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Discussion Paper

Formal subdivision of the Holocene Series/Epoch: a Discussion Paper by a Working Group of INTIMATE (Integration of ice-core, marine and terrestrial records) and the Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy)

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ABSTRACT: This discussion paper, by a Working Group of INTIMATE (Integration of ice-core, marine and terrestrial records) and the Subcommision on Quaternary Stratigraphy (SQS) of the International Commission on Stratigraphy (ICS), considers the prospects for a formal subdivision of the Holocene Series/Epoch. Although previous attempts to subdivide the Holocene have proved inconclusive, recent developments in Quaternary stratigraphy, notably the definition of the Pleistocene–Holocene boundary and the emergence of formal subdivisions of the Pleistocene Series/Epoch, mean that it may be timely to revisit this matter. The Quaternary literature reveals a widespread but variable informal usage of a tripartite division of the Holocene ('early', 'middle' or 'mid', and 'late'), and we argue that this *de facto* subdivision should now be formalized to ensure consistency in stratigraphic terminology. We propose an Early–Middle Holocene Boundary at 8200 a BP and a Middle–Late Holocene Boundary at 4200 a BP, each of which is linked to a Global Stratotype Section and Point (GSSP). Should the proposal find a broad measure of support from the Quaternary community, a submission will be made to the International Union of Geological Sciences (IUGS), via the SQS and the ICS, for formal ratification of this subdivision of the Holocene Series/Epoch. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS: 8.2- and 4.2-ka events; Holocene; Mawmluh Cave stalagmite; NGRIP ice core; stratigraphic subdivision.

Introduction

The Holocene is the most recent stratigraphic unit within the geological record and covers the time interval from 11.7 ka BP until the present day. The term *Holocene*, which means 'entirely recent', was first used by Gervais (1867–69) 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 was formally adopted by the International Geological Congress (IGC) in 1885 to refer to this episode and to the appropriate unit in the stratigraphic record. Along with the preceding *Pleistocene*, the Holocene is now formally defined as a Series/Epoch within the Quaternary System/Period (Gibbard *et al.*, 2005).

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 sequences are often extremely well preserved, continuous and able to be examined at a high temporal resolution. It is somewhat surprising, therefore, that relatively little attention has hitherto been paid to a *formal* subdivision of the Holocene Series/Epoch, and particularly in the light of recent developments in Quaternary stratigraphic subdivision and nomenclature (Cita *et al.*, 2006, 2008; Head *et al.*, 2008; Litt & Gibbard, 2008; Gibbard & Head, 2009; Gibbard *et al.*, 2010).

In 2010, the Subcommission on Quaternary Stratigraphy (SQS) of the International Commission on Stratigraphy (ICS) invited INTIMATE (Integration of ice-core, marine and

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terrestrial records, an INQUA International Focus Group) to establish a Joint Working Group on the Holocene. This is the second Joint INTIMATE/SQS Working Group, the first having brought forward a proposal for the formal definition of the base of the Holocene which was accepted and ratified by the International Union of Geological Sciences (IUGS) in 2008 (Walker *et al.*, 2008, 2009). The remit of the new Working Group (WG), mandated by the SQS, is to determine whether there is a basis and, indeed, a need for a formal subdivision of the Holocene. The WG has come to the view that there is now a compelling case for subdividing the Holocene, but is anxious to establish whether the wider Quaternary community is also of the opinion that this is desirable and, more importantly, that a formal subdivision will be seen to be of practical value. This is therefore a Discussion Paper that invites comment. Should a broad measure of support emerge, then a proposal will be submitted to the IUGS, via the SQS and ICS, for ratification of a formal subdivision of the Holocene Series/Epoch.

Background and context

At the 1977 INQUA Congress held in Birmingham, UK, the Holocene Commission appointed a Working Group to report on a chronostratigraphical subdivision of the Holocene. The group consisted of Jan Mangerud (Chair), John Birks and Klaus-Dieter Jäger, and their deliberations were published in a Special Issue of *Striae* (Mangerud *et al.*, 1982a). Regional experts were invited to provide a description of the ways in which the Holocene record had been subdivided (or not) in 21 different areas of the world, and their responses fell into three broad categories. First were regions where the data were too few or too limited to permit the delimitation of any Holocene chronostratigraphical subdivisions (e.g. Australia, New Zealand, South America, Japan). Second were regions where, although detailed data were available, the patterns of inferred environmental change were so variable in both space and time that there seemed little to be gained by defining a chronostratigraphy (e.g. United States and southern Canada, tropical Africa, Near East, British Isles); in these regions the use of radiocarbon dates to order observed geological and biological evidence was advocated. Third, there were regions where Holocene chronozones, defined in terms of radiocarbon years, had been proposed, including Norden, Arctic Canada, the Alps, the then Soviet Union and (in principle) central Europe (Mangerud *et al.*, 1982b).

The WG acknowledged that while there had, at that time, been a movement towards a more strict application of the general rules of stratigraphic classification as expressed in the *International Stratigraphic Guide* (Hedberg, 1976), and hence the Holocene as a geological unit of Epoch status could potentially be subdivided into regional or global stages, the majority of the reviewers had tended to focus on subdivisions of lower rank, such as regional chronozones. Mangerud *et al.* considered three approaches towards a formal subdivision: (a) by means of stratotypes; (b) by the use of inferred climatic changes; and (c) by the use of radiocarbon dates. In addition, they considered the employment of radiocarbon years directly, without any subdivision into named units.

The conclusion of the WG was that neither (a) nor (b) was useful as a basis for Holocene subdivision, the former because of their limited application at anything above the regional scale, and the latter because signals of climate change in the geological or biological records are time-transgressive or diachronous. Of the remaining approaches involving radiocarbon dates, the WG suggested that both could be useful as bases for the subdivision of the Holocene, although no formal recommendation was made as to which was the more suitable. Equally, no proposals were made for a formal overall chronostratigraphic subdivision of the Holocene Series/Epoch.

And there, effectively, the matter has rested. Over the past 30 years, however, there have been important developments in Quaternary science that suggest that the time may now be right to look again at a formal subdivision of the Holocene.

