.0 kyr for Termination II and IV. The use of "stage" for climatically significant deposits has a long history in Quaternary stratigraphy (Railsback et al., 2015), and seems likely to endure in the context of marine isotope stratigraphy.

10. Perspectives on formal subdivision of the Quaternary System

The narrative of Earth history continues to influence the development of the geological time scale. Both ends feature glaciations, the Ediacaran GSSP marking the end of the Marinoan glaciation (of the latest Cryogenian Period) and the Gelasian representing the intensification of another. Shifts in the Earth System are particularly important for subdividing the Quaternary. The Gelasian, Calabrian, and Greenlandian GSSPs all coincide with important climate shifts or transitions, and the Middle and Upper Pleistocene bases similarly reference climate change. The Anthropocene too, as presently envisioned and if approved, will begin at a major change in the Earth System state, the so-called Great Acceleration.

GSSPs are nonetheless useful only if they can be correlated globally. A marker bed allows the horizon of a GSSP to be traced visibly within the type locality. For the Quaternary these are represented by sapropelic layers for the Gelasian and Calabrian GSSPs, and a tephra bed for the proposed Middle Pleistocene GSSP. In recognizing the importance of paleomagnetic polarity boundaries for global and marine–terrestrial correlation, the Gelasian, Calabrian, and proposed Middle Pleistocene GSSPs are all placed within ~20 kyr of a major paleomagnetic boundary. These sections also have independent astrochronological control which is essential for determining whether the position of the boundary has been affected by lock-in depth or post-depositional remagnetization. ^{10}Be analysis is an important but presently underutilized method for confirming the true position of a paleomagnetic boundary. Classical (evolutionary) biostratigraphy plays a subordinate role in assisting other chronologies, whereas ecostratigraphy-based biostratigraphy in contrast can provide valuable refinements at the suborbital scale.

The Monte San Nicola GSSP defining the base of the Quaternary, corresponds to MIS 103, not to MIS 104 as sometimes reported, and occurs between 0 and ~3 m *below* the Gauss–Matuyama boundary, not ~1 m (20 kyr) above it as reported by Rio et al. (1994, 1998). The Gauss–Matuyama boundary also aligns with MIS 103. High-resolution paleomagnetic sampling of the GSSP interval, ideally supplemented with^{10}Be analysis, is needed to assess the precise position of the Gauss–Matuyama boundary at this important GSSP.

The Greenlandian (and Holocene), Northgrippian and Meghalayan GSSPs represent significant departures from tradition: the first two are defined in ice cores and the last is in a speleothem. These GSSPs are not placed at visibly conspicuous layers but at horizons with highly distinctive geochemical signatures dated with unequalled precision that simultaneously allow local, regional and global correlation (Walker et al., 2018, 2019). The primary guides for these GSSPs are climate perturbations, recognized globally by paleoenvironmental signals including geochemistry and fossil assemblage analyses. In reality, radiocarbon dating allows these stage boundaries to be determined precisely regardless of whether the associated events are recognised or not.

The Quaternary is the only period where geological, historical, and instrumental time overlap, assisting in the measurement and calibration of geological processes. New approaches have been needed to address the high levels of precision required for formal Quaternary chronostratigraphy. These include the adoption of two GSSPs in ice cores (Greenlandian and Northgrippian GSSPs), a GSSP in a speleothem (Meghalayan GSSP), GSSPs dated with ultra-high precision (Northgrippian GSSP at 8236 ± 47 yr b2k, Meghalayan GSSP at 4250 ± 30 yr b2k), and the introduction of the rank of subseries (for the Holocene) to the geological time scale. All three Holocene stages/subseries have exceptionally short durations: the Greenlandian at 3464 yr, Northgrippian at 3986 yr, and Meghalayan presently at 4269 yr. The Gelasian Stage with a duration of 780,000 kyr was previously the shortest stage in the time scale. These short durations reflect both the needs and capabilities of high precision chronostratigraphy in the Quaternary.

Formal subdivision of the Holocene represents a significant departure from the norm in that no clear step-changes occur in Holocene climatic evolution. Subdivision in this instance is justified by the long-standing community-led tradition of using the loosely defined terms "early", "middle" and "late", with formalization simply providing clarity. Even so, the GSSPs are placed at abrupt climate perturbations, the 8.2 ka and 4.2 ka events, as this facilitates their global recognition and correlation. In assessing the utility of climate signals in time scale subdivision, it should be understood that chronostratigraphy is a theoretical construct only, and its application a matter of temporal perspective.

Justification based on usage has relevance also for the Anthropocene which by now is exceptionally widely used as a geological term and will only benefit by formalization. This must be considered an urgent matter, given the plethora of concepts that have arisen in different fields and the confusion this brings. The Great Acceleration provides an important rationale for formalization, and the rank of epoch can be justified by the many indicators of Earth System change that have exceeded the natural envelope of Holocene variability. From a practical perspective, a formal Anthropocene will also offer a rigid chronostratigraphic framework to complement the many diachronous time scales that already chart human cultural activities. As a final benefit, the resulting convergence of geological and near-contemporary historical time will offer the geosciences greater visibility as they engage in our planet's future challenges.

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