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Formal ratification of the subdivision of the Holocene Series/Epoch (Quaternary System/Period): two new Global Boundary Stratotype Sections and Points (GSSPs) and three new stages/subseries

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The Holocene is probably the most intensively studied series/epoch within the geological record, and embodies a wide array of geomorphological, climatic, biotic and archaeological evidence; yet little attention has hitherto been paid to a formal subdivision of this series/epoch. Here we report a tripartite division of the Holocene into the Greenlandian, Northgrippian and Meghalayan stages/ages and their corresponding Lower/Early, Middle, Upper/Late subseries/subepochs, each supported by a Global Boundary Stratotype Section and Point (GSSP). The GSSP for the lowermost stage, the Greenlandian, is that of the Holocene as previously defined in the NGRIP2 Greenland ice core, and dated at 11,700 yr b2k (before 2000 CE). The GSSP for the Northgrippian is in the NGRIP1 Greenland ice core, and dated at 8236 yr b2k, whereas that for the Meghalayan is located in a speleothem from Mawmluh Cave, Meghalaya, northeast India with a date of 4250 yr b2k. The proposal on which this subdivision is based was submitted by the Subcommission on Quaternary Stratigraphy, approved by the International Commission on Stratigraphy, and formally ratified by the Executive Committee of the International Union of Geological Sciences on 14th June 2018.

Introduction

The Holocene is the uppermost chronostratigraphic unit within the geological record and covers the time interval from 11.7 ka until the present day. The term 'holocènes', which means 'entirely recent', was first used by Paul Gervais (1867–69, p. 32) to refer to the warm episode that began with the end of the last glacial period, and which had previously been referred to as 'Recent' (Lyell, 1839) or 'Post-Glacial' (Forbes, 1846). 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 Holocene is now officially defined as a series/epoch within the Quaternary System/Period (Walker et al., 2008, 2009; Gibbard and Head, 2010; Gibbard et al., 2010; Head and Gibbard, 2015).

Holocene stratigraphic records provide evidence, *inter alia*, of climate and sea-level change, geomorphological and hydrological processes, vegetational developments, and faunal migrations. In addition, they contain a unique range and wealth of archaeological data that attest to the development of society and the evolving relationships between people and the environment under near modern boundary conditions. Holocene successions are often extremely well-preserved, continu-

ous and amenable to examination at high temporal resolution. It is surprising, therefore, that relatively little attention has been paid, hitherto, to the formal subdivision of the Holocene, and particularly in view of recent initiatives in Quaternary stratigraphic subdivision and nomenclature (Cita et al., 2006, 2008, 2012; Head et al., 2008; Walker et al., 2008, 2009; Gibbard and Head, 2009, 2010; Gibbard et al., 2010; Head and Gibbard, 2015).

In 2010, a Working Group of the Subcommission on Quaternary Stratigraphy (SQS) and members of the INTIMATE (Integration of Ice Core, Marine and Terrestrial Records) Research Group was convened at the suggestion of Philip Gibbard, then chair of SQS, to consider this matter. Initial deliberations of the Group were set out in a position paper (Walker et al., 2012) and, in due course, a proposal was submitted to the International Commission on Stratigraphy (ICS) via the SQS. This outlined a formal subdivision of the Holocene into three stages/ages and their corresponding subseries/subepochs, each supported by a Global Boundary Stratotype Section and Point (GSSP). The proposal was approved by the ICS and subsequently ratified unanimously by the Executive Committee of the International Union of Geological Sciences (IUGS) on 14th June 2018. Here we explain briefly the background to the proposal and present details on the new Holocene stages/ages and subseries/subepochs, and their associated GSSPs.

Background and Context

A formal subdivision of the Holocene was first outlined by Mangerud et al. (1974) who proposed that for Northern Europe, the Flandrian (regional) Stage (equivalent to the Holocene Series) should be divided into three substages with boundaries defined by radiocarbon-dated chronozones based on palynologically-defined biozones: Early Flandrian (Preboreal and Boreal: 10,000–8000 ^{14}C yr BP[1]); Middle Flandrian (Atlantic and Subboreal: 8000–2500 ^{14}C yr BP); and Late Flandrian (Sub-Atlantic: post 2500 ^{14}C yr BP). But time-transgression in vegetational response to climate change suggests that such a chronostratigraphic subdivision of the Holocene based on biological evidence is not applicable at anything other than the local or perhaps regional scale (Björck et al., 1998; Wanner et al., 2008). Nevertheless, the concept of a tripartite subdivision of the Holocene clearly has validity, with the terms 'Early', 'Middle' ('Mid-') and 'Late' Holocene being routinely applied in the Quaternary science literature. Yet, despite their common usage the precise temporal limits of each of these subdivisions has never been formally agreed.

One reason for this is that unlike earlier time intervals in the Quaternary, the Holocene contains few long-term climatic or environmental trends that register globally and that provide a basis for subdividing into distinct climatostratigraphic units. Hence any subdivision is best achieved through formalizing the subdivisions that are already being used ('Early', 'Middle' and 'Late Holocene') by underpinning them, where possible, with clearly defined marker horizons. These should ideally be globally applicable and should differentiate the Holocene Series/Epoch into three stages/ages and their corresponding subseries/

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[1]Note that 'BP' here, as well as below, means 'before 1950', whereas ice-core age estimates are reported using the designation 'b2k', i.e., relative to 2000 CE.

subepochs, based on distinct age boundaries defined by formally ratified GSSPs (Walker et al., 2012).

