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The Global Stratotype Section and Point (GSSP) for the base of the Holocene Series/Epoch (Quaternary System/Period) in the NGRIP ice core

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The Greenland ice core from NorthGRIP (NGRIP) contains a proxy climate record across the Pleistocene–Holocene boundary of unprecedented clarity and resolution. Analysis of an array of physical and chemical parameters within the ice enables the base of the Holocene, as reflected in the first signs of climatic warming at the end of the Younger Dryas/Greenland Stadial 1 cold phase, to be located with a high degree of precision. This climatic event is most clearly reflected in an abrupt shift in deuterium excess values, accompanied by more gradual changes in $\delta^{18}O$, dust concentration, a range of chemical species, and annual layer thickness. A timescale based on multi-parameter annual layer counting provides an age of 11,700 yr b2k (before AD2000) for the base of the Holocene, with an estimated 2σ uncertainty of 99 yr. It is proposed that an archived core from this unique sequence should constitute the Global Stratotype Section and Point (GSSP) for the base of the Holocene Series/Epoch (Quaternary System/Period)

Introduction

Holocene is the name given to the second series or epoch of the Quaternary System/Period, the most recent interval of Earth history, which extends to and *includes the present day*. Despite being the most intensively studied interval of recent geological time, a definition of the base of the Holocene (the Pleistocene–Holocene boundary) has not been formally ratified by the International Commission on Stratigraphy (ICS). Here we summarise a proposal to the ICS for a Global Stratotype Section and Point (GSSP) for the base of the Holocene Series/Epoch.

The Pleistocene–Holocene boundary

The conventional approach to subdivision of the Quaternary stratigraphic record is to employ evidence for contrasting climate conditions to characterise individual stratigraphic (geologic-climatic) units (American Commission on Stratigraphic Nomenclature, 1961, 1970). For a variety of reasons, however, the Pleistocene–Holocene boundary has proved difficult to define in conventional Quaternary depositional sequences (Morrison, 1969; Bowen, 1978). Moreover, although an age of 10,000 ^{14}C yr BP for the base of the Holocene is widely cited in the Quaternary literature (e.g., Mangerud et al., 1974), precise dating of the boundary has also proved to be problematical (Lowe & Walker, 2000). One context where many of these difficulties may be overcome is the polar archive, and here we present a proposal for defining a GSSP for the Pleistocene–Holocene boundary on the basis of its clear climatic signature in the NorthGRIP (NGRIP) Greenland ice-core record.

The appropriateness of defining a global geological stratotype in an ice-core sequence might be questioned, but there are sound reasons for this proposal:

i) As glacier ice is a sediment, defining the Holocene boundary stratotype in an ice-core is as justified as basing a stratotype on hard or soft rock sequences.

(ii) Ice sheets form through the annual incremental accumulation of snow, and hence there is a continuity of accumulation (sedimentation) across the Pleistocene–Holocene boundary.

(iii) Because of its geographical location in the high latitude North Atlantic, Greenland is a sensitive barometer of hemispherical-scale climate change, and was especially so at the Pleistocene–Holocene transition when the Greenland ice sheet lay mid-way between the wasting Eurasian and Laurentide ice masses.

(iv) The base of the Holocene in the Greenland ice-core record can be very precisely dated by annual ice-layer counting (see below). The boundary stratotype for the Holocene (GSSP) can therefore be defined at a level of chronological precision that is likely to be unattainable in any other terrestrial stratigraphic context.

(v) The Greenland ice-core record has been proposed by an INQUA project group (INTIMATE) as the stratotype for the Late Pleistocene in the North Atlantic region (Walker et al., 1999) and an 'event stratigraphy' was initially developed for the Last Termination based on the oxygen isotope record in the GRIP ice core (Björck et al., 1998). More recently, the INTIMATE group has proposed that the new NGRIP isotopic record should replace GRIP as the stratotype, using the GICC05 chronology described below (Lowe et al., 2008).