1. A much wider range of Holocene depositional archives resolved at decadal scale or less is now available. These include ice cores from Greenland, Antarctica and other ice caps, dendrochronological series, marine sequences, peat deposits, lacustrine sediments and speleothems. Time-series data from these sources provide high-resolution records of Holocene climatic events and trends that were not available to the original INQUA WG, and which could now form the basis for a formal chronostratigraphic division of the Holocene.
2. The number and spatial distribution of Holocene records is now much larger from both land and sea. This increased coverage means that it is now possible to differentiate, with some confidence, changes that are local in significance from those that may be regional, hemispherical or even global.
3. Advances in geochronology have produced a more secure time-stratigraphic framework for the Holocene. These include refinements in radiocarbon (e.g. accelerator mass spectrometry, radiocarbon calibration and age modelling), U–Th and luminescence dating; the construction of high-precision dendrochronological series; and the development of high-resolution timescales based on varved sediments and ice-core data. In addition, time-stratigraphic marker horizons, notably tephra isochrones, but also palaeomagnetic events, constitute a basis for regional and, in some instances, hemispherical correlation. Synchronization of atmospheric trace gas records between Greenland and Antarctic ice-cores offers a potential basis for bi-polar correlation (although differences in gas-age/ice-age relationships between Greenland and Antarctica mean that this exercise is not straightforward: Bender *et al.*, 1997). Overall, however, these various approaches can provide a more secure foundation for chronostratigraphic subdivision and correlation than has previously been the case.
4. The Pleistocene–Holocene boundary has recently been formally defined using conventional stratigraphic procedures (*sensu* Hedberg, 1976), suggesting that these approaches might now also be applied to the Holocene Series/Epoch. The stratotype (Global Stratotype Section and Point: GSSP) has been located at 1492.45 m in the Greenland NGRIP2 ice core, with an age of 11.7 ka b2k (before AD 2000; Walker *et al.*, 2008, 2009).
5. It has been proposed (and has been generally accepted) that the Pleistocene Series/Epoch should be subdivided into four Stages (or Ages), two of which are now ratified: the Gelasian (2.60–1.80 Ma) and the Calabrian (1.80 Ma to 780 ka), and two that are not yet formally defined but are awaiting ratification: the 'Ionian' (780–125 ka) and the 'Tarentian' (125–0.117 ka: Cita, 2008). These stages, which have (or will have) formally defined GSSPs, are also equated to the Early (including the Gelasian and Calabrian Stages), Middle and Late Pleistocene Sub-series/Sub-epochs, respectively. Once the Pleistocene has been divided in this way, the Holocene will remain the only unit of Series/Epoch status

within the Geological Timescale that remains formally undivided.

Although there is clearly little to be gained by subdividing the Holocene simply to bring it into line with other Series or Epochs, the question does arise as to whether there is practical value in such a subdivision. In other words, would the Quaternary community find it useful to have a formal division of the Holocene? And, if so, how many subdivisions would be appropriate?

In their seminal paper on the Quaternary stratigraphy of Norden, Mangerud *et al.* (1974) proposed that the Flandrian Stage (the 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: 10.0–8.0 k ^{14}C a BP); Middle Flandrian (Atlantic and Subboreal: 8.0–2.5k ^{14}C a BP); and Late Flandrian (Sub-Atlantic: post 2.5 k ^{14}C a BP). But time-transgression in vegetational response to climate change, ambiguities in the use of the Blytt and Sernander terminology, and problems associated with radiocarbon dating suggest that such a chronostratigraphic subdivision of the Holocene would not be applicable at anything other than the local or perhaps regional scale (Björck *et al.*, 1998; Wanner *et al.*, 2008; and see above). However, the proposal of a tripartite subdivision of the Holocene appears to have more validity. Indeed, examination of the Quaternary literature shows that such a subdivision is already being widely employed, the terms 'Early', 'Middle' ('Mid-') and 'Late' Holocene being routinely applied, *inter alia*, in palaeoclimate studies (e.g. Early Holocene climate fluctuations), in palaeoecological work (e.g. Mid-Holocene elm decline) and in geomorphological investigations (e.g. Late Holocene fluvial activity). Of the 89 papers published in 2011 in *The Holocene*, a leading international journal for Holocene research, 35 (39.3%) included the term 'Early Holocene', 'Mid (or Middle) Holocene' or 'Late Holocene' in the title, while all 14 papers in the current issue at the time of writing (November 2011) included at least one of these terms somewhere in the text.

Yet, despite their entrenchment in the literature, the precise temporal limits of each of these subdivisions have never been formally agreed upon; nor have they been defined chronostratigraphically with reference to a stratotype. To some, the Early Holocene might extend to 9 ka BP while to others it might have ended a thousand years or more later; there is a similar range in age for the boundary between the Middle and Late Holocene. For example, in different papers in a recent issue of *Quaternary International* dealing with the Middle Holocene Archaeology of South America, the beginning of the Middle Holocene ranges in age from 8 to 6 ka BP, while the end of the Middle Holocene varies between 5 and 2.5 ka BP (Hoguin & Restifo, 2012). Such inconsistency of usage can clearly lead to confusion. However, given the difficulties that confounded previous attempts, the question arises as to whether it may now be possible to propose a formal globally applicable chronostratigraphic subdivision of the Holocene that follows conventional geological procedures. If so, can such a scheme be underpinned by reference to global stratotypes and, more importantly perhaps, will a formal subdivision be a useful tool in Quaternary research?

In reflecting on this matter, it should be noted that the division of the preceding Epoch, the Pleistocene, is not based on globally recorded environmental changes. The boundary between the Middle and Late Pleistocene, for example, which is currently informally placed at the beginning of the Eemian Interglacial [Marine Isotope Stage (MIS) 5e], could equally have been located at the onset of MIS 7; but over the years, it has become the norm to regard the Late Pleistocene as being synonymous with the last interglacial–glacial cycle. Given that the Holocene is a period during which there has been little in the way of substantive or globally synchronous climatic or environmental change, it would be unrealistic to seek a division of that Epoch reflecting such changes. Rather, any subdivision must essentially be one of convenience as, effectively, has been the case with the Pleistocene. If so, then the logical way forward is to accept and formalize what is current custom and practice and to proceed by using clearly defined marker horizons to underpin the subdivision. These horizons should be of global, or at least hemispherical, significance and should differentiate the Holocene Series/Epochs into three Sub-series/Sub-epochs[1] based on clearly defined age boundaries for the Early–Middle Holocene and Middle–Late Holocene.