The Case for Subseries/Subepochs in the Holocene

Holocene stratigraphers use geochronology universally. Annual/seasonal layering in ice cores, speleothems, and lacustrine and anoxic marine records, along with growth bands in shells, corals and wood, all provide ages by direct counting from the present (Head et al., 2017). The base of the Holocene itself is dated in exactly this way (Walker et al., 2009). In addition, a wide range of geochronometric methods is used routinely in the dating of Holocene sedimentary successions, including radiocarbon, uranium series, lead-210 and thermoluminescence dating, all of which give age estimates in years before present (or a proxy for the present). These methods of dating are more precise and reliable than traditional means of stratigraphic correlation. Consequently, Holocene records typically show data relative to a timescale in years, not core or sediment depth. Accordingly, it is natural to use the terms 'Early', 'Middle' and 'Late' for Holocene records (Head et al., 2017). Although subseries/subepochs have always been acceptable under the International Stratigraphic Guide (Hedberg, 1976: table 2; Salvador 1994; table 3), in practice this rank has not been sanctioned by the IUGS. But the terminology is pervasive in the literature of the Quaternary, and especially of the Holocene, and hence it is entirely appropriate that while the new subdivisions described here are formally designated as stages and ages, they are formally accompanied by their corresponding subseries and subepochs.

The Ratified GSSPs

We report two new GSSPs, one in an ice core and one in a cave deposit (a speleothem). While both of these might be seen as unconventional media for GSSPs, there are good reasons why they have been chosen. The precedent for using an ice core as a GSSP was set with the formal ratification of the Pleistocene–Holocene boundary in the Greenland NorthGRIP2 (NGRIP2) ice core (Walker et al., 2008, 2009), and so the designation here of a GSSP based on stable isotope records in an ice core follows previously established practice. The use of a speleothem, on the other hand, is new. It is justified by the fact that speleothems (a) are stratified successions that occur in most terrestrial regions on Earth; (b) can be analysed at unusually high levels of stratigraphic resolution (sub-decadal to annual); and (c) contain a stable isotopic record that can be underpinned by a high-precision chronology based on U-Th dating. The stable isotope profile in Holocene speleothem calcite has been shown to be an extremely sensitive proxy for climate (e.g., Cheng et al., 2009; Wu et al., 2012; Cheng et al., 2015), and thus dated shifts in the isotopic signal provide a highly detailed and chronologically precise record of Holocene climate change. As such, speleothems are unique yet widespread geological archives and, especially in the Holocene, constitute highly detailed stratigraphic successions and hence potential contexts for GSSPs.

The Greenlandian Stage/Age; Lower/Early Holocene Sub-series/Subepoch

The Greenlandian Stage/Age is named with reference to the central Greenland ice sheet, where the North Greenland Ice Core project (NGRIP: Fig. 1) core was drilled to bedrock in 2003 (75.10°N; 42.32°W). The GSSP defining the base of the stage/age and corresponding sub-series/subepoch is located at 1492.45 m in the NGRIP2 ice core, and was ratified as the base of the Holocene Series/Epoch in 2008. It has an estimated age of 11,700 yr b2k (before 2000 CE; Walker et al., 2008, 2009). This GSSP now also defines the base of the Greenlandian Stage/Age, and the base of the Lower/Early Subseries/Subepoch, as the lowest stage and subseries of the Holocene. The primary marker for this GSSP in the NGRIP2 ice core is an abrupt shift to lower deuterium excess values, reflecting reorganisation of the evaporation regime at the precipitation source at the end of the Greenland Stadial 1/Younger Dryas Stadial. Together with changes in dust load and other parameters, the GSSP marks the first signs of a fundamental change in the climate
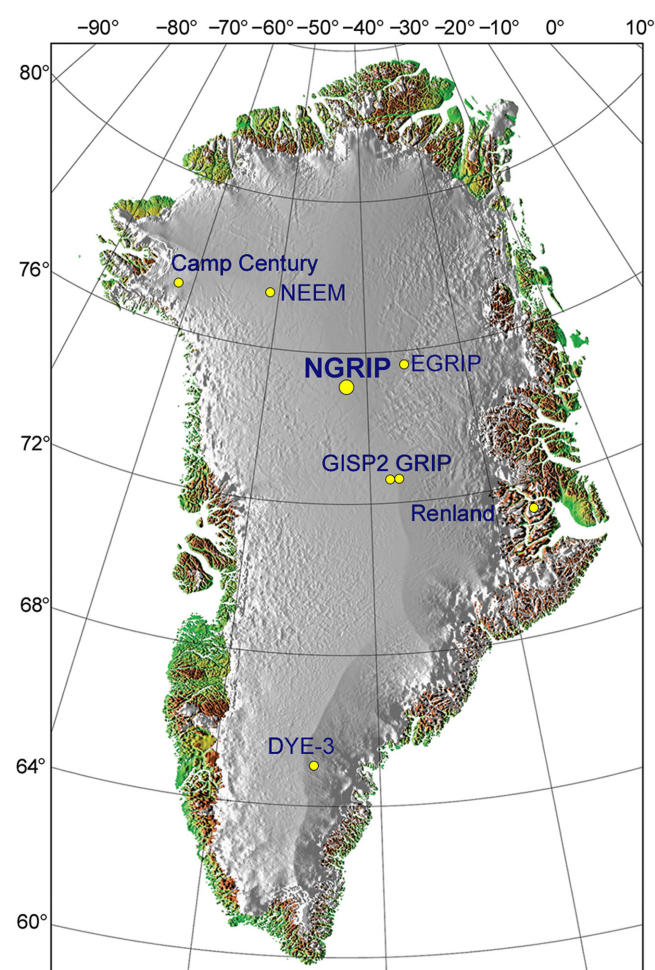
Figure 1. Location of the NorthGRIP coring site on the Greenland ice sheet, which serves as the type locality for the Greenlandian and Northgrippian stages/ages and their corresponding Lower/Early and Middle Holocene subseries/subepochs. Also shown are other deep drill sites, including GRIP and DYE-3 cores used in the construction of the GICC05 time scale upon which the chronology of the NGRIP1 and NGRIP2 records are based.