The NGRIP ice core

In Greenland, five major deep-drilling programmes (Figure 1) have been undertaken over the last 40 years (Johnsen et al., 2001), the most recent of which, NorthGRIP (NGRIP) was drilled to bedrock in 2003 (borehole NGRIP2, central Greenland ice sheet; 75.10°N; 42.32°W). This is the deepest core so far recovered from Greenland (3085 m), and the base is dated to c. 123 k yr BP (Dahl-Jensen et al., 2002; North Greenland Ice Core Project Members, 2004). The NGRIP cores are archived at the University of Copenhagen, and access to these can be gained through the NGRIP curator via the NGRIP Steering Committee. The NGRIP core contains the most highly-resolved stratigraphic record in any of the Greenland ice cores of the transition from the Pleistocene to the Holocene, and this is reflected in both the visual stratigraphy (annual ice layer thickness) and in a range of chemical indicators (Figure 2). In addition, a high-resolution stratigraphic timescale (Greenland Ice Core Chronology 2005, or GICC05: Vinther et al., 2006; Rasmussen et al., 2006; Andersen et al., 2006) has been developed based on annual layer counting using stable isotopes and high-resolution impurity measurements. It is proposed that the Global Stratotype Section and Point (GSSP) for the base of the Holocene (Pleistocene–Holocene boundary) should be defined in the NGRIP ice-core record at the horizon which marks the clearest signal of climatic change at the end of the last glacial episode (Younger Dryas Stadial/Greenland Stadial 1) of the Pleistocene.

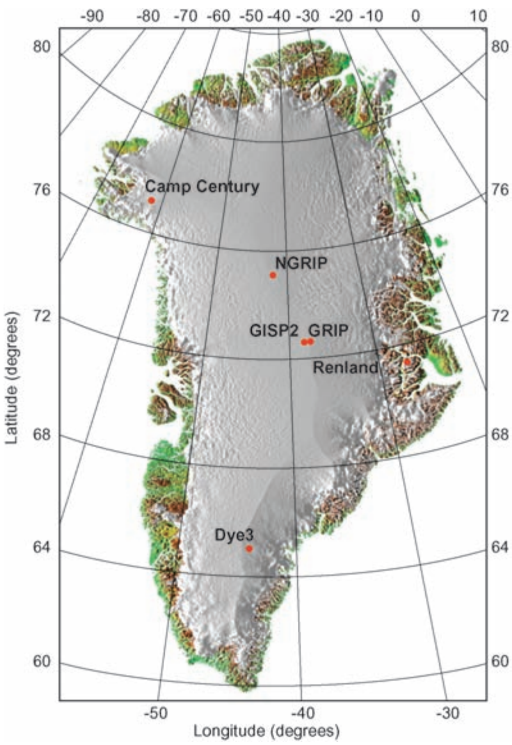

***Figure 1** The locations of five deep drilling sites on the Greenland ice sheet: NGRIP (75.1°N, 42.3°W), GRIP (72.5°N, 37.3°W), GISP-2 (72.5°N, 38.3°W), Dye-3 (65.2°N, 43.8°W) and Camp Century (77.2°N, 61.1°W). Also shown is the shallower site (324m) of Renland (71.3°N, 26.7°W). At all of these sites, the ice-core record extends back to the last (Eemian) interglacial. Map by S. Ekholm, Danish Cadastre.*

Proposed GSSP for the base of the Holocene Series/Epoch

In the Greenland ice cores, the transition to the Holocene is marked by a shift to 'heavier' oxygen isotope values ($\delta^{18}O$) between Greenland Stadial 1 (GS-1)/Younger Dryas ice and ice of early Holocene age; a rapid decline in dust concentration from GS-1 to modern levels; a significant change in ice chemistry (e.g., reduction in sodium concentration); and an increase in annual ice-layer thickness (Johnsen et al., 2001; Figure 2). These changes reflect a marked change in atmospheric circulation regime accompanied by a temperature rise, of c. 10 ± 4°C, at the onset of the Holocene (Severinghaus et al., 1998; Grachev and Severinghaus, 2005).

In the NGRIP core, this climatic shift is most clearly marked by a change in *deuterium excess* values (Figure 2b: red curve) which occurs before or during the interval over which the changes outlined above are recorded. Deuterium (D) and ^{18}O are important isotopic components of precipitation and in high northern latitudes and the relative deviation per mille (‰) from that in Standard Mean Ocean Water (SMOW) is indicated by δD and $\delta^{18}O$, respectively (Johnsen et al., 1989). The approximate current relationship between δD and $\delta^{18}O$ is given by: $\delta D = 8.0\ \delta^{18}O + 10‰$, the 10‰ being the so-called deuterium excess. Deuterium excess in the Greenland ice-core records indicates changes in the physical conditions at the oceanic origins of arctic precipitation and, in particular, can be considered a proxy for past sea-surface temperature in the moisture source regions of the oceans (Johnsen et al., 1989; Masson-Delmotte et al., 2005; Jouzel et al., 2007). The deuterium excess record shows a 2–3‰ decrease at the Pleistocene–Holocene transition, corresponding to an ocean-surface temperature decline of 2–4°C. This is interpreted as a change in the source of Greenland precipitation from the warmer mid-Atlantic during glacial times to colder higher latitudes in the early Holocene (Johnsen et al., 1989; Masson-Delmotte, et al., 2005). The change reflects a sudden reorganisation of the Northern Hemisphere atmospheric circulation related to the rapid northward movement of the oceanic polar front at the end of the Younger Dryas Stadial/Greenland Stadial 1 (Ruddiman and Glover, 1975; Ruddiman and McIntyre, 1981). Hence the deuterium excess record is an excellent indicator of the first major climatic shift at the Pleistocene–Holocene boundary.

