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Subdividing the Holocene Series/Epoch: formalization of stages/ages and subseries/subepochs, and designation of GSSPs and auxiliary stratotypes

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ABSTRACT: The Holocene, which currently spans ~11 700 years, is the shortest series/epoch within the geological time scale (GTS), yet it contains a rich archive of evidence in stratigraphical contexts that are frequently continuous and often preserved at high levels of resolution. On 14 June 2018, the Executive Committee of the International Union of Geological Sciences formally ratified a proposal to subdivide the Holocene into three stages/ages, along with their equivalent subseries/subepochs, each anchored by a Global boundary Stratotype Section and Point (GSSP). The new stages are the Greenlandian (Lower/Early Holocene Subseries/Subepoch) with its GSSP in the Greenland NGRIP2 ice core and dated at 11 700 a b2k (before 2000 CE); the Northgrippian (Middle Holocene Subseries/Subepoch) with its GSSP in the Greenland NGRIP1 ice core and dated at 8236 a b2k; and the Meghalayan (Upper/Late Holocene Subseries/Subepoch) with its GSSP in a speleothem from Mawmluh Cave, north-eastern India, with a date of 4250 a b2k. We explain the nomenclature of the new divisions, describe the procedures involved in the ratification process, designate auxiliary stratotypes to support the GSSPs and consider the implications of the subdivision for defining the Anthropocene as a new unit within the GTS. Copyright © 2019 John Wiley & Sons Ltd.

KEYWORDS: auxiliary stratotypes; Greenlandian; Holocene subdivision; Meghalayan; Northgrippian.

Introduction

In 2012, a Discussion Paper was published in the *Journal of Quaternary Science* that outlined a proposal by a Working Group of the Subcommission on Quaternary Stratigraphy (SQS) of the International Commission on Stratigraphy (ICS) for a formal subdivision of the Holocene Series/Epoch (Walker *et al.*, 2012). An online Discussion Forum was also established following publication of that paper which invited comments on the provisional subdivisional scheme. In due course, a final proposal was formulated by the Working Group and submitted via the ICS to the International Union of Geological Sciences (IUGS), where it was ratified by the Executive Committee (EC) of that body on 14 June 2018. Final ratification brought to a successful conclusion an evaluatory process that had spanned more than 8 years of consultation and deliberation. It formally established a tripartite subdivision of the Holocene Series/Epoch, with three new stages/ages (the Greenlandian, Northgrippian and Meghalayan) and their associated subseries/subepochs, each underpinned by Global boundary Stratotype Sections and Points (GSSPs: Fig. 1).

Full details of the new subdivision have been reported in Walker *et al.* (2018), and in summary form in Walker *et al.* (2019). As neither of these is a mainstream Quaternary journal, however, we here take the opportunity to update the proposals that were first outlined in the Discussion Paper of 2012, and to bring these to the attention of the wider Quaternary community. In addition, we provide further information on the new Holocene subdivision and on the procedures that led to its ratification; on the stratigraphic terminology used in the new scheme; on the GSSPs that underpin the subdivision; and on the designation of auxiliary stratotypes that support them. Finally we consider the matter of the Anthropocene, and whether subdivision of the Holocene as outlined here in any way impacts on attempts to establish the Anthropocene as a new unit within the international geological time scale (GTS).

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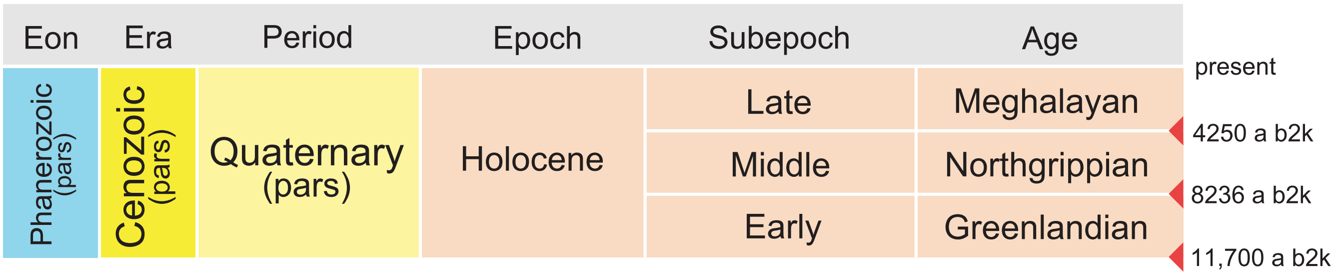

Figure 1. The new formal subdivision of the Holocene Series/Epoch. Note that only parts of the Phanerozoic, Cenozoic and Quaternary are shown.

The Holocene Series/Epoch

The term "Holocene" has been used by geologists for almost 150 years. It originated as "holocène" (meaning "entirely recent") and was first used by Gervais, 1867–69, (1867, 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 "Postglacial" (Forbes, 1846). It was introduced during the Second International Geological Congress (IGC) in Bologna (1882), and a "Holocenian" Stage was subsequently 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 and was formally ratified by the IUGS in 2008 (Gibbard *et al.*, 2010; Head and Gibbard, 2015; Walker *et al.*, 2008, 2009).

Over the course of the last century or so, the Holocene has become one of the most intensively studied intervals within the entire geological record embodying, as it does, a remarkable range of geomorphological, sedimentological, climatic, isotopic, biological and archaeological evidence, often at very high stratigraphical resolution. Moreover, several geochronological methods of high temporal resolution can be applied to Holocene records (Walker, 2005), and hence Holocene successions can often be precisely and accurately dated and correlated. It is somewhat surprising therefore that little interest had hitherto been shown in a formal subdivision of this series/epoch (Walker *et al.*, 2012). Indeed, before the initiative described here, apart from the Pridoli Series of the Silurian System and some series in the Carboniferous System, the Holocene was the only unit of this rank that remained undivided in a formal manner. Although an *informal* tripartite subdivision of the Holocene into early, middle (or mid-) and late phases is widely used, the time intervals vary widely (Table 1) and the terms are often not clearly defined (e.g. Fyfe *et al.*, 2018; Reusche *et al.*, 2018). Practice also varies with respect to the use of lower or upper case for the terms "early," "middle," and "late," sometimes within the same publication. These inconsistencies can lead to confusion and highlight the need for the standardization of definitions and terminology in a formally approved stratigraphic scheme.

Table 1. Variation in the age brackets used for Holocene subdivisions in some current literature.

Source	Age of proposed Holocene divisions (cal ka BP)		
	Early	Mid/ middle	Late
Ayache *et al.* (2018)	11 to 8–7	8–7 to 5–4	5 to 1950 CE
Vossel *et al.* (2018)	9 to 7.4	7.4 to 2.2	2.2 to 0
Dean *et al.* (2018)	11.7 to 6.5	6.5 to 1.6	1.6 to 0
Azuara *et al.* (2018)	11.7 to 7.0	8.0 to 4.0	4.0 to 0
Woolderink *et al.* (2018)	11.7 to 8.9	8.9 to 3.1	3.1 to 0
Aragón-Moreno *et al.* (2018)	Undefined	5.6 to 4.0	4.0 to 0
Hubay *et al.* (2018)	10.67 to 9.0	9.0 to 6.5	6.5 to 0
Novenko *et al.* (2018)	Undefined	7.0 to 2.1	2.1 to 0.1
Emmanouilidis *et al.* (2018)	Undefined	6.5 to 6.1	3.3 to 2.5
Yuan *et al.* (2018)	10.0 to 6.0	6.0 to 2.0/1.0	Undefined*

*In this paper, reference is made to a "late Holocene," which is not explained.