A proposal for a formal subdivision of the Holocene

The Early–Middle Holocene Boundary

We propose that the so-called 8.2 ka BP event (hereafter, the 8.2 event) should mark the boundary between the Early and Middle Holocene Sub-series/Sub-epoch. The 8.2 event is a major short-lived cooling episode that is clearly reflected in the isotopic signal in Greenland ice cores (Hammer *et al.*, 1986; Alley *et al.*, 1997; Alley & Ágústsdóttir, 2005). It is generally considered to reflect curtailment of North Atlantic Deepwater (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 (Barber *et al.*, 1999; Rohling & Pälike, 2005; Kleiven *et al.*, 2008). The reasoning for using this event as the key marker for the early–middle Holocene is as follows:

1. The 8.2 event is most clearly recorded as a marked shift to low ^{18}O/^{16}O and D/H values (reflecting abrupt cooling) in oxygen isotope records from the Greenland Ice Sheet (Fig. 1). There is also a decline in ice-core annual layer thickness (Rasmussen *et al.*, 2007), deuterium excess (Masson-Delmotte *et al.*, 2005), a conspicuous minimum in atmospheric methane (a global 'event'), and a subsequent increase in atmospheric CO$_2$. Within the δ^{18}O minimum that constrains this event in all Greenland ice cores, 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. 2), is characterized by high fluoride content and can most likely be attributed to an Icelandic volcano. It is a key reference point in the Greenland GICC05 timescale (Rasmussen *et al.*, 2006; Thomas *et al.*, 2007), and is dated on that timescale to 8236 b2k (before AD 2000), with a maximum counting error of 47 years. As such, it constitutes an excellent GSSP for the Early–Middle Holocene boundary. The case for using an ice core as a GSSP was first made in the proposal for the formal definition of the

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[1] Strictly speaking, 'Early', 'Middle' and 'Late' Holocene are geochronological terms (i.e. relating to time intervals within the rock record) and, conventionally, are applied only to *Sub-epochs* within the geological timescale. The correct chronostratigraphic terminology (i.e. relating to the rock sequence from a particular time interval) would be 'Lower', 'Middle' and 'Upper' Holocene *Sub-series*. However, the distinction between these two parallel timescales in stratigraphy is currently being debated and, indeed, may no longer prove to be necessary (Zalasiewicz *et al.*, 2004). Accordingly, as the terms 'Early' and 'Late' are much more widely employed than 'Lower' and 'Upper', we are here using these to qualify both *Sub-series* and *Sub-epochs* within the Holocene Series/Epoch.

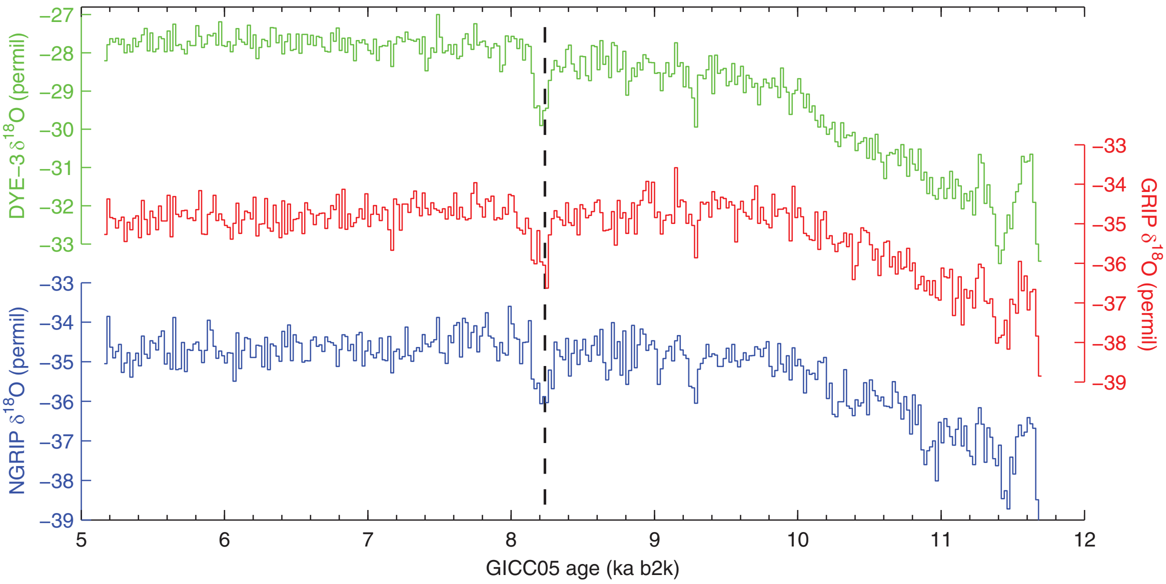

Figure 1. Water stable isotope ratios ($\delta^{18}O$) at 20-year resolution in three Greenland ice cores, DYE-3, GRIP and NGRIP, over the time interval 5.0–11.7 ka b2k (before AD2000) on the GICC05 time scale (Rasmussen *et al.*, 2006; Vinther *et al.*, 2006). The location of the proposed Early–Middle Holocene Boundary inside the 8.2 ka event is shown by the dashed black line.