and circulation patterns of Greenland and its surrounding areas (Steffensen et al., 2008). The NGRIP2 ice core is curated at the University of Copenhagen (Walker et al., 2008, 2009). The upper boundary of the Greenlandian Stage/Age and the Lower/Early Holocene Subseries/Subepoch is defined by the GSSP of the superjacent Northgrippian Stage/Age.

The Northgrippian Stage/Age; Middle Holocene Subseries/Subepoch

The Northgrippian Stage/Age (corresponding to the Middle Holocene Subseries/Subepoch) is named with reference to the NGRIP1 ice core from central Greenland (75.10°N; 42.32°W) which is the type section for the GSSP. It is defined in the ice core at a depth of 1228.67 m at an interval that shows a clear signal of climatic cooling following a period of generally rising temperatures during the Early Holocene (Fig. 2). This cooling occurs around 8.2 ka in the NGRIP1 core and corresponds with the '8.2 ka climatic event', a short-lived, near global episode that is reflected in a wide range of proxy climate records (see below). It is generally considered to reflect curtailment of North Atlantic Deep Water (NADW) formation and its associated northward heat transport, due to catastrophic meltwater release from glacial lakes Agassiz and Ojibway into the North Atlantic during wastage of the Laurentide Ice Sheet (Alley and Ágústdóttir, 2005; Kleiven et al., 2008; Hoffman et al., 2012), perhaps accompanied by collapse and accelerated melting of ice domes over Hudson Bay (Matero et al., 2017). The stratigraphic signature of the 8.2 ka event therefore serves as the primary correlation event for the GSSP of the Northgrippian Stage/Age and Middle Holocene Subseries/Subepoch in the Greenland NGRIP1 ice core.

In the Greenland NGRIP1 ice core, the 8.2 ka event is marked by a significant shift in the oxygen isotope record to more negative $\delta^{18}O$ and δD values, reflecting abrupt cooling (Fig. 2), and by a decline in ice-core annual layer thickness (Rasmussen et al., 2007) and deuterium excess (Masson-Delmotte et al., 2005). The water isotope diffusion-derived temperature record indicates a cooling of ~5 °C (Gkinis et al., 2014). Within the $\delta^{18}O$ minimum that constrains this event, there is also a strong volcanic signal marked by a double acidity peak reflected in electrical conductivity measurements (ECM). This layer, at 1228.67 m depth in the NGRIP1 core (Fig. 3), is characterized by high fluoride content and can most likely be attributed to an Icelandic volcano. While it has not been linked to a specific eruption, the layer is found in all deep Greenland ice cores (Rasmussen et al., 2006; Vinther et al., 2006; see below). Moreover, while the climate signal inferred from the oxygen isotope record allows the GSSP to be placed within the coldest part of the 8.2 ka event in the NGRIP1 core, examination of other proxy climate records shows that the 8.2 ka event is part of a longer term episode of climate cooling (Rohling and Pälike, 2005; see below), and hence the use of the independent volcanic signal enables the GSSP to be located with a high degree of precision in the NGRIP1 ice core record.

The 8.2 ka event is most strongly registered in localities around the North Atlantic Ocean (e.g., Snowball et al., 2010; Cohen and Hijma, 2014; Holmes et al., 2016), and therefore the Greenland NGRIP1 ice core is an appropriate high-latitude stratotype (GSSP). However, proxy climate records from other parts of the world also show anomalies
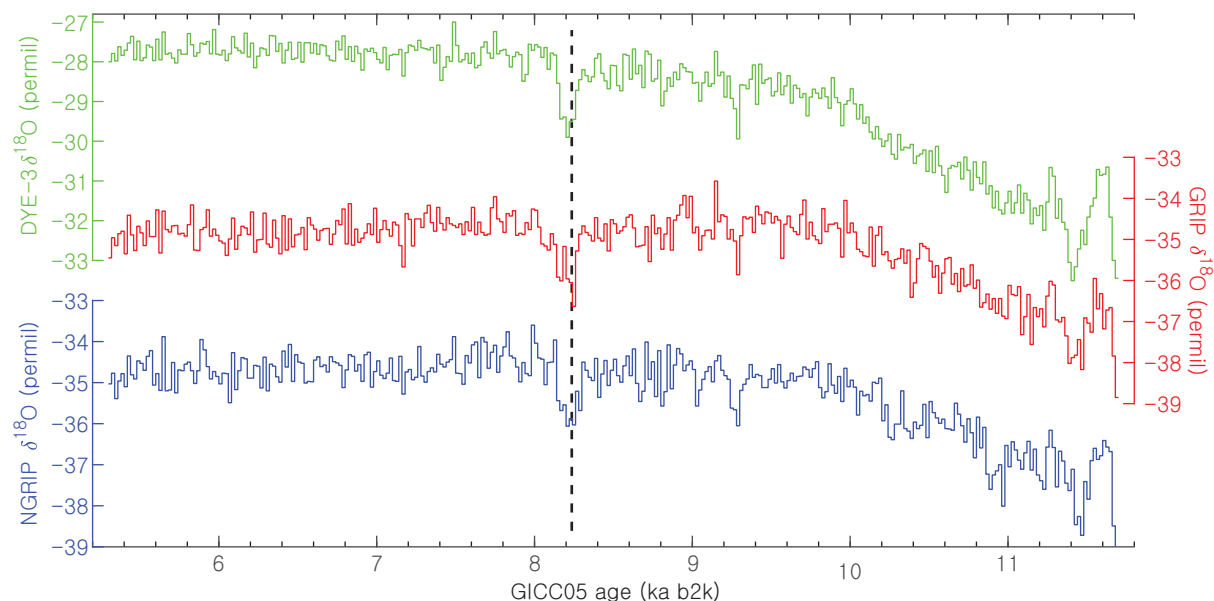
Figure 2. Water stable isotope ratios ($\delta^{18}O$) at 20-year resolution in three Greenland ice core records, DYE-3, GRIP and NGRIP (NGRIP1 and NGRIP2 combined), over the time interval 11.7–5.3 ka b2k (before 2000 CE) on the GICC05 time scale (Rasmussen et al., 2006; Vinther et al., 2006). The location of the Early–Middle Holocene boundary inside the 8.2 ka event is shown by the dashed black line. Note that the $\delta^{18}O$ records are aligned using the volcanic matching of the records. Differences in expression of the 8.2 ka event in the stable isotope records represent real differences in the isotope signal, and not dating or matching uncertainty.

