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A new formal subdivision of the Holocene Series/Epoch in Estonia

Tiit Hang[a], Siim Veski[b], Jüri Vassiljev[b], Anneli Poska[b], Aivar Kriiska[c] and Atko Heinsalu[b]

[a] Institute of Ecology and Earth Sciences, University of Tartu, Ravila 14A, 50114 Tartu, Estonia; Tiit.Hang@ut.ee
[b] Department of Geology, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia
[c] Institute of History and Archaeology, University of Tartu, Jakobi 2, 51005 Tartu, Estonia

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Abstract. Over the past 25 years since the ratification of the last official Holocene Stratigraphic Chart in Estonia, the stratigraphic framework of global Quaternary geology has significantly progressed. The Pleistocene/Holocene boundary is defined in the NGRIP2 ice core from Greenland, with an age of 11 700 calendar yr b2k (before AD 2000). The International Subcommission on Quaternary Stratigraphy developed a formal tripartite stratigraphical subdivision of the Holocene into the Greenlandian, Northgrippian and Meghalayan stages/ages, each supported by a Global Boundary Stratotype Section and Point (GSSP). All three GSSPs are defined on the basis of geochemical markers reflecting abrupt global climatic events dated with high accuracy and serving as a reliable foundation for cross correlation. In the light of this development we present a new formal subdivision for the Holocene in Estonia. The new chart is climatostratigraphic with tripartite subdivision. The chronological boundaries and corresponding names for the stages/ages are aligned with the International Holocene Stratigraphic Chart. The correlation is achieved using synchronous and significant global climatic oscillation events, preserved in Estonian Holocene sedimentary proxy archives. The correlation relies on the direct dating of these Holocene sedimentary successions, particularly AMS ^{14}C dating, lake sediment varve counts, etc. The subdivision of the Baltic Sea sediments in the new Holocene stratigraphic chart is based on the internationally recognized stages in the Baltic Sea history and the chronology of their boundaries. Long-term traditions in geoarchaeological studies in Estonia require a common understanding of the chronological background. Therefore, the subdivision of the Estonian Prehistoric period was included in the new Holocene Stratigraphic Chart of Estonia which was approved by the Estonian Commission on Stratigraphy on 15 January 2020.

Key words: Estonia, Holocene, Greenlandian, Meghalayan, Northgrippian, stratigraphic subdivision.

INTRODUCTION

The Quaternary System/Period, spanning the last 2.588 Myr during which the Earth global climate distinctly cooled and the genus *Homo* emerged and developed, is divided into two formally adopted series/epochs: the Pleistocene and Holocene (Gibbard et al. 2005, 2010). The Holocene, which stands out as an extended interglacial time, is the most recent stratigraphic series/epoch within the geological record, covering the time interval from 11 700 yr until the present day (AD 2000). It coincides with the human history from the Stone Age to the present. The preceding series, the Pleistocene, is a significantly longer sequence of alternating glacial and interglacial cycles. The term *holocène*, which means ‘entirely recent’, was introduced during the Second International Geological Congress in Bologna as early as 1882 to refer to the warm episode that began with the end of the last glacial period.

Being the latest and shortest series/epoch within the history of the Earth, the Holocene contains a rich archive of evidence in stratigraphical contexts that are often continuous and frequently preserved at very high levels of resolution. As thus, the Holocene has become one of the most intensively studied intervals within the geological record providing a remarkable range of climatic, sea-level change, geomorphological, sedimentological, geochemical, biostratigraphical and also archaeological evidence. In addition, advances in geochronology (e.g. accelerator mass spectrometry (AMS), radiocarbon calibration and age modelling, annually laminated sediments and tree-rings, ice-core and stalagmites, lacustrine/marine sequences, tephrochronology) have produced a more secure chronostratigraphic framework for the Holocene; the successions can be globally dated and correlated, providing a more secure foundation for a high-resolution timescale previously achievable.