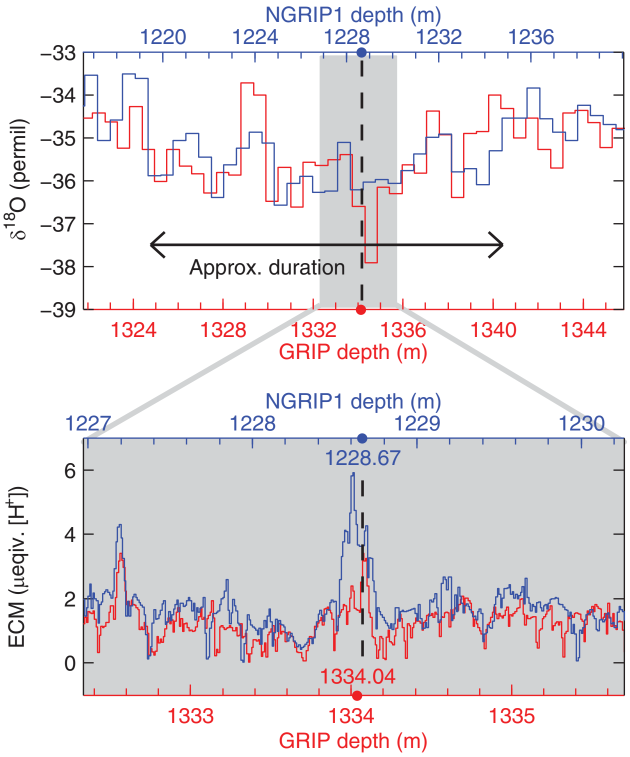

Figure 2. Top: water stable isotope ratios ($\delta^{18}O$) at 55-cm resolution from the GRIP and NGRIP ice cores around the 8.2 ka event. The event duration depends on the criteria and data set used, but Rasmussen *et al.* (2007) suggest that in NGRIP1 the event be defined from *c.* 8300 b2k (1234.78 m) to *c.* 8140 b2k (1219.47 m) as indicated by the black horizontal arrow. Bottom: 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 a high fluoride content and can most likely be attributed to an Icelandic volcano. It is dated on the GICC05 timescale to 8236 b2k (8186 cal. a BP), and is proposed as the marker for the Early–Middle Holocene boundary.

Pleistocene–Holocene boundary, and was accepted by the SQS, by the ICS and by the IUGS (Walker *et al.*, 2008, 2009). There should therefore be no procedural difficulty in the proposal that the GSSP for the Early–Middle Holocene boundary should be defined in the same archive.

2. The 8.2 event has since been detected in numerous proxy climate records, including pollen and lake sediment sequences (Sadori & Narcisi, 2001; Nesje *et al.*, 2006); chironomid and cladoceran assemblages (Larocque-Tobler *et al.*, 2010; Szeroczyńska & Zawisza, 2011); lacustrine oxygen isotope data (Von Grafenstein et al., 1998; Hammarlund *et al.*, 2005); cave speleothems (Boch *et al.*, 2009); and both deepwater and planktonic marine foraminiferal assemblages (Ellison *et al.*, 2006; Ebbesen *et al.*, 2007; Marino *et al.*, 2009). Alignment of these records (e.g. Fig. 3) yields a regionally synchronous 'event' that lasted 150 ± 30 (1σ) years (Daley *et al.*, 2011).
3. While the 8.2 event is most strongly registered in localities around the North Atlantic Ocean, it has also been found in proxy records from other parts of the world (Fig. 3), including cave speleothems in Oman, Yemen, China and Brazil (Fleitmann *et al.*, 2007; Cheng *et al.*, 2009); lake sequences in tropical Africa (Gasse, 2000) and the Tibetan Plateau (Zhang & Mischke, 2009); pollen records from the Mediterranean (Magri & Parra, 2002; Peyron *et al.*, 2011); ice cores from eastern Africa (Thompson *et al.*, 2002); pollen data from Siberia (Velichko *et al.*, 1997); and marine records from the north-west Pacific (Hua *et al.*, 2008). In the South Atlantic, pollen and geochemical data from Nightingale Island in the Tristan da Cunha island group (Ljung *et al.*, 2007) suggest a short-lived increase in precipitation that reflects either an intensification of the South Atlantic westerlies, or a sea surface temperature increase resulting from an Atlantic bipolar seesaw mechanism (Broecker, 1998). The latter is also indicated by coupled climate model simulations which show a warm response at around 8.2 ka BP in the South Atlantic and Southern Oceans (Wiersma *et al.*, 2011). The 8.2 event may also be recorded in lake sediment sequences in East Antarctica (Cremer *et al.*, 2007) and New Zealand (Augustinus *et al.*, 2008). The 8.2 ka event is therefore unusual in late Quaternary records in being near global in nature (Rohling & Pälike, 2005). As such, it con-

stitutes an ideal time-stratigraphic marker horizon for defining the Early–Middle Holocene boundary.

4. Possible cultural effects of the 8.2 event have been noted in north Africa, southern and south-eastern Europe, and the Near East, where increased aridification associated with cooler North Atlantic surface waters appears to have impacted on both settled and hunter-gatherer communities (Weninger *et al.*, 2006; González-Sampériz *et al.*, 2009; Mercuri & Sadori, 2011). Throughout Mediterranean Europe, the event broadly coincides with the Mesolithic–Neolithic transition ('neolithization': Berger and Guilaine, 2009) and, in parts of south-eastern Europe, Anatolia, Cyprus and the Near East, may have triggered the spread of early farmers (Weninger *et al.*, 2006). Further north in Finland, depletion of marine resources during the 8.2 event appears to have led to social and cultural changes in coastal hunter-gatherer communities, manifest in particular in developments in artefact technology (Manninen & Tallavaara, 2011).

We therefore suggest that the boundary between the Early and Middle (Mid-) Holocene Sub-series/Sub-epoch should be based on the 8.2 event. As this registers most strongly in mid- and high-latitude records, an appropriate stratotype (GSSP) is the Greenland NGRIP1 ice core, in which the event is marked by a significant excursion in the oxygen isotope profile, is defined by the volcanic signal referred to in (1) above, and is dated by the high-resolution GICC05 ice-core timescale (Vinther *et al.*, 2006). The advantage of using the volcanic marker as the GSSP is that some investigators see the 8.2 event as part of a longer climatic anomaly (reflecting a much longer background cooling) extending from *c.* 8.65 to 8.0 ka (O'Brien *et al.*, 1995; Rohling & Pälike, 2005; Thomas *et al.*, 2007; Fig. 3). Here, however, we are isolating a single and readily identifiable stratigraphic horizon within the isotopically defined 8.2 event in the NGRIP1 core as the GSSP. Moreover, should tephra subsequently be found at this point in the ice core, it could be used to provide a direct link between the ice-core GSSP and other sedimentary records. As noted, the above date of the proposed Early–Middle Holocene boundary in the NGRIP1 GSSP is 8236 b2k; this is equivalent to an age of 8186 a BP on the calibrated radiocarbon timescale. As radiocarbon is the most widely employed method for dating Holocene events, we would therefore suggest an age for the Early–Middle Holocene boundary of 8200 cal a BP.