Towards a formal subdivision of the Holocene

The earliest attempt to develop a subdivision of the Holocene was made by the Scandinavian botanists Axel Blytt and Rutger Sernander who, in the early years of the 20th century, proposed a stratigraphical scheme using plant macrofossil records from peat bogs in Scandinavia (Sernander, 1908). Their terminology, based on interpreted climatic changes, comprised, in ascending chronological order, the pre-Boreal, Boreal, Atlantic, sub-Boreal and sub-Atlantic episodes. These terms were applied to European pollen-based biozones by Lennart von Post and others (Godwin, 1975), and were subsequently incorporated into a seminal paper by Mangerud *et al.* (1974) on the Quaternary stratigraphy of Norden (the Nordic countries). This proposed that the Flandrian (regional) Stage (equivalent to the Holocene Series) should be divided into three substages with boundaries defined by the North European chronozones based on the Blytt–Sernander pollen zones and dated by radiocarbon: Early Flandrian (Preboreal and Boreal: 10 000–8000 ^{14}C a BP[1]); Middle Flandrian (Atlantic and Sub-boreal: 8000–2500 ^{14}C a BP); and Late Flandrian (Sub-Atlantic: post 2500 ^{14}C a BP). However, time-transgression in vegetational response to climate change, ambiguities in the use of the Blytt and Sernander classification and problems associated with radiocarbon dating suggested that such a chronostratigraphical subdivision of the Holocene would not be applicable at anything other than the local or perhaps regional scale (Björck *et al.*, 1998; Walker, 1995; Wanner *et al.*, 2008). Yet the scheme continues to be used today, and often in regions for which it was never initially intended (e.g. Bolikhovskaya *et al.*, 2018; Furlanetto *et al.*, 2018; Khokhlova *et al.*, 2019).

A number of important advances in Quaternary geoscience have since encouraged a re-evaluation of the possibility of a formal chronostratigraphical subdivision of the Holocene Series/Epoch. These include increasing numbers of Holocene successions resolved at annual to decadal scales, such as ice cores from Greenland, Antarctica and elsewhere; high-resolution

[1]Note that "BP" here, as well as below, means "before 1950." This age datum differs by 50 years from ice-core age estimates, now generally reported relative to a baseline year of 2000 CE (b2k).

stratigraphical records from peat deposits and lacustrine sediments; and annually resolved tree-ring series and speleothems. These are often highly detailed palaeoenvironmental archives of regional, hemispherical or even global significance. The resulting worldwide proliferation of Holocene records, together with a growing interest in global compilations and interregional comparisons (e.g. Marcott *et al.*, 2013), have further underpinned the need to develop a more globally applicable subdivision than those based on Northern European evidence alone. In addition, refinements in numerical dating techniques (notably radiocarbon, uranium series, luminescence, exposure dating and annual layer counting chronologies) offer an increasingly secure geochronological foundation, while temporal stratigraphical markers such as tephra isochrons enhance accuracy in regional and, in some instances, extra-regional correlation. These various lines of evidence and associated dating methods offer a stronger foundation for time-stratigraphical subdivision and correlation than was previously possible. The case for subdividing the Holocene Series/Epoch has been further strengthened by the formal definition, following conventional chronostratigraphical procedures (Hedberg, 1976; Salvador, 1994), of the Pleistocene–Holocene boundary, with the ratified GSSP in the Greenland NGRIP2 ice core (Walker *et al.*, 2008, 2009; see below).

A major difficulty in seeking a basis for a formal subdivision of Holocene time, however, is that, unlike the Pleistocene where subdivisions can be made on the basis of a clear distinction between glacials and interglacials, there is little evidence in the Holocene for globally distinctive and long-lasting climatic episodes. And yet a climatically based scheme is required as this is the only way in which a globally applicable subdivision can be established. One way to achieve this is by using event stratigraphy. Events are short-lived episodes that have left some trace in the geological record and which may therefore be used as a means of correlation (Whittaker *et al.*, 1991). While event stratigraphy has, hitherto, seldom been used as a basis for a formal stratigraphic division of the GTS (the Cretaceous–Palaeogene boundary impact event being the most obvious example, although this also caused a step change), this approach has been used with some success to develop a template for stratigraphic subdivision in the North Atlantic region during the last glacial–interglacial transition and throughout the last cold stage, based on the records of water stable isotopes and dust loading in Greenland ice cores (Björck *et al.*, 1998; Rasmussen *et al.*, 2014; Walker *et al.*, 1999). To be applicable to the Holocene, however, this approach would require the identification of clearly defined, and closely dated, climatic events that are recorded in various proxy climatic records across widely separated parts of the world.

Examination of Holocene climatic data shows that two such events, one occurring at ~8.2 ka BP and a second at ~4.2 ka BP, are evident in many proxy climatic archives. Hence, it was proposed that the widespread signatures of these two events could underpin a tripartite subdivision of the Holocene, similar to that suggested by Mangerud *et al.* (1974). Indeed, as noted above, such a subdivision is already in widespread informal use, the Holocene literature showing that the terms "early," "middle" (or "mid-") and "late" have, for many years, been routinely used in a range of depositional and environmental settings. Therefore, the SQS Holocene Subdivisional Working Group came to the view that it was appropriate to adopt what is effectively current custom and practice, but to standardize and formalize these existing subdivisions by underpinning them with GSSPs based on clearly defined marker horizons.

The nomenclature of the Holocene subdivisions

In the GTS, the basic unit of geological subdivision is the stage/age. Note that "stage" is a *chronostratigraphical* or time–rock term that refers exclusively to all rocks/sediments formed during a specified interval of geological time, whereas "age" is a *geochronological* or time term referring to the time interval itself. A stage is defined only by its base, leading to the so-called "topless stage." Its top is defined by the base of the superjacent stage, thus circumventing any possible ambiguity in the boundary separating one stage from the next. The base of a stage, and its counterpart age, is defined by a GSSP and represents a theoretically synchronous surface. *Lithostratigraphy*, by contrast, is defined solely by rock and sediment characteristics, and its units (beds, members, formations and so on) are nearly always diachronous, at least to some degree. This paper is concerned only with chronostratigraphy and geochronology. The GSSP defining the base of a unit of higher rank in the GTS also defines the base of a unit of subordinate rank(s), ensuring a strict hierarchical classification. The base of a series/epoch, such as the Holocene, must therefore be defined by the GSSP that, in turn, defines the base of its lowest stage. Conventionally (but see below) there have been just five ranks in the GTS: eonothem/eon, erathem/era, system/period, series/epoch and stage/age. These ranks are obligatory for the Phanerozoic, but the stage holds special place as the fundamental building block of the GTS. The nomenclature of each stage/age derives from the locality or geographical region in which the defining GSSP is located. Hence, in the Pleistocene, the basal Gelasian Stage derives from the town of Gela in Sicily (Rio *et al.*, 1998), whereas the superjacent Calabrian Stage is named after the Calabrian region of southern Italy where the Vrica GSSP that defines the base of the Calabrian Stage is to be found (Cita *et al.*, 2012).

Although stage names appear in the GTS, the conventional practice in Quaternary science has not been to use these, but rather their subepoch ("Early," "Middle" and "Late") or, in some cases, their subseries ("Lower," "Middle," "Upper") equivalents. While subseries/subepochs have always been acceptable under the International Stratigraphic Guide (Hedberg, 1976; Salvador, 1994), division at this rank in the stratigraphical hierarchy has not been used previously in the GTS and, indeed, had not to date been formally sanctioned by the IUGS (Finney and Bown, 2017; Head *et al.*, 2017). Hence, it was necessary to make an exception for the Quaternary that would accommodate the Holocene subdivisional scheme. Accordingly, the terms Greenlandian, Northgrippian and Meghalayan were proposed at stage/age rank to represent the three divisions that correspond, respectively, to Early/Lower, Middle and Upper/Late subseries/subepochs. The terminology generally follows the preferred and conventional practice described above of naming stages after the geographical localities or features with which the GSSPs are associated; hence Greenland, the Greenland NorthGRIP (NGRIP) ice core which contains two of the GSSPs, and the north-east Indian state of Meghalaya where the cave that contains the third GSSP is to be found (see below). Strictly the Greenlandian is named after an ice core as geographical features are sparse on an ice cap. The base of the Holocene Series/Epoch was ratified in 2008 (Walker *et al.*, 2008, 2009), unconventionally and provisionally, without an accompanying stage/age. Now the Greenlandian Stage forms the lowermost division of the Holocene and is anchored by the previously defined base-Holocene GSSP. Above the Greenlandian are the Northgrippian and Meghalayan stages/ages and their accompanying Middle and Upper/Late Holocene subseries/subepochs, both of which are defined by new GSSPs (Fig. 1).