The first rather simple stratigraphical divisions of Estonian Holocene continental deposits based on pollen analyses were published already in the first half of the last century by Thomson (1933, 1939). His schemes were supplemented by climate periods, main constituents of forest, Baltic Sea stages and Prehistoric periods. Later, Orviku (1956) proposed a scheme based on different litho-, morpho- and biostratigraphical evidence and covering also the main part of the lateglacial since the Alleröd chronozone. In the 1960s he differentiated the lateglacial and Holocene, resulting in a rather detailed scheme which comprised subdivisions for the continental and marine deposits, but lacked chronostratigraphy (Aaloe et al. 1960; Orviku 1960). The first formal Holocene Stratigraphic Chart of Estonia (HSCE), comprising the chronostratigraphical scale connected with the pollen zones, was accepted in 1976 (Kajak et al. 1976).

The next formal HSCE was approved in 1993 alongside with the regional chart for the Baltic States at the Stratigraphical Conference of the Baltic States in Vilnius (Raukas et al. 1995). The chart followed the Scandinavian subdivision of the Holocene suggested by Mangerud et al. (1974). In the HSCE (Raukas et al. 1995) the lower boundary of the Holocene was defined as a climatic amelioration event at 10 000 ^{14}C yr before present (BP), and the Holocene was divided into three substages with boundaries defined by ^{14}C dated chronozones based on the palynologically-defined pollen assemblage zones: the Lower Holocene (including the Pre-Boreal and Boreal chronozones (10 000–8000 ^{14}C yr BP), the Middle Holocene (including the Atlantic and Sub-Boreal chronozones 8000–2500 ^{14}C yr BP) and the Upper Holocene (including the Sub-Atlantic chronozone 2500–0 ^{14}C yr BP) (Fig. 1). Although initial radiocarbon calibration tools were available at the time of chart compilation, in the chronological background an uncalibrated radiocarbon timescale was still implemented. The uncalibrated ^{14}C ages are given with the unit BP (radiocarbon years before AD 1950). However, as the local pollen assemblage zones are time-transgressive, their boundaries were not strictly bounded up with chronozones (Raukas et al. 1995).

The stratigraphy of both continental and marine deposits was included in this chart. The Holocene sedimentary sequences of the Baltic Sea were divided into four major stages: the Yoldia Sea (10 300–9300 ^{14}C yr BP), the Ancylus Lake (9300–8000 ^{14}C yr BP), the Litorina Sea (8000–4000 ^{14}C yr BP) and the Limnea Sea (4000–0 ^{14}C yr BP). It was also pointed out that these stages have never been properly defined as stratigraphical units.

Over the past 25 years since the ratification of the last official HSCE (Raukas et al. 1995) there has been a significant progress within the stratigraphic framework of global Quaternary geology. The Pleistocene/Holocene boundary was defined in 2008 (Walker et al. 2008), at a depth of 1492.45 m in the North Greenland Ice Core Project (NGRIP2) ice core from Greenland, with an age based on annual layer counting at 11 700 calendar yr b2k (before AD 2000). The International Subcommission on Quaternary Stratigraphy of the International Commission on Stratigraphy developed a formal tripartite stratigraphical subdivision of the Holocene into the Greenlandian, Northgrippian and Meghalayan stages/ages and their corresponding Lower/Early, Middle and Upper/Late Holocene subseries/subepochs, each supported by a Global Boundary Stratotype Section and Point (GSSP). The GSSP for the Greenlandian Stage/Age is that of the Holocene, as previously defined in the NGRIP2 ice core, and dated at 11 700 yr b2k. The GSSP for the Northgrippian Stage/Age is in the NGRIP1 ice core, and dated at 8236 yr b2k, whereas that for the Meghalayan Stage/Age is located in a speleothem from Mawmluh Cave, Meghalaya, northeast India with a date of 4250 yr b2k. The subdivision was ratified by the International Union of Geological Sciences on 14 June 2018 (Walker et al. 2018, 2019). Note that the term b2k, which refers to the ice-cores zero year of AD 2000, is 50 years later than the zero age for calibrated ^{14}C age-scale which is AD 1950. Hence the equivalent age on the calibrated ^{14}C timescale for the base of the Greenlandian is 11 650 cal yr BP, for the base of the Northgrippian 8186 cal yr BP and for the base of the Meghalayan 4200 cal yr BP. In the subdivision of the Holocene, all three GSSPs are defined on the basis of geochemical markers, which reflect abrupt global climatic events that are dated with a very high degree of accuracy. The start of the Greenlandian coincides with an abrupt and rapid global temperature rise at the onset of the Holocene (Buizert et al. 2014), the onset of the Northgrippian corresponds to a short-lived cooling episode that occurred globally about 8200 cal yr BP (Rohling & Pälike 2005) and the Meghalayan matches with a near-global aridification and cooling event at 4200 cal yr BP (Railsback et al. 2018).