Although this proposal is not strictly in accordance with conventional terminological procedures, in that defined 'stages' should, where possible, be named with respect to stratotypes (e.g. the 'Calabrian' for the late Early Pleistocene stage), we would argue that the Holocene is a special case, and that in this instance such terminology is inappropriate. Rather, the proposal seeks to formalize what is current 'custom and practice', and hence to retain the terms ('Early', 'Middle' and 'Late') that are already in common useage, and with which the Quaternary community is clearly comfortable.

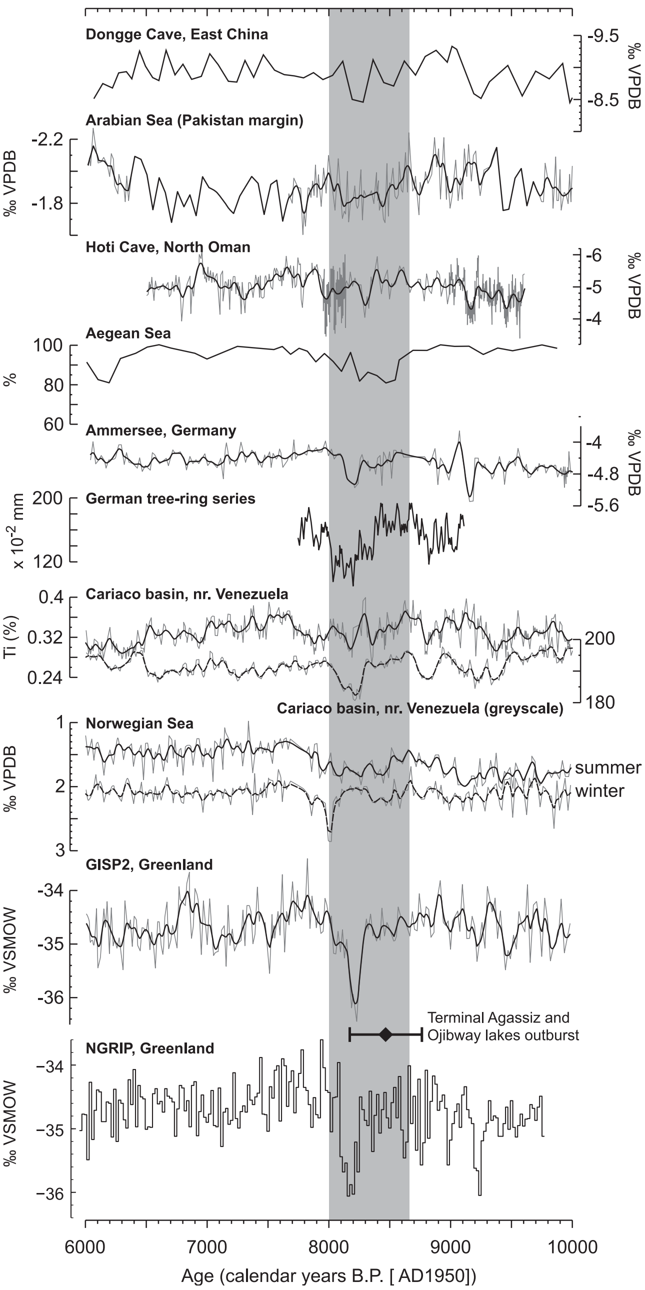

Figure 3. Selected published proxy records for the 8.2 event. Dongge Cave: speleothem $\delta^{18}O$ trace (Yuan *et al.*, 2004); Pakistan margin: marine core $\delta^{18}O$ record (Staubwasser *et al.*, 2002); Hoti Cave, Oman: speleothem $\delta^{18}O$ signal (Neff *et al.*, 2001); Aegean Sea: planktonic foraminiferal data (Rohling *et al.*, 2002); Ammersee: lake sediment $\delta^{18}O$ record (Von Grafenstein *et al.*, 1999); German tree ring-width record (Spurk *et al.*, 2002); Cariaco Basin: titanium record (Haug *et al.*, 2001); Cariaco Basin: greyscale profile (Hughen *et al.*, 1996); Norwegian Sea: marine core $\delta^{18}O$ record (Risebrobakken *et al.*, 2003); GISP2: $\delta^{18}O$ trace (Grootes *et al.*, 1993); NGRIP $\delta^{18}O$ record (Rasmussen *et al.*, 2006; Vinther *et al.*, 2006); Agassiz/Ojibway Lakes: date of lakes drainage (Barber *et al.*, 1999). The vertical grey bar marks the approximate duration of the climatic anomaly associated with the 8.2 event (see text). Modified after Rohling & Pälike (2005), with permission from Eelco Rohling.

The Middle–Late Holocene Boundary

We propose that the Middle–Late Holocene Boundary should be placed at 4.2 ka BP as defined by a mid/low-latitude aridification event (hereafter, the 4.2 event). This was a widespread climatic phenomenon that is reflected in proxy records from North America, through the Middle East to China; and from Africa, parts of South America, and Antarctica (Mayewski *et al.*, 2004; Staubwasser & Weiss, 2006).