The ratification process

Before moving to a discussion of the new Holocene stages and GSSPs, it is important to explain the procedures involved in the ratification process. The supreme body that represents global geoscience is the IUGS (www.iugs.org). Nested within the IUGS are a number of Scientific Commissions, each representing a different aspect of earth science (geoheritage, tectonics and structural geology, etc). The commission responsible for stratigraphic matters is the ICS (www.stratigraphy.org). The voting membership of the ICS comprises a three-person voting executive committee (Chair, Vice Chair and Secretary-General), and the chairs of each of the subcommissions representing the geological divisions of the GTS (Precambrian, Silurian, Permian, Cretaceous, etc), along with the chair of the Subcommission on Stratigraphic Classification, totalling 19 voting members. The principal objective of the ICS is the establishment of a standard, globally applicable GSSP-defined stratigraphical scale, which it seeks to achieve through the coordinated contributions of its subcommissions and constituent working groups. Hence, the SQS (www.quaternary.stratigraphy.org) is tasked with developing a formal stratigraphical subdivision of the Quaternary System/Period through the operation of designated working groups, one of which is the Working Group on the Subdivision of the Holocene, while another is the Working Group on the Anthropocene (see below).

Proposals for new stratigraphical schemes formulated by each working group progress to the IUGS through a series of interim steps. Each proposal is voted on first by the members of the particular working group and then by the full voting membership of the relevant subcommission (e.g. the SQS). If a supermajority of 60% in favour is achieved in each of these ballots, the proposal is then submitted to the voting membership of the ICS for further evaluation. Again a 60% supermajority in favour is required for the proposal to reach the final step, the EC of the IUGS, where a further vote is taken. If the proposal proves acceptable, then it is formally ratified by the IUGS EC and new stage and other names, and associated GSSPs, are recorded on the international GTS, the last-named being marked by a "golden spike" symbol (Fig. 1). This rigorous evaluatory system, whereby proposals are assessed and voted on at four separate levels, ensures broad representation, international acceptance, and the overall integrity of the procedures and decisions that underpin the international GTS.

The beginning of this long procedure normally involves individual groups conducting primary research on different promising successions. This can take many years and may result in several candidates being proposed for a single GSSP. The relevant working group then evaluates and votes upon the competing proposals. Again a supermajority of 60% in favour is required for a proposal to move forward to the next level. In the case of the Working Group on the Subdivision of the Holocene, a sufficient array of detailed stratigraphical evidence already existed in the public domain, so the choice of GSSP simply required the Working Group itself to evaluate these published records, formulate a set of proposals and vote on them. These were then formally submitted to the SQS and ICS, as explained above.

The new Holocene GSSPs

Two new GSSPs have been approved to underpin the stratigraphical subdivision of the Holocene, one utilizing an ice core from Greenland and the other a cave speleothem from India. The precedent for designating an ice core as a boundary stratotype was set some 10 years ago with the formal ratification of the basal Holocene GSSP in the NGRIP2 ice core (Walker *et al.*, 2008, 2009). This now also serves as the GSSP for the newly defined Greenlandian Stage/Age (see below). The use of a speleothem, however, is new. But speleothems are stratified successions that can be analysed at remarkably high resolution (subdecadal to annual); in addition, they contain an oxygen isotope record that can be supported by an independent, high-precision chronology based on U-series dating that can sometimes be independently verified by annual layer counting. The stable isotope profile in Holocene speleothem calcite is known to be a highly sensitive climate proxy (e.g. Boch *et al.*, 2009; Cheng *et al.*, 2009; Fleitmann *et al.*, 2007; Wu *et al.*, 2012), and therefore changes in the isotopic signal provide a detailed and chronologically accurate record of Holocene climate change. As such, speleothems provide a remarkable archive of high-resolution climate data, and offer a basis for fixing events within very short time intervals.

The new Holocene subdivisions

Greenlandian Stage/Age; Lower/Early Holocene Subseries/Subepoch

The lowest stage of the Holocene Series/Epoch is termed the Greenlandian Stage/Age, defined with its corresponding Lower/Early Holocene Subseries/Subepoch by the GSSP of the Holocene Series/Epoch in the NGRIP2 Greenland ice core (75.10°N, 42.32°W; Walker *et al.*, 2008; Fig. 2). The GSSP is located at 1492.45 m in the ice core, where it is marked by a

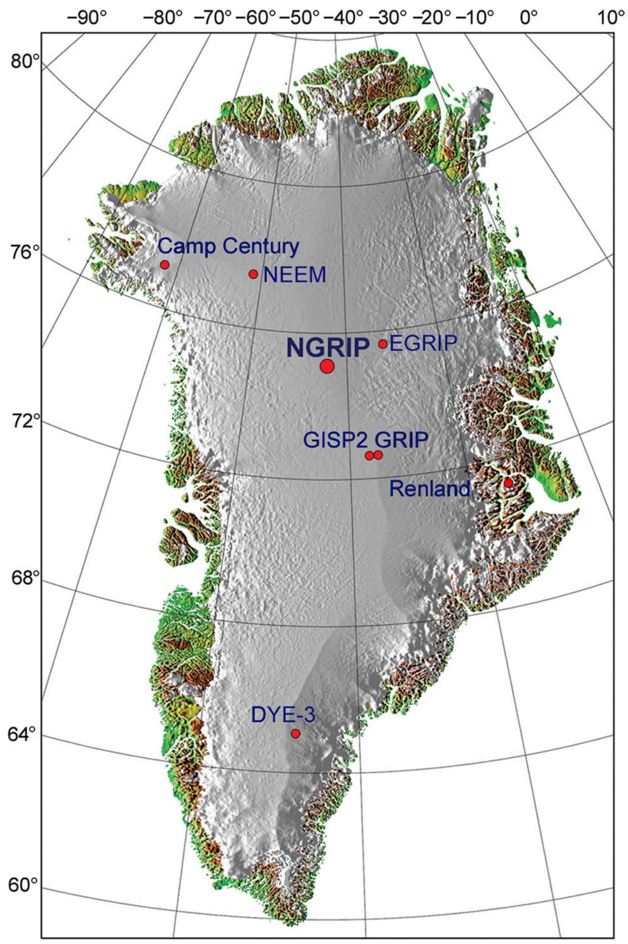

Figure 2. Location of the NorthGRIP (NGRIP) core site on the Greenland ice sheet. Also shown are the other Greenland deep drill sites, including GRIP and DYE-3, cores used in the construction of the GICC05 timescale upon which the chronology of the NGRIP1 and NGRIP2 records is based (after Walker *et al.*, 2018).

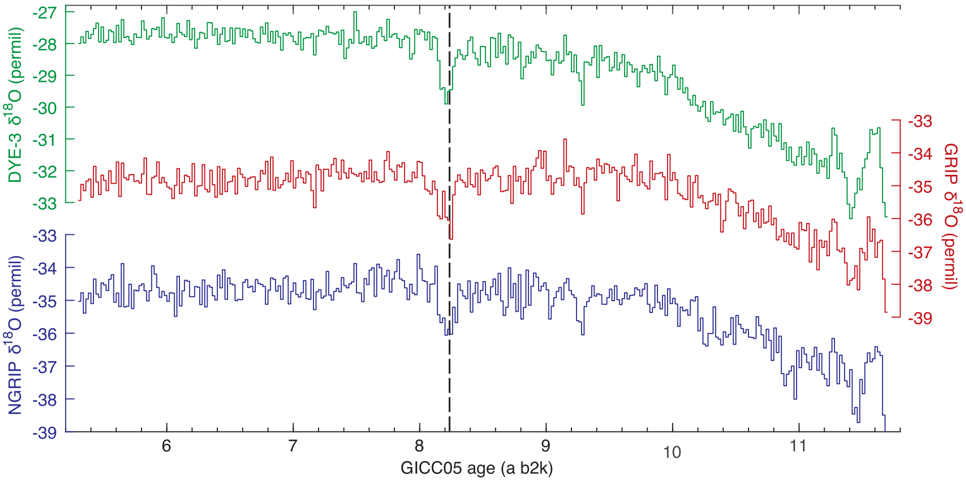

Figure 3. Water stable isotope ratios ($\delta^{18}O$) at 20-year resolution in three Greenland ice core records, DYE-3, GRIP and NGRIP (NGRIP1 and NGRIP2 combined), over the time interval 11.7–5.3 ka b2k (before 2000 CE) on the GICC05 time scale (Rasmussen *et al.*, 2006; Vinther *et al.*, 2006). The location of the Early-Middle Holocene boundary inside the 8.2-ka event is shown by the dashed black line (after Walker *et al.*, 2012).