A recent ongoing call is to define a new series/epoch following the Holocene, to be named the Anthropocene (e.g. Waters et al. 2018). This term is being increasingly employed by environmental scientists to identify the period of human-induced global change since the mid-19th century. It should not be confused with the term Anthropogene, which was used in the former Soviet Union as a synonym for Pleistocene. However, so far the official proposal for the Anthropocene has not been ratified by the International Union of Geological Sciences. In the light of the aforementioned important developments in global Quaternary science, as well as in the local studies of the Holocene sediment sequences in Estonia, the revision of the HSCE was needed. Since 2017 the Estonian Commission on Stratigraphy has discussed the earlier versions of the chart. This new stratigraphic subdivision is directly correlated with the global Holocene scale. The

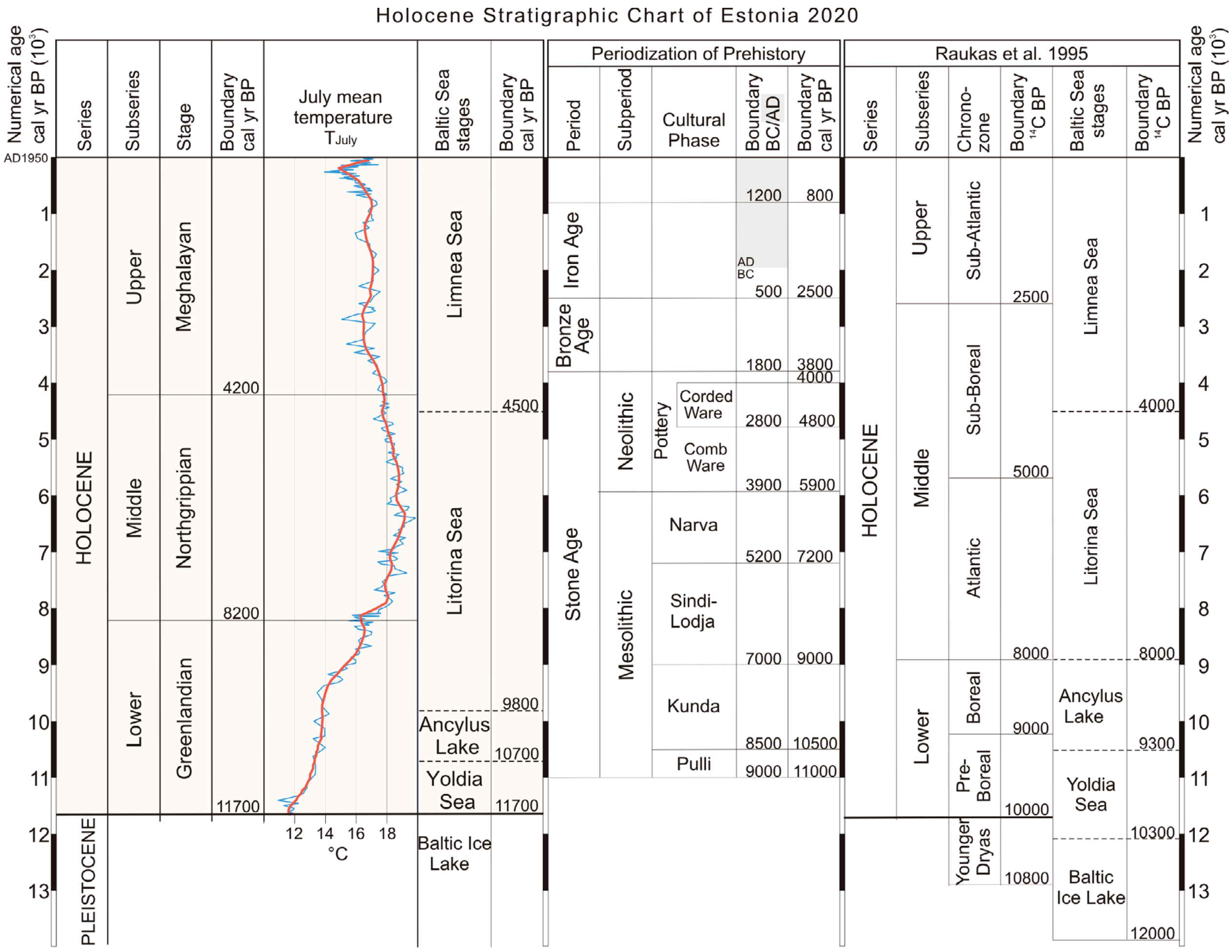

Fig. 1. The new Holocene Stratigraphic Chart of Estonia. The pollen-inferred July mean temperature curve (blue) and the smoothed curve (red) by LOESS with span 0.05 is a compilation from Lake Rõuge Tõugjärv and Lake Nakri records (Veski et al. 2004, 2015). The previous Holocene Stratigraphic Chart of Estonia after Raukas et al. (1995) with the uncalibrated ^{14}C age scale is included.

direct correlation is achieved using highly characteristic, synchronous and significant global climatic oscillation events, which are also preserved in Estonian Holocene sedimentary climatic proxy archives, particularly pollen assemblages/pollen-based temperature reconstruction records, as well as geochemical markers, etc. The correlation also relies on the direct dating of these Holocene sedimentary successions, particularly AMS ^{14}C dating, lake sediment varve counts, etc., all of which give precise and reliable age estimates for cross correlation.