around 8.2 ka, including those from speleothems in southern Asia, China, Brazil and California (Cheng et al., 2009; Wu et al., 2012; Oster et al., 2017); lake sequences in the Levant (Vossel et al., 2018), tropical Africa (Gasse, 2000), northern India (Dixit et al., 2014) and the Tibetan Plateau (Zhang and Mischke, 2009); pollen records from the Mediterranean (Pross et al., 2009; Peyron et al., 2011); ice cores from eastern Africa (Thompson et al., 2002); pollen data from Siberia (Velichko et al., 1997); tidal flat sediments from China (Chen et al., 2015); and marine records from the north-west Pacific (Hua et al., 2008). The 8.2 ka event may also be recorded in lake sediment successions in East Antarctica (Cremer et al., 2007) and New Zealand (Augustinus et al., 2008). The 8.2 ka event is therefore near global in nature (Rohling and Pälike, 2005) and, as such, constitutes an ideal time-stratigraphic marker horizon for defining the base of the Northgrippian Stage/Age and the Lower/Early Holocene Subseries/Subepoch.

The age of the GSSP is derived from annual ice layer counting (the GICC05 timescale) using a range of physical and chemical parameters many of which vary seasonally, thereby enabling annual ice layers to be determined with a high degree of precision. These include dust concentration, conductivity of ice and melted samples, $\delta^{18}O$ and δD, and a range of chemical species including Ca^{2+}, NH_4^+, NO_3^-, Na^+ and SO_4^{2-} (Rasmussen et al., 2006; Vinther et al., 2006). In the upper levels of Greenland ice cores, annual ice layers can be readily identified on the basis of $\delta^{18}O$ and δD records and seasonal variations in ice chemistry (Meese et al., 1997; Vinther et al., 2006). However, because of the relatively low accumulation rate at the drill site and a high sensitivity of the annual cycles in $\delta^{18}O$ and δD to diffusion, NGRIP1 $\delta^{18}O$ and δD data are not suitable for the identification of annual ice layers. In order to obtain a complete Holocene chronology for NGRIP1, therefore, the Early Holocene record was linked with that from other Greenland

core sites, DYE-3 and GRIP (Fig. 1). The former is located in south-eastern Greenland where a higher ice accumulation rate has produced the best resolved of all the Greenland ice-core timescales for the Middle and Late Holocene (Vinther et al., 2006). A key feature in all of the ice cores is the 8.2 ka event which, as in NGRIP1, is marked by a reduction in δD, by a prominent ECM double peak and by a marked increase in fluoride content reflecting a volcanic event (see above). Collectively, these features constitute a unique time-parallel marker horizon for correlating all Greenland ice-core records.

In the DYE-3 core, the annual layer situated in the middle of the ECM double peak is dated to 8236 yr b2k with a maximum counting error of 47 yr (Vinther et al., 2006)[2]. Note that the term b2k, which refers to the ice-core zero age of 2000 CE, is 50 years later than the zero year for radiocarbon which is 1950 CE; hence the equivalent age on the calibrated radiocarbon timescale is 8186 cal. yr BP. Accordingly, the GSSP for the Northgrippian Stage/Age and Middle Holocene Subseries/Subepoch is defined at a depth of 1228.67 m in the Greenland NGRIP1 ice core with an age of 8236 yr b2k.

In order to examine the stratotype horizons for the Greenlandian and Northgrippian stages/ages, deep ice-coring is necessary. However, the NGRIP1 and NGRIP2 cores are archived at the Centre for Ice and Climate, The Niels Bohr Institute, University of Copenhagen, Denmark, and access to these can be gained through the NGRIP curator (currently