shift to "heavier" $\delta^{18}O$ values following Greenland Stadial 1 (GS-1); by a reduction in dust concentrations from GS-1 to modern levels and by a significant reduction in Na (sea-salt) values; and by an increase in annual ice-layer thickness (Johnsen *et al.*, 2001; Steffensen *et al.*, 2008). The boundary is most clearly marked, however, by an abrupt decline in deuterium (D) excess values. This is a *prima facie* cooling signal but indicates a shift in ice-sheet moisture source from the middle to the northern North Atlantic as the oceanic polar front rapidly retreated northwards, a shift that occurred within just a few years (Steffensen *et al.*, 2008). These various proxy signals reflect a major change in atmospheric circulation regime and a temperature rise of ~10 ± 4 °C, at the onset of the Holocene (Buizert *et al.*, 2014; Grachev and Severinghaus, 2005). The boundary is dated on the Greenland ice-core timescale (GICC05; Rasmussen *et al.*, 2006) to 11 703 calendar a b2k (before 2000 CE) with a maximum counting error (MCE) of 99 years; this corresponds to 11 653 a BP using the datum of the radiocarbon timescale. However, in view of the 99-year uncertainty, it was considered appropriate to assign a rounded age of 11 700 a b2k (11 650 a BP) to the Pleistocene–Holocene boundary (Walker *et al.*, 2009).

Northgrippian Stage/Age; Middle Holocene Subseries/Subepoch

The second stage/age of the Holocene, the Northgrippian Stage/Age, is defined with its corresponding Middle Holocene Subseries/Subepoch in the NorthGRIP1 (NGRIP1[2]) Greenland ice core (75.10°N, 42.32°W; Fig. 2). In NGRIP1, as in other Greenland records, there is a clear signal of climate cooling following a period of generally rising temperature during the Early Holocene (Fig. 3). This cooling occurs at~8.2 ka in the NGRIP1 core (where it marks the GSSP) and corresponds to the "8.2-ka climatic event," a short-lived near-global episode that is reflected in a wide range of proxy climate records (e.g. Allan *et al.*, 2018; Chase *et al.*, 2015a; Cheng *et al.*, 2009; Daley *et al.*, 2011; Morrill *et al.*, 2013; Oster *et al.*, 2017; Roffet-Salque *et al.*, 2018; Rohling and Pälike, 2005; Siani *et al.*, 2013; Sicre *et al.*, 2013). In the Greenland NGRIP1 ice core, the event is located at a depth of 1228.67 m (Fig. 4, upper) where it is indicated by a marked shift in the stable oxygen isotope record to more negative $\delta^{18}O$ and δD values; by a decline in ice-core annual layer thickness (Rasmussen *et al.*, 2007) and deuterium excess (Masson-Delmotte *et al.*, 2005); by a substantial, sudden and short-lived minimum in atmospheric methane (a global event); and by a subsequent increase in the atmospheric content of CO_2. The water isotope diffusion-derived temperature record indicates a cooling of ~5 °C (Gkinis *et al.*, 2014). The GSSP is placed in the middle of a double peak in electrical conductivity measurements (Fig. 4, lower) in a layer that also includes fluoride that is probably derived from a volcanic eruption in Iceland. Hence, while the climate signal determined from the oxygen isotope record sets the GSSP within the coldest part of the 8.2-ka event, the independent volcanic signal enables the GSSP to be precisely located in the NGRIP1 ice core and correlated to other Greenland ice cores (Fig. 2).

The age of the GSSP is derived from the GICC05 timescale, which is based on annual layer counting using a range of physical and chemical parameters in three Greenland ice cores: DYE-3, GRIP and NGRIP (Rasmussen *et al.*, 2006; Vinther *et al.*, 2006). However, low accumulation rates at the NGRIP1 drill site mean that annual layers in $\delta^{18}O$ cannot easily be identified in that core. The chronology for NGRIP1 therefore derives from the DYE-3 and GRIP records where accumulation rates are higher, the cores being linked by reference horizons of volcanic origin identified from electrical conductivity measurements. In the DYE-3 ice core, the annual layer situated in the middle of the electrical conductivity double peak is dated to 8236 a b2k with a MCE of 47 years (Vinther *et al.*, 2006). This is the best age estimate of the GSSP for the Northgrippian Stage/Age and Middle Holocene Subseries/Subepoch, and corresponds to 8186 a BP using the datum of the calibrated radiocarbon time scale.[3]

[2]There are two ice-core records from NorthGRIP because during the initial drilling operation in 1997, the drill became stuck and a new core had to be drilled. The two cores are referred to as NGRIP1 (the original core) and NGRIP2 (the new core), respectively. Measurements have been performed on the NGRIP1 core down to a depth of 1372 m (which includes the 8.2-ka event), whereas measurements on the NGRIP2 core start at a depth of 1346 m (corresponding to approximately 9.5 ka b2k). This is why the GSSP for the Middle Holocene (Northgrippian Stage/Age) is in core NGRIP1, whereas the GSSP for the base of the Holocene (Greenlandian Stage/Age is in core NGRIP2.

[3]Recent analyses involving Bayesian wiggle-matching of cosmogenic nuclide records suggest a temporal offset between the IntCal13 and

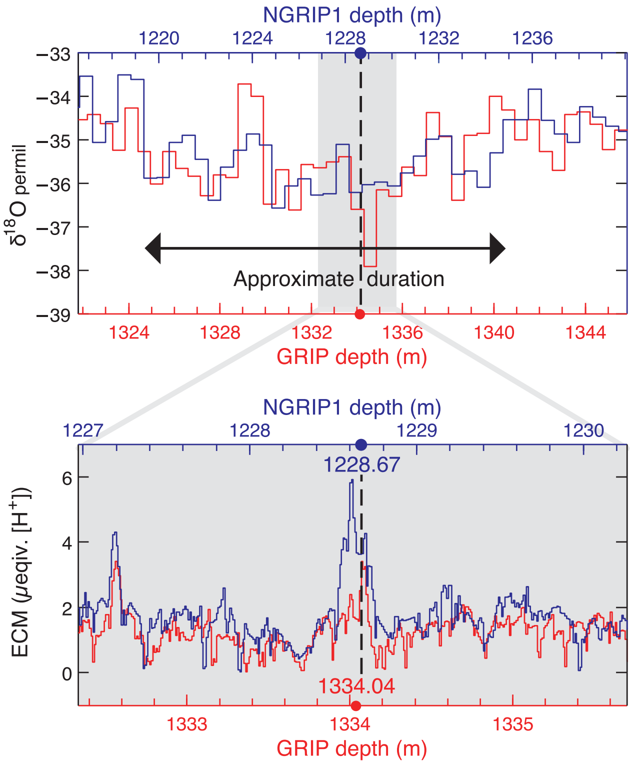

Figure 4. Upper: water stable isotope ratios ($\delta^{18}O$) at 55-cm resolution from the GRIP and NGRIP1 ice cores around the 8.2-ka event. The black horizontal double arrow indicates the duration of the event from ~8300 a b2k (1234.78 m) to ~8140 a b2k (1219.47 m). Lower: during the period of low $\delta^{18}O$ 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 high fluoride content and can most probably be attributed to an Icelandic volcano. It is dated on the GICC05 timescale to 8236 a b2k (8186 cal a BP), and is the primary marker for the Early-Middle Holocene boundary (after Walker *et al.*, 2012).