Sampling at 5 cm intervals (annual resolution or greater) across the Pleistocene-Holocene transition in the NGRIP core enables the abrupt decline in deuterium excess to be pinpointed with great precision (Figure 2b). At 1492.45 m depth, the 2–3‰ decrease in deuterium excess occurs within a period of 1–3 yr and, over the next few decades, the $\delta^{18}O$ changes from glacial to interglacial values (reflecting the temperature-dependent nature of the fractionation of oxygen isotopes), and there is an order of magnitude drop in dust concentration, reflecting a reduction in dust flux to the ice sheet. The

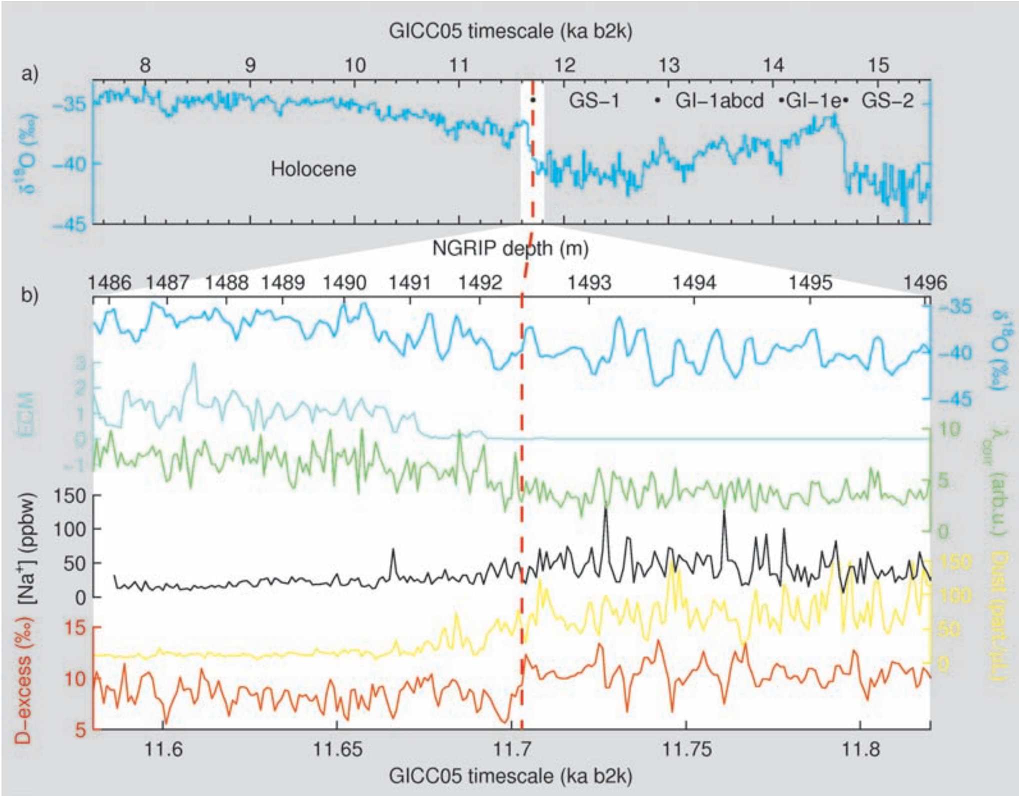

Figure 2 (a) The δ^{18}O record through the Last Glacial–Interglacial Transition showing the position of the Pleistocene–Holocene boundary in the NGRIP core; (b) High-resolution multi-parameter record across the Pleistocene–Holocene boundary: δ^{18}O, electrical conductivity (ECM), annual layer thicknesses corrected for flow-induced thinning, (ªcorr) in arbitrary units, Na$^+$ concentration, dust content, and deuterium excess.

base of the Holocene can therefore be defined on the basis of the marked change in deuterium excess values that occurred over an interval of c. 3 yr, and the stratigraphic boundary is further underpinned by shifts in several other key proxies that occurred over subsequent decades. As such, the NGRIP ice core constitutes a stratotype for the base of the Holocene of unparalleled detail and chronological precision.