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[2]The uncertainty estimate of the GICC05 timescale is derived from the number of potential annual layers that the investigators found difficult to interpret. These layers were counted as ½ ± ½ yr, and the so-called maximum counting error (mce) is defined as one half times the number of these features. Strictly speaking, the value of the mce cannot be interpreted as a standard Gaussian uncertainty estimate, but it is estimated that the true age of the base of the Northgrippian is within ±47 yr of 8236 yr b2k with more than 95% probability (Andersen et al., 2006).
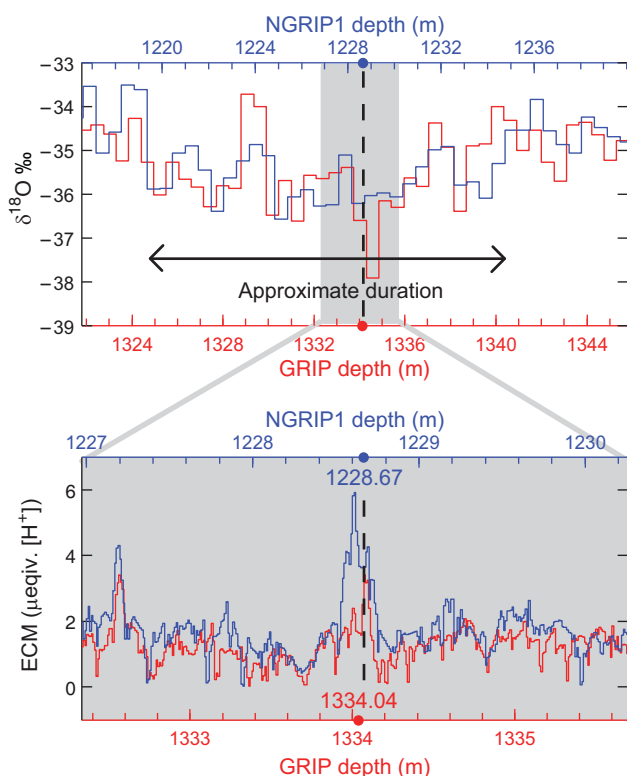
Figure 3. Top: water stable isotope ratios (δ¹⁸O) at 55-cm resolution from the GRIP and NGRIP1 ice cores around the 8.2 ka event. The event duration depends on the criteria and dataset used, but Rasmussen et al. (2007) suggested that in NGRIP1 the event be defined from ~8300 yr b2k (1234.78 m) to ~8140 yr b2k (1219.47 m) as indicated by the black horizontal double arrow. Bottom: during the period of low δ¹⁸O values (the section marked by the grey bar in the upper panel and expanded in the lower panel), a distinct acidity double peak is reflected in electrical conductivity measurements (ECM). This layer, at 1228.67 m depth in the NGRIP1 core and 1334.04 m in the GRIP core (black dashed line), is characterized by a high fluoride content and can most likely be attributed to an Icelandic volcano. It is dated on the GICC05 timescale to 8236 yr b2k (8186 cal. yr BP), and is the primary marker for the Early–Middle Holocene boundary (after Walker et al., 2012).

J.-P. Steffensen) via the NGRIP Steering Committee. Hence, although the stratotype localities are in a remote region and, unlike other GSSPs, cannot be easily seen in the field, free access to the NGRIP1 and NGRIP2 cores, in which the Greenlandian and Northgrippian GSSPs are defined, can be assured at the University of Copenhagen.

The Meghalayan Stage/Age; Upper/Late Holocene Subseries/Subepoch

The Meghalayan Stage/Age is named with with reference to the northeastern Indian State of Meghalaya in which Mawmluh Cave, which is the stratotype locality, is located (Fig. 4). The cave is on the Meghalayan Plateau, an area of conglomerates, sandstones, coal and limestones, that has been intensely karstified due to the exceptional amount of rainfall received in the region. Indeed, this is believed to be one of the wettest locations on Earth. The 7 km long Mawmluh Cave

(entrance 25°15'44"N; 91°42'54"E) is at the southern edge of the plateau, is overlain by 30–100 m of limestone and sandstone, and formed along the contact between the Lower Eocene Lakadong dolomite (within the Sylhet Limestone Formation) and the Therria Sandstone (Breitenbach et al., 2015). The closest municipality is the town of Sohra (Cherrapunji), which is approximately 58 km southeast of the provincial capital, Shillong, and 15 km north of the border with Bangladesh.