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

The uppermost subdivision of the Holocene Series/Epoch, the Meghalayan Stage/Age, is defined together with the corresponding Upper/Late Holocene Subseries/Subepoch by a GSSP in a speleothem (KM-A; Fig. 5) from Mawmluh Cave (known in the local Khasi language as Krem Mawmluh) in the state of Meghalaya in north-east India (cave entrance: 25°15′44″N, 91°42′54″E; Fig. 6). The GSSP is located at a horizon within the speleothem (at 7.45 mm depth measured from the top of the speleothem) that shows evidence for an abrupt precipitation reduction at ~4200 a BP that reflects the 4.2-ka BP climatic event (Rousseau *et al.*, 2019). Occurring at ~4 ka BP, this abrupt climatic shift appears to involve significant reorganizations of ocean and atmosphere circulation patterns (Weiss, 2019). It has been termed the "Holocene Turnover" (Paasche *et al.*, 2004) that subsequently resulted in the establishment of a new climatic regime or mode (Paasche and Bakke, 2009), or the "4.07 ka BP climatic anomaly" in southern Africa (Railsback et al., 2018). The event appears to be global in nature, occurring in proxy records across seven continents from North America and northern Europe, through the Mediterranean, Middle East

GICC05 timescales during the Holocene (Adolphi and Muscheler, 2016). If correct, this would lead to an adjustment of − 34 ± 4 years for the electrical conductivity measurements peak in NGRIP1 giving a calibrated radiocarbon age of 8152 a BP.

Figure 5. Speleothem KM-A from Mawmluh Cave, Meghalaya, north-east India, showing the position of the 4.2-ka event. The speleothem is ~308 mm long (photograph Ashish Sinha).

(Weiss, 2017b, 2017a) and India (Berkelhammer *et al.*, 2012; Kathayat *et al.*, 2018) to China (Cai *et al.*, 2017; Zhang *et al.*, 2018) and Australia (Denniston *et al.*, 2013); and across Africa (Chase *et al.*, 2015b; Ruan *et al.*, 2016), Andean–Patagonian South America (Schimpf *et al.*, 2011), and Antarctica (Peck *et al.*, 2015). In the North Atlantic and western Canada, the event is reflected in atmospheric and oceanic cooling (Gkinis *et al.*, 2014; Orme *et al.*, 2018; Zhang *et al.*, 2019) and so-called "neoglaciation" with glacier readvances (Balascio *et al.*,

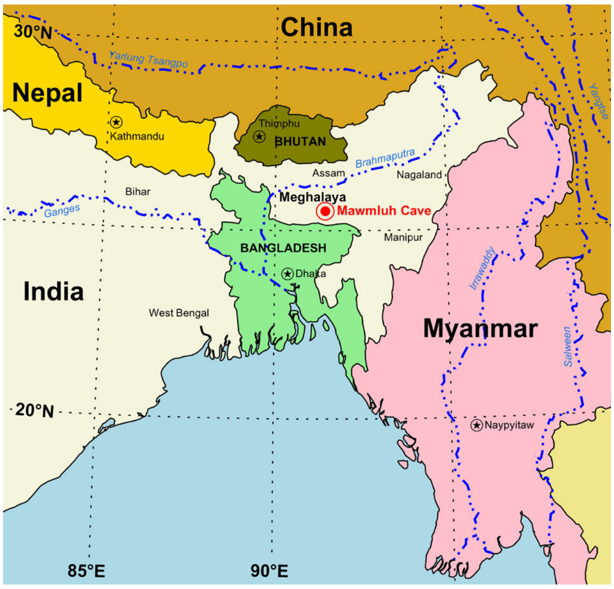

Figure 6. Location of Mawmluh Cave in the state of Meghalaya, north-east India.

2015; Geirsdóttir *et al.*, 2019; Menounos *et al.*, 2008), while in the mid- and low latitudes across both hemispheres it is marked by aridification (Booth *et al.*, 2005; Wanner *et al.*, 2015). Extensive megadrought prevailed across mid-latitude North America from Idaho to Massachussets, "with median moisture levels reaching a minimum from 4.2 to 3.9 ka" (Shuman and Marsicek, 2016, p. 42). In the eastern hemisphere the 4.2-ka event caused disruption or deflection of the westerlies, the Indian Summer Monsoon and the East Asian Monsoon (Weiss, 2016). It led to an ~250-year widespread drought in many mid- and low-latitude regions that was broken perhaps only briefly, and has been linked to synchronous societal collapse, habitat-tracking, and eventual resettlement and reorganization across Spain (López-Sáez *et al.*, 2018), Greece (Davis, 2013), Egypt (Hassan *et al.*, 2017), Palestine (Harrison, 2012; Weiss, 2017a), Mesopotamia (Weiss, 2017b), the Indus Valley (Petrie *et al.*, 2017) and China (Li *et al.*, 2018).

As the 4.2-ka event is most strongly recorded in proxy climate records from mid- and low latitudes, it is appropriate that the GSSP should be located within those latitudes, and Mawmluh Cave in north-east India offers an ideal site. In this deep limestone cave, calcite forms in isotopic equilibrium with percolating precipitation, and hence variations in the $\delta^{18}O$ signal in speleothem calcite closely resemble changes in mean values of regional precipitation-weighted $\delta^{18}O$ variations. The $\delta^{18}O$ record from stalagmite KM-A in which the GSSP is placed (Fig. 7) extends from ~3500 to >12 000 a BP at a resolution of ~5 years per sample. The most significant isotopic excursion in the entire record dates close to the time of the 4.2-ka event, with an overall enrichment of~1.5‰ in $\delta^{18}O$, approximately equivalent to a 20–30% decrease in rainfall and marking a significant change in the strength of the Indian Monsoon (Berkelhammer *et al.*, 2012).

The chronology for speleothem KM-A derives from an age model employing a Monte Carlo fitting procedure through 12 U–Th dates (Scholz and Hoffmann, 2011). The analytical uncertainties on the two U–Th dates closest to the 4.2-ka event

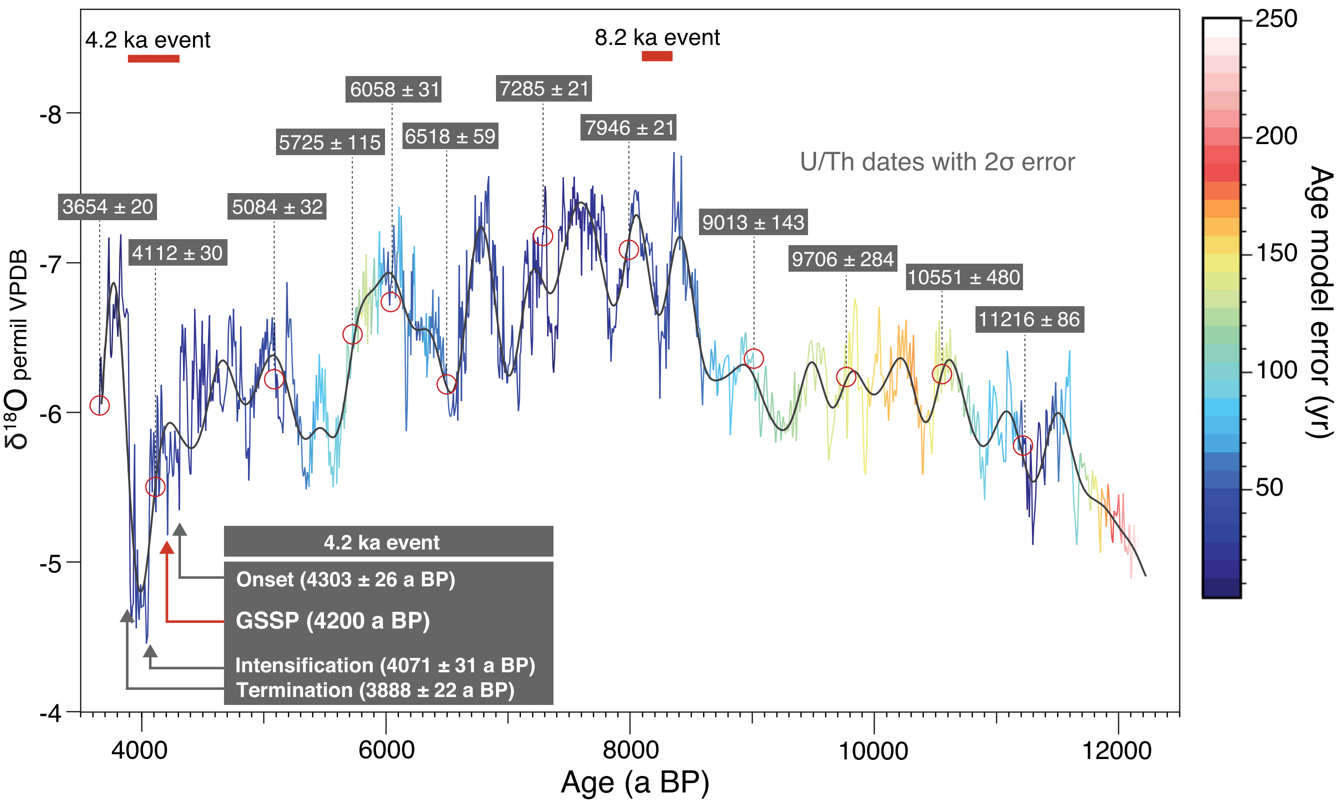

Figure 7. The Mawmluh Cave $\delta^{18}O$ record for speleothem KM-A after Berkelhammer *et al.* (2012). The continuous black line through the isotope trace is a low pass filter removing any variability with a frequency higher than 10 years. Red circles mark the U–Th dates obtained, which are shown with 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 blue lines, and the beginning of the most intensive phase of weakened monsoon is shown by a third arrowed blue line: their dates are given with uncertainty that is also assessed using the Monte Carlo fitting procedure (Berkelhammer *et al.*, 2012). The position of the GSSP, with a modelled age of 4200 a BP (4250 b2k) is indicated by the red arrow. Note that the 8.2-ka event also registers as a significant excursion in the stable isotope record (after Walker *et al.*, 2018).