The chronostratigraphic boundaries of the Baltic Sea stages are incorporated from synoptic studies by Björck (1995) and Andrén et al. (2011). Long-term traditions in geoarchaeological studies in Estonia have proved to be very effective. Thus, archaeologists support palaeogeographical and palaeoecological studies with additional chronological data from their archives, while scientific methods contribute with the palaeoecological, relative sea-level and shore displacement reconstructions. Such an interdisciplinary approach needs a common understanding of the chronological background. This is why we include the subdivision of the Estonian Prehistoric period in the new HSCE.

Here we present the new formal HSCE. It was approved by the Estonian Commission on Stratigraphy on 15 January 2020.

A FORMAL SUBDIVISION OF THE HOLOCENE SERIES/EPOCH IN ESTONIA

The Greenlandian Stage/Age, Lower/Early Holocene Subseries/Subepoch (11 700–8200 cal yr BP)

The Greenlandian Stage/Age (corresponding to the Lower/Early Holocene Subseries/Subepoch) has a stratotype boundary coincident with the Holocene Series/Epoch and is defined in the NGRIP2 ice core (75.10°N, 42.32°W) from central Greenland. The GSSP is located at 1492.5 m in the ice core and is marked by an abrupt shift in stable isotope values and other geochemical markers (Walker et al. 2008, 2018, 2019). The name of the stage/age comes from the locality where the GSSP is situated, hence Greenland. The age of the boundary is dated on the Greenland ice-core timescale to 11 703 calendar yr b2k with a 2σ uncertainty of 99 yr, which corresponds to 11 653 cal yr BP using the datum of the ^{14}C timescale (Walker et al. 2019). A major global climatic warming event, approximately 11 700 cal yr BP, marks the end of the glacial late Pleistocene and the beginning of the Earth's modern interglacial. During this rapid warming interval, temperatures in Greenland rose by up to 10 °C in just a few decades (Alley 2000) and a large-scale re-organization with transitions in various components of the climate system started.