Mawmluh Cave contains numerous speleothems (Breitenbach et al., 2015; Myers et al., 2015), the oldest published record from these being from speleothem KM-A (Fig. 5). This has provided a uranium-series dated Upper Pleistocene to Upper Holocene stable isotope profile (δ¹⁸O: Fig. 6; Berkelhammer et al., 2012), which shows a marked shift to heavier isotopic values at ~4.2 ka, reflecting an abrupt reduction in precipitation due to a weakening of the monsoon across the Indian sub-continent and southeast Asia. More widely, it initiates the 4.2 ka event, a significant reorganisation of ocean and atmosphere circulation patterns (the 'Holocene Turnover': Paasche et al., 2004; Paasche and Bakke, 2009). It has also been described as the '4.07 ka climatic anomaly' (Railsback et al., 2018). This event is recorded in proxy records across seven continents from North America and Europe, through West Asia to China; and from Africa, Andean-Patagonian South America, Antarctica and the central North Pacific (Mayewski et al., 2004; Staubwasser and Weiss, 2006; Schimpf et al., 2011; Peck et al., 2015; Chase et al., 2017; Weiss, 2017; Bailey et al., 2018). Most mid- and low-latitude records indicate the abrupt onset of a two to three century aridification (e.g., Booth et al., 2005; Parker et al., 2006; Dixit et al., 2014b; Cheng et al., 2015; Kaniewski et al., 2017), while a few show a shift to wetter conditions (e.g., Zielhofer et al., 2017). Significant deflection or weakening of the East Asian Summer Monsoon and the Indian Summer Monsoon occurs from ~4.2 ka (Wang et al., 2005; Yang et al., 2011; Kathayat et al., 2017), while the abrupt onset of century-scale drought in Australia begins at this time with alteration of the Indo-Australian Monsoon (Quigley et al., 2010; McGowan et al., 2012). In northern high latitude regions, 'neo-glacial' conditions with marked glacier advances are pronounced at ~4.2 ka (e.g., Andresen and Björck, 2005; Menounos et al., 2008; Larsen et al., 2012; Balascio et al., 2015) with glaciers, while lower Antarctica sea-surface temperatures and increased sea-ice cover start abruptly at ~4.2 ka onwards (Peck et al., 2015). In many low latitude regions, the abrupt aridification around 4.2 ka may, in some areas, have had profound societal effects, with rain-fed region abandonments, habitat-tracking to riverine refugia, and societal collapses visible archaeologically across Spain, Greece, Palestine, Egypt, Mesopotamia, the Indus Valley and the Tibetan Plateau (Stanley et al., 2003; Ponton et al., 2012; Weiss, 2014; d'Alpoim Guedes et al., 2016; Weiss, 2017; Blanco-Gonzalez et al., 2018) synchronous with the collapse of significant Neolithic societies in the regions of the Yangtze and Yellow River and North China (Liu and Feng, 2012; Guo et al., 2018). In central Africa, the first stage of Bantu expansion is coincident with the 4.2 ka event (Maley and Vernet, 2015), while significant changes in farming practices around 4.2 ka are evident in the American Southwest and the Yucatan (Merrill et al., 2009; Torrescano-Valle and Islebe, 2015). As with the 8.2 ka event, therefore, the 4.2 ka event was global or near global in nature and constitutes a time-stratigraphic marker horizon for defining the base of the Meghalayan Stage/Age and the Upper/Late Holocene Subseries/Subepoch.
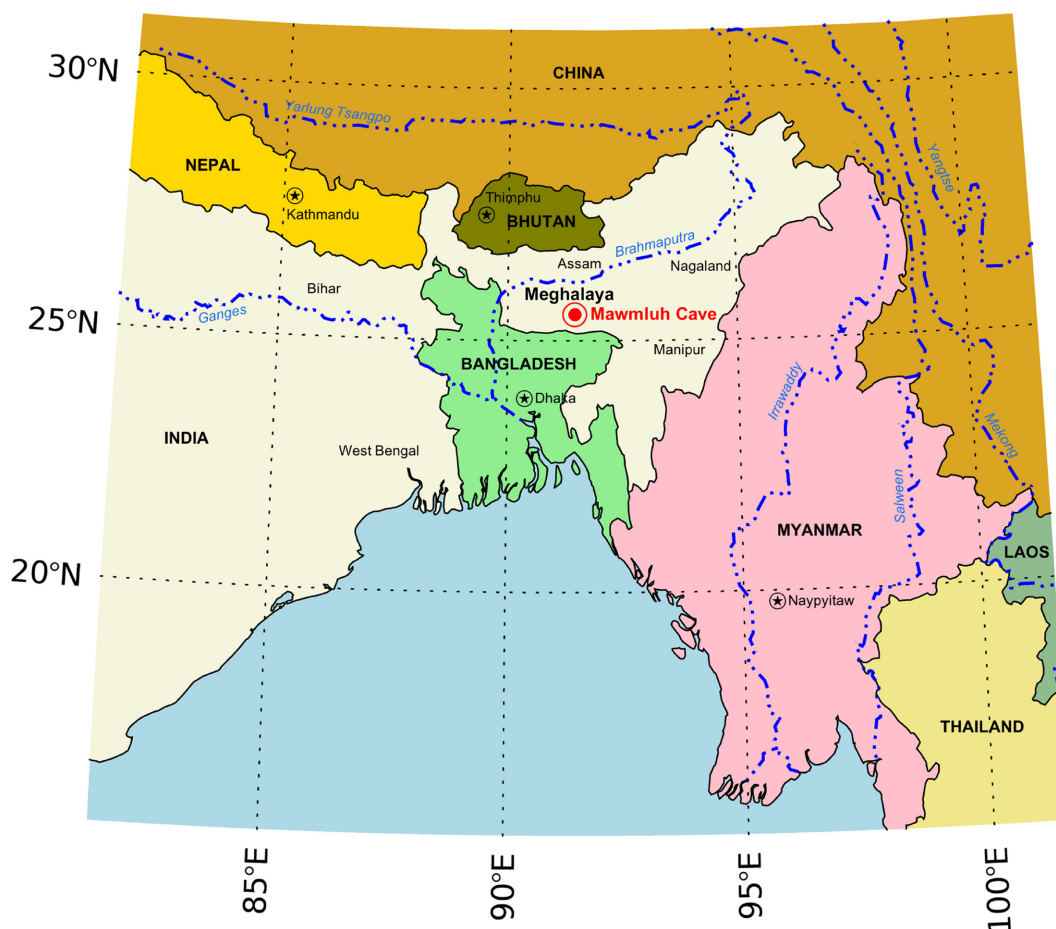
Figure 4. Location of Mawmluh Cave in northeastern India, the type locality for the Meghalayan Stage/Age and its corresponding Upper/ Late Holocene Subseries/Subepoch.

Figure 5. (a) Speleothem KM-A from Mawmluh Cave, Meghalaya, northeast India, showing (b) the position of the 4.2 ka event. The speleothem is ~308 mm long.