The forcing mechanisms behind the 4.2 event are less obvious than is the case with that at 8.2 ka BP, however. There is, for example, no evidence for massive freshwater releases into the North Atlantic or for significant northern hemisphere ice growth; likewise, there are no systematic concentrations of volcanic aerosols or increases in atmospheric CO_2. Mayewski *et al.* (2004) suggest that southward migration of the Inter-Tropical Convergence Zone (ITCZ) might account for the low-latitude aridity (which is the hallmark of the event), and would be consistent with the increase in strength of the westerlies over the North Atlantic, increased precipitation, and consequent glacier advance in western North America (see below). The onset of aridification also coincides with a 1–2 °C 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 (Sun, 2000), which became more pronounced in the mid-latitude regions after *c.* 4.0 ka BP (Barron & Anderson, 2010). More active El Niño events inhibit and weaken the Asian monsoon, and the interval from around 4.0 ka BP onwards registers in many Pacific and Asian proxy records as one of weak or failed Asian monsoons with resulting widespread drought conditions (Fisher *et al.*, 2008, and references therein). Irrespective of cause, however, the fact that the 4.2 event is manifest in a range of geomorphological, stratigraphical and archaeological records from many parts of the world (Weiss, 2012; Fig. 4) means that it constitutes an appropriate temporal marker for the Middle–Late Holocene. These records include the following:

1. In mid-continent North America, widespread and severe drought conditions are evident around 4.2 ka BP in, for example, pollen, diatom and testate amoebae assemblages, cave speleothem stable isotopes and dune systems (Dean, 1997; Booth *et al.*, 2005). Increasing aridity at this time is also reflected in proxy records from the Mediterranean, the Middle East, the Red Sea and the Arabian Peninsula (Bar Matthews et al., 1997; Cullen *et al.*, 2000; Narcisi, 2000; Frumkin *et al.*, 2001; Magri & Parra, 2002; Arz *et al.*, 2006; Drysdale *et al.*, 2006; Parker *et al.*, 2007; Di Rita and Magri, 2009; Roberts *et al.*, 2011).
2. There are many records from the tropical and sub-tropical regions of Africa and South America of a shift to a drier climatic regime around 4.0 ka BP (Marchant & Hooghiemstra, 2004). For example, increased aridity at *c.* 4.2 ka BP is reflected in both West African and East African lake sequences (Damnati, 2000; Gasse, 2000; Russell *et al.*, 2003) and in ice-core records from Kilimanjaro (Thompson *et al.*, 2002), while in South America, drought conditions are indicated by a marked increase in dust content in the Nevado Huascarán ice core from northern Peru (Davis & Thompson, 2006), and are evident in diatom and sediment data from Lake Titicaca (Tapia *et al.*, 2003). In the south-east Pacific, onset of drought conditions post 4.5 ka BP have been detected in lake records from Easter Island (Sáez *et al.*, 2009; Cañellas-Boltà *et al.*, 2012).
3. In China, the 4.2 event is also marked by drought and, paradoxically, by extreme flooding (Huang *et al.*, 2007, 2011). A shift to more arid conditions around 4000 a BP is also found in proxy records from the Indus Delta and from other parts of north-western India (Staubwassser *et al.*, 2003; Prasad & Enzel, 2006), while on the Tibetan Plateau, lacustrine evidence indicates the onset of much colder conditions at *c.* 4.0 ka BP (Mischke & Zhang, 2010). A weakening of the South Asian summer monsoon at ~ 4 ka BP is reflected in marine records from the Arabian Seas (Gupta *et al.*, 2003), while the 4.2 event also registers as a weak monsoon event in speleothem records from Dongge Cave in southern China (Wang *et al.*, 2005) and Mawmluh Cave in north-east India (Berkelhammer *et al.*, 2012), while in Taiwan an increase in palaeoprecipitation, reflecting a strengthening of the East Asia summer monsoon, begins about 4.2 ka BP (Yang *et al.*, 2011).
4. In Australia, pollen evidence from the tropical north-east suggests the onset of an ENSO-dominated climatic