(3654 and 4112 a BP) are 20 and 30 years, respectively, with a third date at 5084 a BP having an uncertainty of ±32 years (Fig. 7). The KM-A record shows linear growth rates during this period, providing further confidence in the age model, and hence in the timing (onset and duration) of the 4.2-ka event (Berkelhammer *et al.*, 2012). The changes in the stable isotope record during that interval comprise a two-step sequence, with an abrupt initial enrichment at 4300 ± 26 a BP and a more pronounced and similarly rapid shift to more positive values at 4071 ± 31 a BP. The sharp increase in $\delta^{18}O$ values is the primary marker for the boundary, and hence the GSSP is placed between these two shifts, yielding a date of 4200 a BP that is effectively the mid-point between their modelled ages. 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, to maintain consistency with the earlier Holocene GSSPs (the Greenlandian and Northgrippian), which are dated using the GICC05 ice-core chronology, the age of the Mawmluh speleothem GSSP is expressed as 4250 a b2k (before 2000 CE: see above).

Recently, two additional speleothem records have been published from Mawmluh Cave that span the time interval of the 4.2-ka event (Kathayat *et al.*, 2018). These new $\delta^{18}O$ profiles from stalagmite samples ML.1 and ML.2 share some similarities with the KM-A record but also show differences. The new records are more closely and directly dated than KM-A and the isotopic profiles display a three-stage structure, with a highly variable Indian Summer Monsoon between ~4255 and 4070 a BP, a distinct pluvial episode at ~4070–4012 a BP, followed by a relatively weaker monsoon that was punctuated by several multidecadal periods of anomalously drier conditions. Stalagmites ML.1 and ML.2 are located some 800 m from the site of KM-A and, given the complexities of cave hydrology and dripwater flow (e.g. Bradley *et al.*, 2010), some differences between these records and that from KM-A might reasonably be expected. Indeed, there are differences in detail between the isotopic signals from ML.1 and ML.2. However, both KM-A and the new records clearly capture the 4.2-ka event, and the overall expression of the event in ML.1 and ML.2 shares broad similarities with that in the $\delta^{18}O$ profile in speleothem KM-A, most notably in terms of the onset at ~4.25 ka BP. As it is this that defines the GSSP in KM-A, the new speleothem records provide additional support for the designation of the Meghalayan boundary stratotype.

Global auxiliary stratotypes

Auxiliary stratotypes, also known as *hypostratotypes* (Hedberg, 1976), are reference sections designed to extend knowledge of the unit or boundary established by a primary stratotype (GSSP) to other geographical areas. Two such auxiliary stratotypes are here selected to support the new GSSPs for the Northgrippian and Meghalayan stages/ages, and their equivalent Middle and Upper/Late Holocene subseries/subepochs based on clearly defined climatic signals of, respectively, the 8.2- and 4.2-ka events. The auxiliary stratotypes are a speleothem from Gruto do Padre in Brazil, where a stable isotope profile from a speleothem contains a record of the 8.2-ka event, and an ice-core succession at Mt Logan, Yukon, Canada, that contains an oxygen isotope signal of the 4.2-ka event.

Gruta do Padre speleothem, Brazil

Gruta do Padre ("the priest's cave"; 13°13′S, 44°03′W: elevation 550 m asl) is located in Bahia State of north-eastern Brazil, ~500 km north-east of Brasilia and at the halfway point between the municipalities of Santana and Canápoli. The cave is located in calcitic bedrock of Neoproterozoic age and, at 16.5 km in length, is currently the third-longest known cave in Brazil. A stalagmite, PAD07 (~422 mm in length), was collected from deep within the cave, around 4 km from the cave entrance, where the humidity is close to 100% and the temperature nearly constant at ~24 °C. The surrounding region is influenced by the South American Summer Monsoon and the South Atlantic Convergence Zone, with rainfall occurring only during the Austral summer months. The $\delta^{18}O$ record from the speleothem (Fig. 8A) is largely a proxy for mean annual $\delta^{18}O$ of rainfall which, in turn, reflects changes in the intensity of the South American monsoon (e.g. Cheng *et al.*, 2009, 2013; Cruz *et al.*, 2005; Wang *et al.*, 2007). The 8.2-ka event is unambiguously recorded in the PAD07 stable isotope profile, with a ~4-year temporal resolution, and is marked by a 2‰ $\delta^{18}O$ shift to lighter isotopic values between 293 and 287 mm at ~8.2 ka. This trend is closely replicated in another speleothem record from Paixão Cave (12°39′S, 41°03′W) further to the east, and indicates a strong South American monsoon event with a significant increase in rainfall (Cheng *et al.*, 2009).

While there are now many 8.2-ka event records from the middle and low latitudes (see Walker *et al.*, 2012), the stable isotope profile from the PAD07 stalagmite is one of the most precisely dated of these (Fig. 8B). This is due to its sample quality (pure and dense calcite), higher U content (~900 p.p.b.), and fast growth rate (~0.23 mm a^{-1} around the time of the event: Cheng *et al.*, 2009). The precision of the key dates is about 20 years or better, which yields a best age estimate for the onset of the 8.2-ka event of 8200 ± 25 a BP (2σ uncertainty). This accords closely with the age of 8186 a BP (8236 b2k) in the NGRIP1 ice core (see above). The Gruta do Padre stalagmite therefore constitutes an excellent secondary marker in the low latitudes for the high-latitude 8.2-ka event as recognized at the GSSP in the Greenland NGRIP1 ice core.

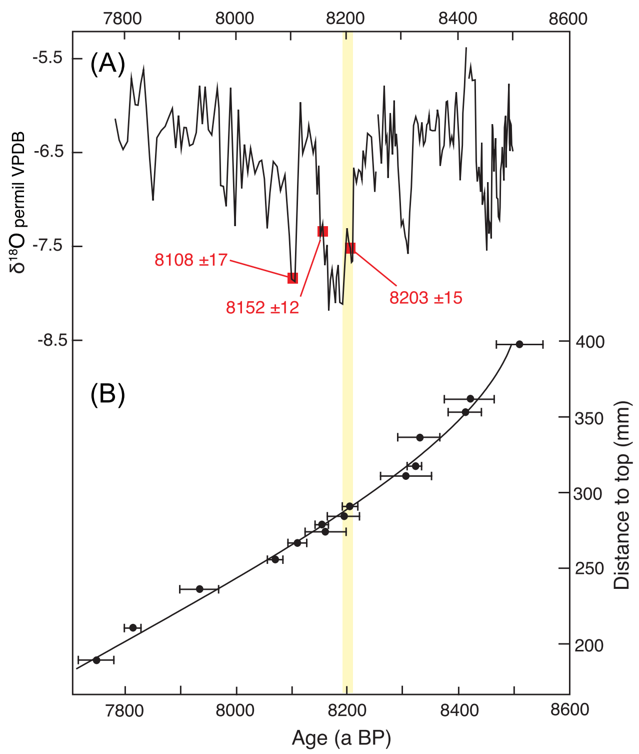

Figure 8. The PAD07 $\delta^{18}O$ record from the Gruta do Padre speleothem, Brazil. (A) The $\delta^{18}O$ time series, with key U–Th dates. (B) The PAD07 age model based on polynomial (cubic) fitting of U–Th dates around the 8.2-ka event. The vertical bar shows the abrupt decrease in $\delta^{18}O$ values from 293 to 287 mm depth around 8200 ± 25 a (after Cheng *et al.*, 2009).