The forcing mechanisms behind the 4.2 ka event are not well understood, but may be linked to the southward migration of the Inter-Tropical Convergence Zone (Mayewski et al., 2004) and/or cooling of North Atlantic surface waters (Bond et al., 1997), while in the Pacific, tropical 'deep' waters may also have cooled sufficiently to allow a switch-on of the modern El Niño Southern Oscillation (ENSO) regime (Gomez et al., 2004), which inhibits and weakens the Asian monsoon resulting in widespread drought conditions (Fisher et al., 2008; Fisher, 2011). As the 4.2 ka event is strongly recorded in proxy climate records from mid- and low latitudes, the stable isotope signal of the event in the Mawmluh Cave speleothem constitutes an appropriate marker horizon for the base of the Meghalayan Stage/Age and Late Holocene Subseries/Subepoch.

The stable isotope profile from the KM-A speleothem (Fig. 6) shows a low-frequency strengthening of the monsoon from ~12,000 until 6000 yr BP. The monsoon subsequently weakened and the stalagmite ceased to grow at 3600 yr BP. The most notable feature of the record is a two-step increase in isotopic values beginning at 4303 yr BP and ending at 3888 yr BP, spanning 415 years (Fig. 6). The more intense period of weakened monsoon occurred from 4071 to 3888 yr BP, spanning an interval of 183 years (shown by the red arrows on Fig. 6). The event was characterised by an overall shift of 1.5‰ in $\delta^{18}O$, approximately equivalent to a 20–30% decrease in monsoon rainfall. The unique characteristics of this record are a combination of good age control
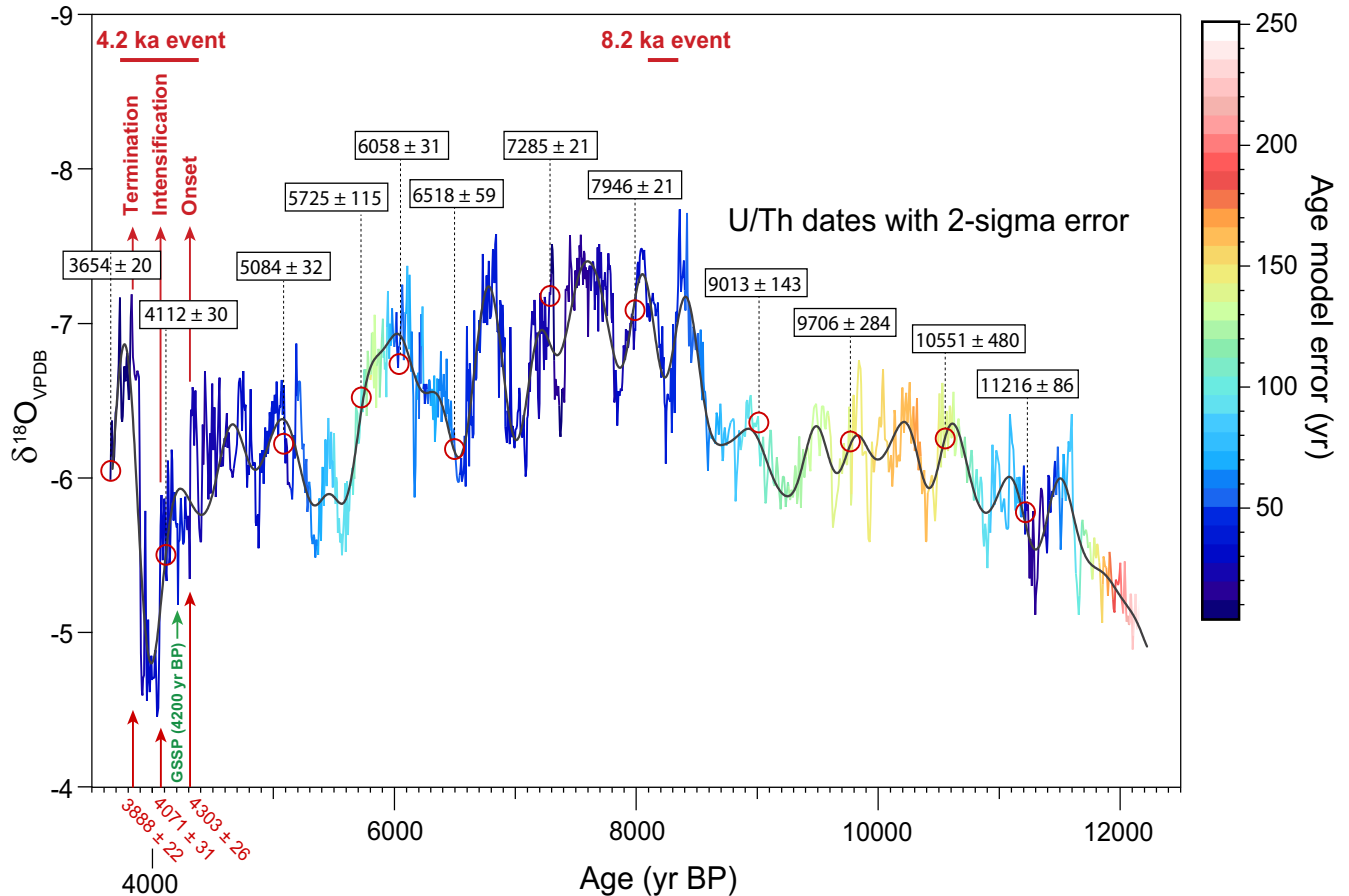
Figure 6. *The Mawmluh Cave δ¹⁸O record for speleothem KM-A, showing the position of the 4.2 ka event on the stable isotope trace (after Berkelhammer et al., 2012). The continuous black line through the isotope trace is a low pass filter removing any variability with a frequency higher than 10 years. Red circles mark all U-Th dates obtained, which are given with their 2σ analytical uncertainty in black boxes. Age uncertainty (95% confidence interval) was assessed using a Monte Carlo fitting procedure through the U-Th dates, and is also shown by variations in colour along the trace. The envelope of the event (onset and termination) is shown by the arrowed red lines, and the beginning of the most intensive phase of weakened monsoon is shown by a third arrowed red line: their dates (in red) are given with uncertainty that is also assessed using the Monte Carlo fitting procedure. See Berkelhammer et al. (2012) for details on the age model calculations. The position of the GSSP, with a modelled age of 4200 yr BP (4250 b2k) is indicated by the green arrow. Note that the 8.2 ka event also registers as a significant excursion in the stable isotope record from Mawmluh Cave.*