The age of the base of the Holocene is derived from annual ice-layer counting across the Pleistocene–Holocene boundary and through ice from the entire Holocene. This involves the analysis of a range of physical and chemical parameters including dust concentration, conductivity of ice and melted samples, δ^{18}O and δD, and a range of chemical species including Ca^{2+}, NH^+, NO^-, Na^+ and SO^{2-} (Rasmussen et al., 2006; Figure 2). Many of these vary seasonally, thereby enabling annual ice layers to be determined with a high degree of precision. In the upper levels of Greenland ice cores, annual ice layers can be readily identified on the basis of the δ^{18}O record and seasonal variations in ice chemistry (Hammer et al., 1986; Meese et al., 1997). However, because of the relatively low accumulation rate at the NGRIP drill site, and the sensitivity of annual cycles in δ^{18}O to diffusion, NGRIP δ^{18}O data are not suitable for the identification of annual ice layers, and there are no continuous chemistry measurements with sufficiently high resolution for the determination of annual layers in the section of the NGRIP core back to c. 1405 m depth (10,227 yr). In order to obtain a complete Holocene chronology for NGRIP, therefore, it is necessary to link the early Holocene record with that from other Greenland core sites, Dye-3 and GRIP (Figure 1). The former is located in south-east Greenland where higher ice accumulation rate has enabled the best resolved of all the Greenland ice-core timescales for the mid- and late-Holocene to be constructed (Vinther et al., 2006). The Pleistocene-Holocene boundary cannot be accurately defined nor dated in that core, however, because of progressive ice-layer thinning due to the flow of the ice. Near the lower limit at which annual ice layers can be resolved in the Dye-3 core, there is a significant decline in δ^{18}O values to below normal Holocene levels that persists for a few decades. This marks the '8.2 ka cold event' that is also clearly recorded in the various proxy climate indicators in the NGRIP core (Thomas et al., 2007). In both Dye-3 and NGRIP, the δ^{18}O reduction marking the 8.2 ka event is also accompanied by a prominent ECM double peak and a marked increase in fluoride content. This represents the fall-out from a volcanic eruption, almost certainly on Iceland. The location of the double ECM peak inside the δ^{18}O minimum around 8000 yr BP constitutes a unique time-parallel marker horizon for correlating all Greenland ice-core records.

In the original Dye-3 core, the annual layer situated in the middle of the ECM double peak was dated at 8214 yr BP with an uncertainty of 150 yr (Hammer et al., 1986). Subsequent high-resolution analysis of the Dye-3 stable isotopes has enabled this age estimate to be considerably refined and it is now dated to 8236 yr b2k with a maximum counting error[1] of only 47 yr (Vinther et al., 2006). The term b2k refers to the ice-core zero age of AD 2000; note that this is 50 yr different from the zero yr for radiocarbon, which is AD 1950. Multi-parameter annual layer counting down from the 8236 yr double ECM horizon within the δ^{18}O minimum in the GRIP and NGRIP cores gives an age for the base of the Holocene, as determined by the shift in deuterium excess values, of 11,703 yr b2k with a maximum counting error of 52 yr (Rasmussen et al., 2006). The total maximum counting error (Dye-3 plus GRIP and NGRIP) associated with the age of the Pleistocene–Holocene boundary in NGRIP is therefore 99 yr, which is here interpreted as equivalent to a 2σ uncertainty. In view of the 99 yr uncertainty, however, it seems appropriate to assign an age to the boundary of 11,700 yr b2k. Accordingly, we recommend that the GSSP for the base of the Holocene be defined and dated at a depth of 1492.45 m in the Greenland NGRIP ice core.

Note 1: The uncertainty estimate of the GICC05 time scale is derived from the number of potential annual layers that the investigators found difficult to interpret. These layers were counted as 0.5

± 0.5 years, and the so-called maximum counting error (mce) is defined as one half times the number the these features. At the base of the Holocene, the mce is 99 years. Strictly speaking, the value of the mce cannot be intepreted as a standard Gaussian uncertainty estimate, but it is estimated that the true age of the base of the Holocene is within 99 yr of 11,703 yr b2k with more than 95% probability. For further discussion see Andersen et al. (2006).

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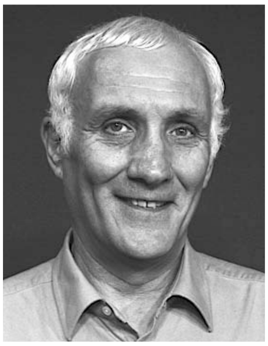

The Working Group *on the base of the Holocene is a Working Group of the Subcommission on Quaternary Stratigraphy and of INTIMATE (Integration of ice-core, marine and terrestrial records), which is itself a Working Group of the INQUA (International Union for Quaternary Research) Palaeoclimate Commission.*