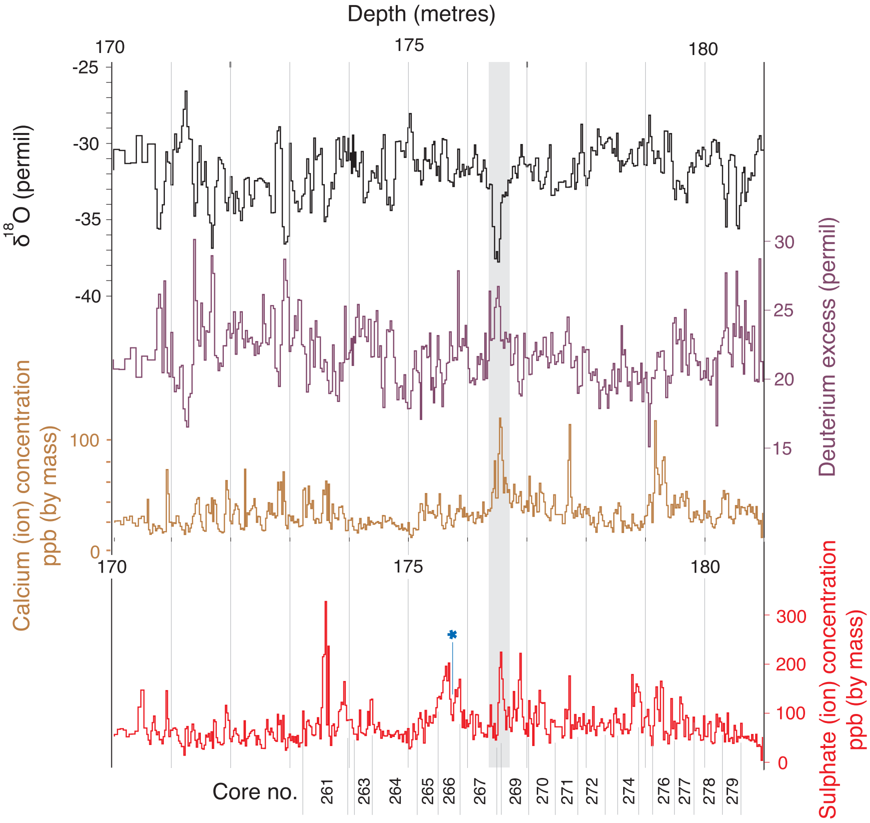

Figure 9. The 4.2-ka event in the Mount Logan ice core. The uppermost record shows $\delta^{18}O$ values from 170 to 181 m depth, the deep $\delta^{18}O$ minimum centred at 176.5 m marking the 4.2-ka event that reflects a major shift in air moisture flow. The second record shows deuterium excess ($d = \delta D - 8\delta^{18}O$) for the same samples, the abrupt maximum during the 4.2-ka event suggesting that more distant tropical moisture reached Mt Logan at that time. The third record shows calcium ion concentrations, and again a marked peak at the 4.2-ka event. The vertical grey bar highlights the event in these three climate proxies. The lowermost record shows sulphate concentrations, with the peaks relating to a series of volcanic eruptions in Alaska, the Aleutians and Kamchatka. The blue star in core 266 indicates the occurrence of tephra from the large Alaskan eruption of Aniakchak, this well-dated tephra (see text) constituting a key time marker very close to the 4.2-ka event in the Mt Logan ice core. Core numbers are shown at the bottom of the diagram.

Hence, the clearly defined and closely dated 8.2-ka event in speleothem PAD07 from Gruta do Padre, Brazil, comprises an Auxiliary Stratotype for the Northgrippian Stage/Age and Middle Holocene Subseries/Subepoch.

Although there is no government-sponsored preservation project for the Gruto do Padre site, Dr Augusto S. Auler (who collected speleothem PAD07) and his colleagues at the Instituto do Carste, Belo Horizonte, Brazil, have visited the cave periodically since 1986 for the purposes of scientific investigations and cave conservation. Access for research purposes is best arranged through the Institute, currently via Dr Auler. The stalagmite is currently curated by Professor Hai Cheng at the Institute of Global Environmental Change, Xi'an Jiaotong University, China, and the Department of Earth Sciences, University of Minnesota, USA, respectively.

Mount Logan plateau ice field, Yukon, Canada

The 4.2-ka event was clearly recorded in the Prospector Russell Col (PRCol) ice core from the plateau ice field on Mount Logan in the Yukon, northern Canada, drilled in 2001/2 (60°59′N, 140°50′W; elevation 5340 m asl; mean temperature − 29 °C; and total depth to bedrock 188 m; Fisher *et al.*, 2004). The event appears as a very large excursion to lowered $\delta^{18}O$ values between 176.4 and 176.7 m in the ice core, and this coincides with higher deuterium excess and calcium values (Fig. 9). This isotopic event spans the time interval from 4250 to 3950 a b2k (i.e. before 2000 CE), with the lowest $\delta^{18}O$ values and highest deuterium excess and calcium concentrations occurring at 4100–4000 a b2k (Fisher, 2011; Fisher *et al.*, 2008). This isotopic signature is considered to reflect enhanced moisture transport from the Tropical Pacific during marked El Niño events, of which that around 4200 a BP was the strongest (Fisher, 2011; Fisher *et al.*, 2008). The Mount Logan record therefore constitutes an excellent auxiliary marker in the high latitudes for the low-latitude 4.2-ka GSSP from Mawmluh Cave, north-east India.

The chronology of the 4.2-ka BP isotopic event in the Mount Logan ice core is anchored by an identified tephra from the large Alaskan eruption of Aniakchak (Blackford *et al.*, 2014) that is recorded at 175.75 m depth in Mt Logan core 266, ~70 cm above the oxygen isotope excursion that marks the 4.2-ka event. The tephra occurs close to the mid-point of a major (acidic) sulphate peak, which is related to a swarm of eruptions in Alaska and the Aleutian Islands (Fisher *et al.*, 2008). A similar tephra identified as being from Aniakchak has been found in the GRIP Greenland ice core where it is dated at 3641 a b2k on the Greenland GICC05 chronology (equivalent to 3591 cal a BP in calibrated radiocarbon years), with a MCE of ± 3 years (Abbott and Davies, 2012). However, the possible offset between the IntCal13 radiocarbon time scale and GICC05 of 19 ± 3 years at around 3500 a BP (Adolphi and Muscheler, 2016) would give an age (in calibrated radiocarbon years) of 3572 ± 4 cal a BP, which is taken to be the best approximation of age for the Aniakchak tephra (Pearce *et al.*, 2017). This falls within the older part of the age range for the tephra (3300–3600 cal a BP) for a large number of sites in Alaska and Yukon (Davies *et al.*, 2016). The estimated age for the 4.2-ka event in