In Estonia, the climatic signal that reflects the beginning of the Holocene is identified on the more conventional basis by local chrono-, bio-, litho- and climatostratigraphic evidence and correlated with global GSSP age (Walker et al. 2009). Mainly minerogeneous clayey, silty and/or sandy sediments with low organic content are indicative of lacustrine deposits during a cold Younger Dryas (*ca* 12 900–11 700 cal yr BP) interval at the termination of the Pleistocene. However, there is often visually a distinct transition from mineral deposits to organic carbon-rich gyttja and/or autochthonous carbonate precipitate sediment accumulation since the onset of the warm Holocene throughout Estonia, except in the lowland areas which were flooded by the waters of the Baltic Sea basin. Correspondingly in Estonia, fossil pollen and macrofossil evidence at the lateglacial/Holocene transition shows abrupt vegetation response in tandem with the climatic changes – the predominantly open tundra-like ecosystem declined and was replaced by pine (*Pinus*) and birch (*Betula*) dominated forests (Saarse et al. 2009, 2011; Amon et al. 2010, 2012, 2014; Kihno et al. 2011; Feurdean et al. 2014; Stivrins et al. 2016). Pollen-based climate reconstructions suggest a distinct increase in all re-constructed climate variables around and shortly after 11 700 cal yr BP, e.g. winter (T_{win}) and summer (T_{sum}) temperature reconstruction of Lake Udriku, northern Estonia and mean July temperature (T_{July}) reconstruction of Lake Nakri, southern Estonia (Veski et al. 2015) and T_{sum} of Lake Tollari, southern Estonia (Belle et al. 2017) (Fig. 2).