derived through U-Th dating of the stalagmite (see below), and a sample resolution of around, or less than, 5 years.

An age model for the stable isotope record for speleothem KM-A was developed using a Monte Carlo fitting procedure through 12 U-Th dates (Scholz and Hoffman, 2011). The analytical uncertainty on the two U-Th dates closest to the 4.2 ka event (3654 and 4112 yr BP) are 20 and 30 years respectively, with a third date at 5084 yr BP having an uncertainty of ±32 years. The KM-A record shows linear growth rates during this period which provides further confidence in the timing (onset and duration) of the 4.2 ka event (Berkelhammer et al., 2012). The first registration of the event in the stable isotope record occurs at ~4300 yr BP followed by a second marked increase in stable isotope values at ~4100 yr BP. The abrupt increase in stable isotope values is the primary boundary marker for the GSSP, and hence a date of 4200 yr BP, which effectively marks the mid-point between these two modelled ages, can be assigned (Fig. 6). The age estimates are well within the range of ages for climatic proxies from other records for the 4.2 ka event described above. Here, the U-Th ages are expressed relative to a

baseline date of 1950 CE and are therefore directly comparable with the calibrated radiocarbon time scale. However, in order to maintain consistency with the earlier Holocene GSSPs (the Greenlandian and Northgrippian) which are dated using the GICC05 ice-core chronology relative to the b2k datum, we quote the age of the Mawmluh speleothem GSSP as 4250 yr b2k (before 2000 CE: see above). Accordingly, the GSSP for the Meghalayan Stage/Age and corresponding Upper/Late Holocene Subseries/Subepoch is defined in the Mawmluh Cave speleothem from northeast India, with a modelled age of 4250 yr b2k.

Access to Mawmluh Cave in Meghalaya, northeast India, can be arranged through the National Cave Research and Protection Organization (http://caves.res.in), which is registered under the Government of India Societies Registration Act of 1860. This is currently headed by Dr Jayant Biswas, at the Central Office, 3/40 Civil Lines, Rajalab, Raipur, 492001C.G., India. The speleothem KM-A, in which the GSSP for the Meghalayan Stage/Age and the coincident Late/Upper Holocene Subseries/Subepoch are recorded, will be conserved at the Birbal Sahni Institute of Palaeosciences, Lucknow, Uttar Pradesh, India.

Summary and Conclusions

Whereas most current GSSPs use biostratigraphic data as primary markers, it has been recommended that future GSSPs should have physico-chemical markers as an integral part of their guiding criteria (Smith et al., 2014; Miller and Wright, 2017). Indeed, as Head and Gibbard (2015) have noted, the International Stratigraphic Guide (Hedberg, 1976, p. 82; Salvador, 1994, p. 88) allows certain methods of correlation, such as climatic, palaeomagnetic, and isotopic, to have greater emphasis for Quaternary chronostratigraphy. The subdivision of the Holocene as outlined above is therefore entirely in keeping with that recommendation, as all three of the GSSPs are defined on the basis of physical and chemical markers. These reflect abrupt climatic events at the onset of the Holocene (~11.7 ka), at ~8.2 ka and ~4.2 ka, all of which are global or near global in their expression. Stable isotope records in particular, from both Holocene ice-core and speleothem successions, have proved to be remarkably sensitive proxies for climate change, and can be dated with a very high degree of accuracy and precision. Indeed, the designated GSSPs described here may be the best-resolved, both stratigraphically and temporally, within the entire geological time scale. They closely accord with the criteria for boundary stratotypes outlined in Remane et al. (1996), and should provide stable points of reference for Holocene stages/ages and subseries/subepochs into the future.

Ratification of the Holocene GSSP in 2008 established the precedent of using an ice core to define a GSSP, and this has now been followed with the Northgrippian Stage GSSP. However, ratification of the Meghalayan Stage GSSP in a speleothem sets a new precedent and not only facilitates unusually high dating precision but allows a GSSP to be displayed for the first time in a museum. Ratification of the Lower/Early, Middle, and Upper/Late Holocene (corresponding precisely to the Greenlandian, Northgrippian and Meghalayan stages/ages) now formalises the rank of subseries/subepoch for the Holocene. This finally resolves the editorial dilemma of whether to capitalise the initial letter of the positional term (Head et al., 2017) for this time interval.

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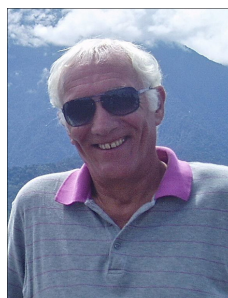
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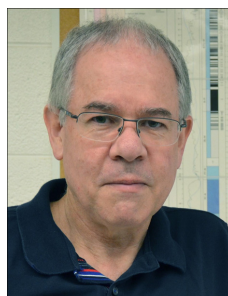
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