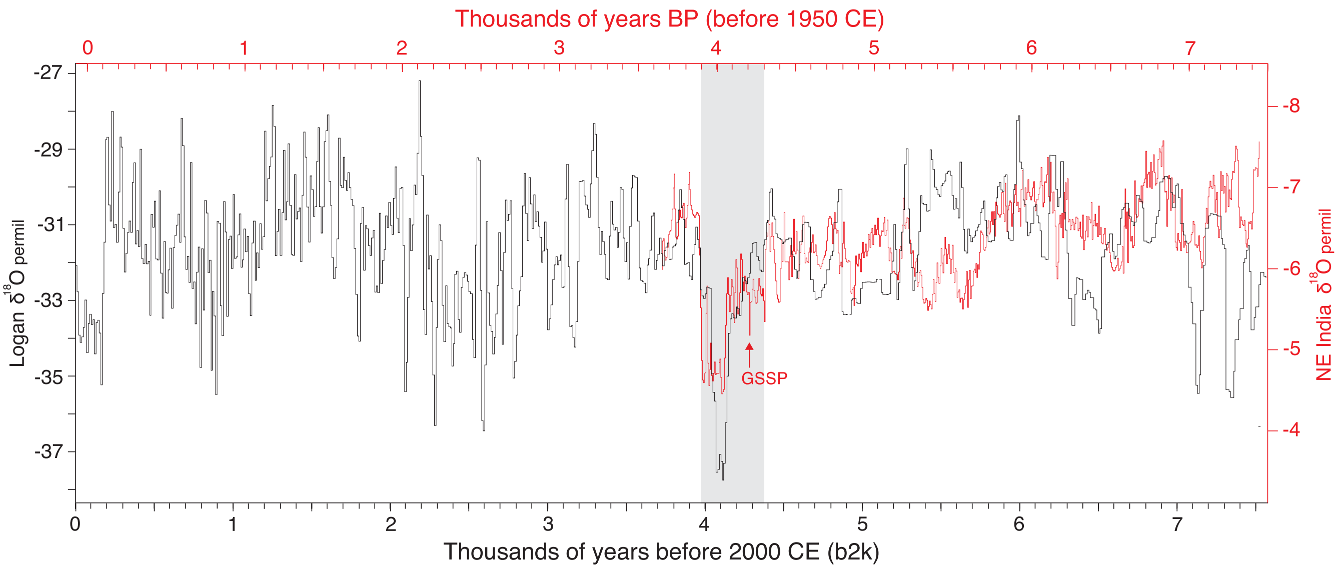

Figure 10. The $\delta^{18}O$ records in the Mt Logan ice core (black line) and Mawmluh Cave (red line). The shaded area marks the duration of the 4.2-ka event, with an onset at~4.3 ka BP and termination at~3.9 ka BP (Walker *et al.*, 2018). Note the close correspondence between the two stable isotope traces and the clear expression in both records of the 4.2-ka climatic event.

the Mount Logan ice core obtained by downcore interpolation from the Aniakchak tephra isochron (Fisher *et al.*, 2008) is 4250 to 3950 a b2k with an error of ±70 years. This is very close to the age range for the event in the high-resolution speleothem isotope (proxy-monsoon) record from Mawmluh Cave in north-east India (Fig. 10).

The original ice core from Mt Logan had been stored in the Canadian Ice Core Archive, Faculty of Sciences, University of Alberta in Edmonton, Canada, currently under the stewardship of Professor Martin J. Sharp. However, a major freezer failure in the cold storage facility in Edmonton on 2 April 2017 led to the loss of almost 180 ice cores (almost 13% of the archive) from across the Canadian Arctic (Derworiz, 2017), one of which was the core from Mt Logan. This clearly presents a difficulty as the parastratotype itself exists below the surface and is geographically remote. Fortunately, plans are in hand to revisit the site to recover a duplicate set of cores from the original drill site. In this future drilling programme, the 4.2-ka event should be locatable between about 176 and 177 m. The Aniakchak tephra, which is key to the dating of the event (see above) should be detectable using electrical conductivity measurements along the ice cores (Fisher *et al.*, 2004, 2008). Recovery of these cores will effectively restore access to the succession represented by the Mt Logan plateau ice field stratotype. Meanwhile, the published records of the melted core continue to serve as a valuable northern high-latitude signature of the 4.2-ka event, allowing this parastratotype to complement the GSSP in the low-latitude location of Mawmluh Cave in north-eastern India.

The Anthropocene

One matter above all others has figured in discussions of the new subdivisional scheme, and that concerns the Anthropocene. Walker *et al.* (2012) stressed that there was no conflict of interest between the two SQS Working Groups on the Holocene and the Anthropocene, the latter convened under the leadership of Professor Jan A. Zalasiewicz. Indeed, it was clearly stated that deliberations over whether the Anthropocene should be formally ratified as a new stratigraphical unit within the GTS would benefit from the prior establishment of a formal framework for the natural environmental context of the Holocene upon which human impacts may subsequently have been superimposed.

This still remains the case today because, while discussions continue on when the Anthropocene began (Ellis, 2018; Lewis and Maslin, 2015; Zalasiewicz *et al.*, 2015); on the approach that should be used to define its onset (Edgeworth *et al.*, 2019; Ruddiman, 2018); on what status it should have as a geological unit (Waters *et al.*, 2016); on what type of GSSP would be appropriate (Waters *et al.*, 2018); and, indeed, on whether the Anthropocene should be formalized at all (Finney and Edwards, 2016; Rull, 2018; Walker *et al.*, 2015; Zalasiewicz *et al.*, 2017a), a consensus is now emerging within the SQS Anthropocene Working Group that the Anthropocene should indeed be formally defined by means of a GSSP, should hold the rank of series/epoch and should have a starting point in the mid-20th century (Zalasiewicz *et al.*, 2017b). The mid-20th century is preferred because it coincides with the so-called "Great Acceleration" (Steffen *et al.*, 2015) and is marked by a stratigraphic signal of radiogenic fallout from thermonuclear weapons testing that began in the early 1950 s (Waters *et al.*, 2015, Zalasiewicz *et al.*, 2015; Waters *et al.*, 2018). If the Anthropocene were eventually to be formalized at the rank of series/epoch (and it must be emphasized that no stratotype sections or candidate GSSPs have yet been proposed, although several potential sites are under consideration: Waters *et al.*, 2018; Zalasiewicz *et al.*, 2019), the Holocene Series/Epoch, the Upper/Late Holocene Subseries/Subepoch and the Meghalayan Stage/Age would consequently all terminate around 1950 CE instead of extending to the present day. The Meghalayan would then have lasted for ~4200 years, making it the longest stage of the Holocene, the Greenlandian having a duration of ~3465 years and the Northgrippian ~3985 years. A termination of the Holocene would simply follow the principle that a chronostratigraphic unit in the GTS is defined only by its base, and that the top is defined by the base of the succeeding unit, as discussed above.

Conclusions

The new Holocene subdivisions have so far been readily adopted and, despite having been introduced only a few months ago, both the subdivisions themselves and the new terminology have already been applied in several recent publications (e.g. Bassetti *et al.*, 2018; Caron *et al.*, 2019; Eynaud *et al.*, 2018; Li *et al.*, 2018; Meeder and Parkinson, 2018; Tarrats *et al.*, 2018). This supports the view expressed previously (Walker *et al.*, 2012; and see above) that a tripartite division of the Holocene with boundaries at ~8.2 and 4.2 ka BP is one that the Quaternary community is comfortable with and finds useful. The establishment of a formal subdivision of the Holocene Series/Epoch into the Greenlandian, Northgrippian and Meghalayan stages/ages and their corresponding Lower/Early, Middle, Upper/Late subseries/subepochs, each being supported by a GSSP, therefore not only provides a coherent chronostratigraphic framework for the Holocene, but one that is logical, practical and globally applicable. Accordingly, it has been endorsed by the International Union for Quaternary Research (INQUA: Ashworth, 2018).

While most current pre-Cenozoic GSSPs use biostratigraphic data as primary markers, it has been recommended that future GSSPs should have physicochemical and, where appropriate, palaeomagnetic markers as an integral part of their guiding criteria (Miller and Wright, 2017; Smith *et al.*, 2014). Indeed, as Head and Gibbard (2015) have noted, the International Stratigraphic Guide (Hedberg, 1976, p. 82; Salvador, 1994) allows certain methods of correlation, such as climatic, palaeomagnetic and isotopic, to have greater emphasis for Quaternary chronostratigraphy. The subdivision of the Holocene as set out here 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 BP), at ~8.2 ka BP and at ~4.2 ka BP, 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 remarkably sensitive proxies for climate change, and can be dated with a very high degree of accuracy and precision. Indeed, the GSSPs designated here are the best resolved, both stratigraphically and temporally, within the entire GTS. They closely accord with the criteria for boundary stratotypes outlined by Remane *et al.* (1995) and should provide stable points of reference for Holocene stages/ages and subseries/subepochs into the future.

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Abbreviations. GS-1, Greenland Stadial 1; GSSP, Global boundary Stratotype Section and Point; GTS, International Geological Time Scale; MCE, maximum counting error; ICS, International Commission on Stratigraphy; IGC, International Geological Congress; IUGS, International Union of Geological Sciences; SQS, Subcommission on Quaternary Stratigraphy.

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