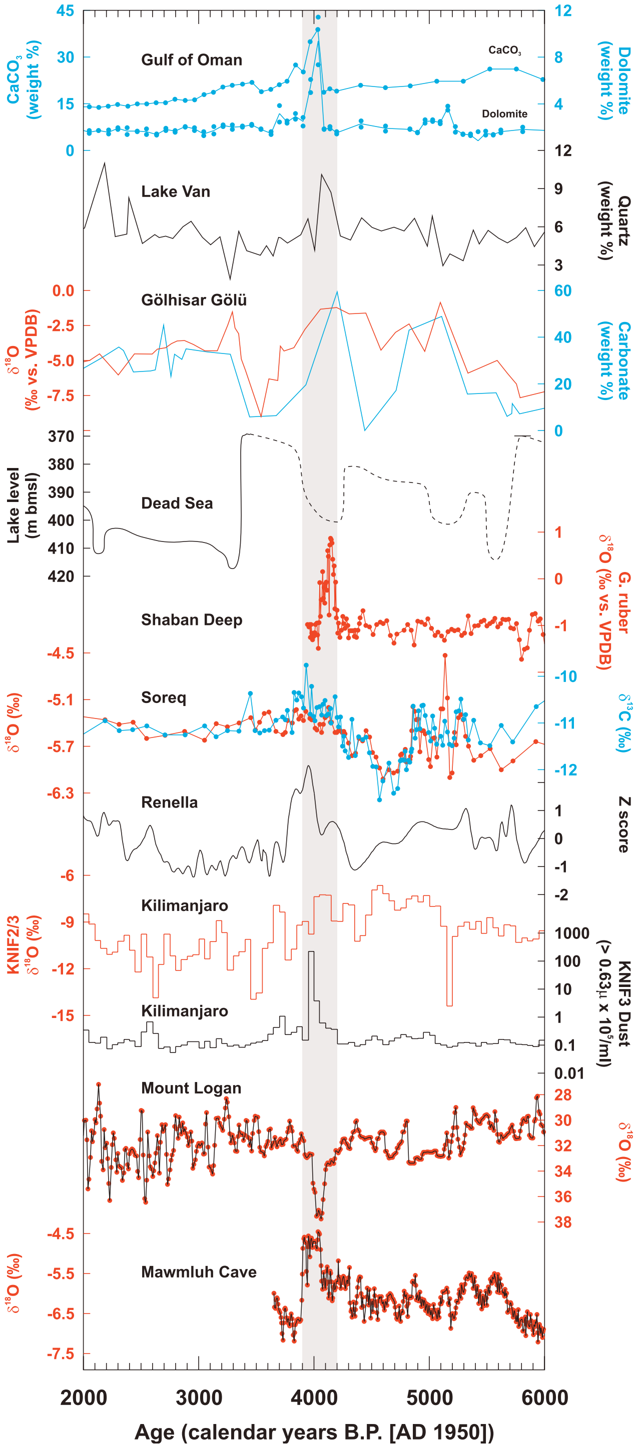

Figure 4. Selected proxy records for the 4.2 event. Gulf of Oman, Middle East: marine core ($CaCO_3$ and $CaMg(CO_3)_2$) records (Cullen *et al.*, 2000); Lake Van and Gölhiar Gölü, Turkey: lake core (quartz, $\delta^{18}O$ and carbonate) record (Lemcke & Sturm, 1997; Eastwood *et al.*, 1999); Dead Sea: lake level records (Migowski *et al.*, 2006; Frumkin, 2009; Kaniewski *et al.*, 2010); Shaban Deep, Red Sea: marine core $\delta^{18}O$ record (Arz *et al.*, 2006); Soreq Cave, Israel: speleothem $\delta^{18}O$ record (Bar Matthews et al., 1997; Enzel *et al.*, 2003; Jex *et al.*, 2010); Renella Cave, Italy: z score on flowstone stable isotope record (Drysdale *et al.*, 2006); Kilimanjaro, Kenya: ice-core $\delta^{18}O$ and dust records (Thompson *et al.*, 2002; David & Thompson, 2006); Mt Logan, Yukon, Canada: ice core $\delta^{18}O$ record (Fisher *et al.*, 2008; Fisher, 2011); Mawmluh Cave, India: speleothem $\delta^{18}O$ record (Berkelhammer *et al.*, 2012). The vertical grey bar marks the likely onset and termination of the 4.2 event. After Weiss (2012).

régime at around 4.0 ka BP (Schulmeister & Lees, 1995). McGlone *et al.* (1992) had earlier concluded from a variety of marine and terrestrial proxy indicators in Australasia and southern South America that a major climatic transition, characterized by the development of a strong ENSO influence, occurred in these regions between 5.0 and 3.0 ka BP, and this assertion has been supported by numerous subsequent studies (e.g. McGlone and Wilmshurst, 1999; Gomez *et al.*, 2004; Quigley *et al.*, 2010). In addition, a marked cooling of southern ocean waters at *c.* 4.3 ka BP is evident in a deep-sea sediment core off South Australia (Moros *et al.*, 2009), while a similar cold phase is found in the deuterium-derived temperature record in the EPICA ice core from Antarctica (Masson-Delmotte *et al.*, 2004).

5. A climate shift around 4.2 ka BP is also evident in many regions of the mid- and high latitudes of the northern hemisphere. In the American Pacific Northwest, for example, a change in climatic regime around 4.2 ka BP is reflected in a range of proxy records, including chironomid assemblages (Clegg *et al.*, 2010), peat inception data (Gorman *et al.*, 2007) and accelerated peat accumulation rates (Yu *et al.*, 2003). In an ice core from Mt Logan in the Yukon, northern Canada, an abrupt excursion in $\delta^{18}O$ (to lower values) at *c.* 4.2 ka BP reflects enhanced moisture transport from the Pacific (Fisher *et al.*, 2008), which also resulted in a widespread advance of mountain glaciers (Menounos *et al.*, 2008).
6. A similar shift to cooler and wetter conditions around 4.2 ka BP is also apparent in Europe, notably in peat sequences in Britain (Hughes *et al.*, 2000), Ireland (Barber *et al.*, 2003) and Sweden (Borgmark, 2005); in chironomid assemblages from northern Fennoscandia (Korhola *et al.*, 2002); in lake-level sequences from central Europe (Magny, 2004); and in diatom data from northern Russia (Laing & Smol, 2003). Elsewhere in the North East Atlantic province, colder conditions at *c.* 4200 a BP have also been detected in proxy records from the Denmark Strait region (Andresen and Björck, 2005), from Iceland (Larsen *et al.*, 2012) and from the Faroe Islands (Andresen *et al.*, 2005).
7. The 4.2 event appears to have been one of the most pronounced climatic events of the Holocene in terms of its effects on human communities, being associated with cultural upheaval in north Africa, the Middle East and Asia (Weiss, 2012). In Mesopotamia, for example, the collapse of the Akkadian Empire around 4.2 ka BP has been linked to sudden aridification (Weiss *et al.*, 1993; De Menocal, 2001), in Egypt the Old Kingdom seems to have collapsed following a series of exceptionally low Nile floods at about 4.1 ka BP (Stanley *et al.*, 2003), while in the Indus Valley of west Pakistan and north-west India, the transition from urban Harappan civilization to a rural post-urban society appears to be associated with the onset of drought conditions around 4.0 ka BP, resulting from a weakened Indian monsoon, reduced precipitation and reduced Indus and Saravati River streamflow (Staubwasser *et al.*, 2003). City and town abandonment at this time is also documented across rain-fed agriculture realms of Iraq, Syria and Palestine, alongside nomadization and habitat-tracking to riparian, paludal and spring refugia (Weiss, 2012). In China, drought conditions during the late fifth millennium BP may have caused the demise of a number of Neolithic cultures (Stanley *et al.*, 1999; Wu & Liu, 2004; Gao *et al.*, 2007; Liu *et al.*, 2010). In northern China, evidence from a range of sites indicates that pastoralism-dominated cultures replaced agricultural-based cultures at *c.* 4.0 ka BP, while in the lower and middle reaches of the Yangtse and Yellow River basins, there is a marked decline in the number of recorded archaeological sites from *c.* 4.0 onwards (Liu & Feng, 2012).

Given this wide range of evidence, it is therefore proposed that the boundary between the Middle and Late Holocene Subseries/Sub-epoch should be based on the 4.2 event. As this is predominantly a mid- and low-latitude phenomenon, the GSSP should be located within these latitudes, and a potential stratotype (GSSP) is the speleothem record (KM-A) from Mawmluh Cave in Cherrapunji, Meghalaya, north-east India. This cave is located at an elevation of 1290 m and is one of the longest and deepest in the Indian subcontinent. High relative humidity (>90%) and minimal temperaure fluctuations (18.0–18.5 °C), relatively constant drip rate and the deep location of the sampling site provide optimal conditions for the calcite to form in isotopic equilibrium with the percolating precipitation. Hence variations in the $\delta^{18}O$ of speleothem calcite closely resemble changes in the precipitation-weighted $\delta^{18}O$. The $\delta^{18}O$ record from speleothem sample KM-A, which is based on 1128 isotopic measurements, extends from *c.* 3.5 to > 12.0 ka BP at a resolution of ~5 years per sample (Fig. 5). The age–depth relationship is constrained by 12 U/Th dates. An age model for the speleothem sequence was developed using the StalAge algorithm of Scholz and Hoffman (2011), where linear interpolation between depth and age is made through each progressive triplet of adjacent U/Th dates. The process is repeated for 10 000 iterations and provides a quantitative method for assessing age uncertainty along the record, which is <30 years in the section of the speleothem spanning the 4.2 event. Moreover, the KM-A record shows linear growth rates during this period which provides confidence in the timing (onset and duration) of the event. Further details are provided in Berkelhammer *et al.* (2012).

The isotopic changes in the Mawmluh Cave KM-A stable isotope record around the time of the 4.2 event comprise a two-step sequence, with an initial enrichment at ~ 4.3 ka and a more pronounced shift (within less than a decade) to more positive values at 4.1 ka, before returning to previous background values some 175 years later (Fig. 5). The event

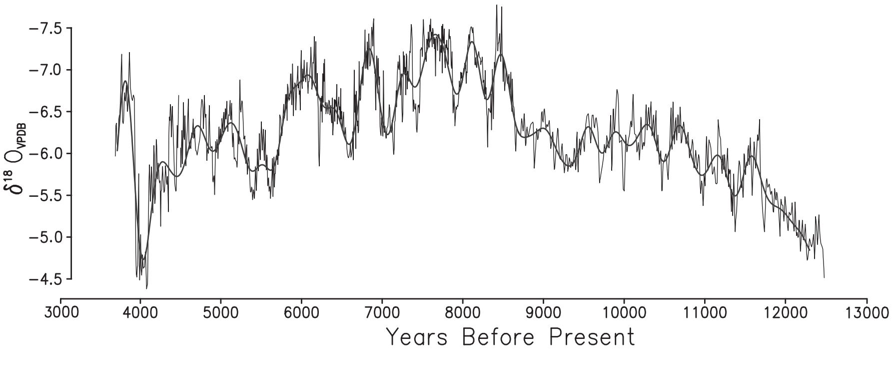

Figure 5. The Mawmluh Cave $\delta^{18}O$ record, showing the 4.2 event (after Berkelhammer *et al.*, 2012).

therefore spans a modelled age interval of ~375 years, with a mid-point in the stable isotope record at ~ 4.1 ka BP. This is well within the range of the ages of the other climatic proxies for the 4.2 event described above. Moreover, given the twofold nature of the abrupt shifts in the Mawmluh Cave stable isotope signal (at 4.3 and 4.1 ka), an age of 4.2 ka effectively splits the difference between these two events. Accordingly, we propose an age for the Middle–Late Holocene boundary of 4200 cal a BP, and that the isotopic signal in the Mawmluh Cave stalagmite should constitute the GSSP for this boundary.

The Anthropocene

It has been suggested that the effects of humans on the global environment, particularly since the Industrial Revolution, have resulted in marked changes to the Earth's surface, and that these may be reflected in the recent stratigraphic record (Zalasiewicz *et al.*, 2008). The term 'Anthropocene' (Crutzen, 2002) has been employed informally to denote the contemporary global environment that is dominated by human activity (Andersson *et al.*, 2005; Crossland, 2005; Zalasiewicz *et al.*, 2010), and discussions are presently ongoing to determine whether the stratigraphic signature of the Anthropocene is sufficiently clearly defined as to warrant its formal definition as a new period of geological time (Zalasiewicz *et al.*, 2011a,b). This is currently being considered by a separate Working Group of the SQS led by Dr Jan Zalasiewicz and, in order to avoid any possible conflict, the INTIMATE/SQS Working Group on the Holocene is of the view that this matter should not come under its present remit. Nevertheless, we do acknowledge that although there is a clear distinction between these two initiatives, the Holocene subdivision being based on natural climatic/environmental events whereas the concept of the Anthropocene centres on human impact on the environment, there may indeed be areas of overlap, for example in terms of potential human impact on atmospheric trace gas concentrations not only during the industrial era, but also perhaps during the Middle and Early Holocene (Ruddiman, 2003, 2005; Ruddiman *et al.*, 2011). However, it is the opinion of the present Working Group that the possible definition of the Anthropocene would benefit from the prior establishment of a formal framework for the natural environmental context of the Holocene upon which these, and also other human impacts, may have been superimposed.

Conclusions

1. It is the conclusion of the Working Group that there is now a compelling case for a subdivision of the Holocene Series/Epoch into Early, Middle and Late Sub-series/Sub-epochs, a procedure which formalizes what is currently custom and practice.
2. The boundaries between the Early–Middle Holocene and Middle–Late Holocene should be defined by reference to stratotypes (GSSPs).
3. It is suggested that for the Early–Middle Holocene Boundary, the 8.2 event constitutes a stratigraphic marker of near-global significance, the GSSP for which should be located where it is registered in the Greenland NGRIP1 ice core.
4. It is further suggested that for the Middle–Late Holocene Boundary, the 4.2 event also represents a stratigraphic marker that is reflected globally, and an appropriate GSSP is a clear isotopic signal in the speleothem record from Mawmluh Cave, north-east India.
5. The Working Group commends these formal subdivisions of the Holocene to the global Quaternary community, and now invites comments on the proposals to be submitted via the *Journal of Quaternary Science* website (http://onlinelibrary.wiley.com/journal/10.1002/%28ISSN%291099-1417/homepage/discussion_forum.htm). The deadline for receipt of comments is 1 March 2013.

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Abbreviations. ECM, electrical conductivity measurements; ENSO, El Niño Southern Oscillation; GSSP, Global Stratotype Section and Point; ICS, International Commission on Stratigraphy; IGC, International Geological Congress; INTIMATE, Integration of ice-core, marine and terrestrial records; ITCZ, Inter-Tropical Convergence Zone; IUGS, International Union of Geological Sciences; NADW, North Atlantic Deepwater; SQS, Subcommision on Quaternary Stratigraphy; WG, Working Group.

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