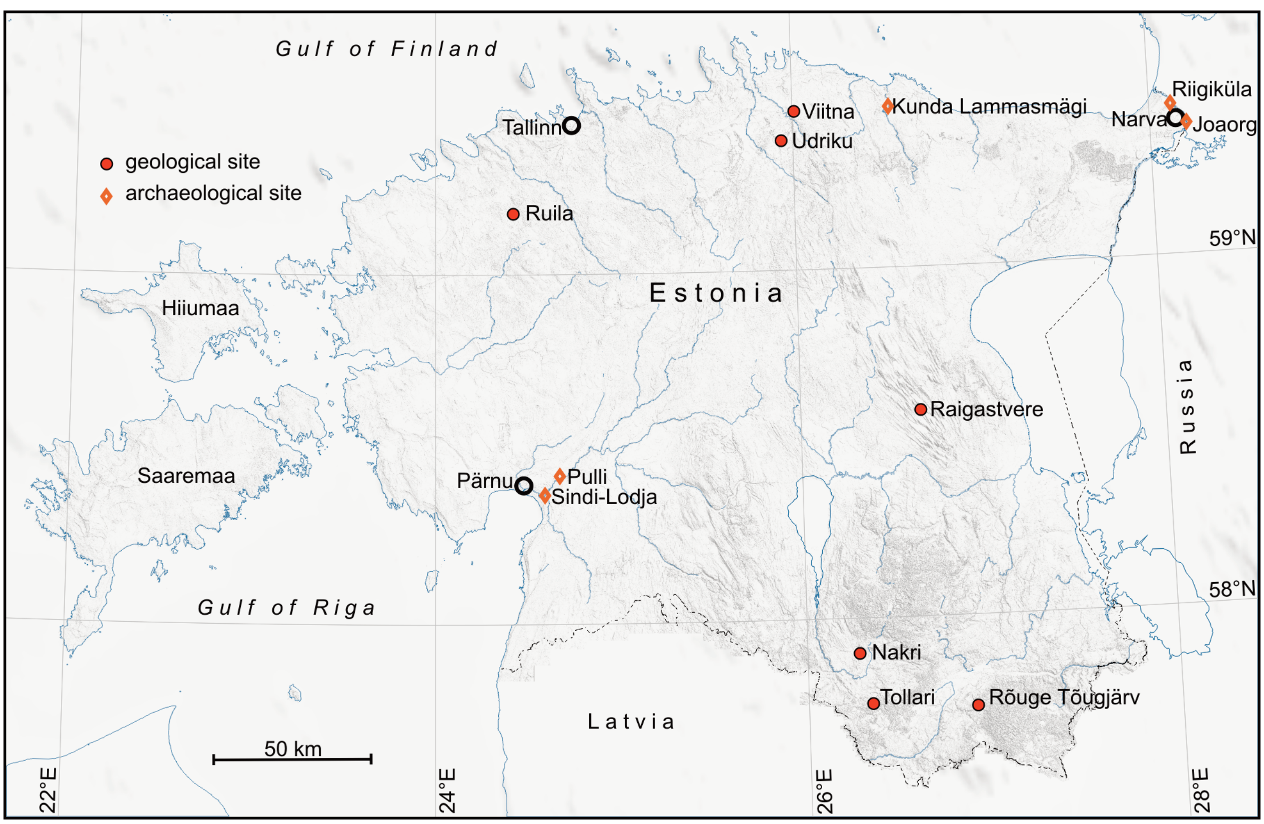

Fig. 2. Map of Estonia with location of sites discussed in the text.

In addition, independent T_{sum} palaeotemperature estimates from the Lake Nakri sediment sequence based on the aquatic chironomids indicates a similar pattern (Heiri et al. 2014). In the Estonian Holocene stratigraphic chart, we apply the timing rounded up to centennial resolution for the Greenlandian base boundary at 11 700 cal yr BP in the calibrated radiocarbon timescale.

The Northgrippian Stage/Age, Middle Holocene Subseries/Subepoch (8200–4200 cal yr BP)

The Northgrippian Stage/Age (corresponding to the Middle Holocene Subseries/Subepoch) is named with geographical locality reference to the NGRIP1 ice core from central Greenland (75.10°N, 42.32°W), which is the type section for the GSSP (Walker et al. 2018). At an ice-core depth of 1228.7 m there is an interval that shows a clear isotope signal of climate cooling following a period of generally rising temperatures during the Early Holocene and corresponds to the so-called 8200-yr climate event. The age of the Northgrippian GSSP is dated to 8186 cal yr BP in the calibrated ^{14}C timescale (8236 yr b2k) with an estimated maximum counting error of ±47 years (Rasmussen et al. 2007). The estimated duration of the cold event is *ca* 160–300 years (Rasmussen et al. 2007; Seppä et al. 2007). The 8200-yr event resulted from the catastrophic final drainage of a vast meltwater basin, Lake Agassiz, after the collapse of the Laurentide Ice Sheet in North America (Barber et al. 1999). The addition of fresh water to the North Atlantic affected thermohaline circulation and likely initiated cooling by hampering ocean northward heat transport (Alley & Ágústsdóttir 2005).

The stratigraphic signature of the short-lived 8200-yr event provides primary correlation opportunities in localities around the North Atlantic Ocean, as well as proxy climate records in the other parts of the world, including lacustrine sedimentary records in Estonia. For example, in Lake Rõuge Tõugjärv (southern Estonia, Fig. 2) the effect of this abrupt climate change on the forest ecosystem is recorded in the pollen assemblage composition and pollen accumulation rates, which is the estimate of past plant population densities. The vegetation change is seen as decline in deciduous broadleaved tree percentages as well as pollen accumulation rates of for example alder (*Alnus*), hazel (*Corylus*) and elm (*Ulmus*), whereas more cold-tolerant taxa, such as birch and spruce, increased in abundance as recorded from Rõuge Tõugjärv (Fig. 2). Pollen-based quantitative annual mean temperature (T_{ann}) reconstruction indicated a temperature drop of 2 °C compared to the pre-cooling period (Veski et al. 2004; Seppä et al. 2007; Ilvonen et al. 2016). Other palaeoclimate proxies, such as lacustrine bulk carbonate oxygen-isotope values, reflected the same pattern (Veski et al. 2004). The cooling culminated between 8250 and 8150 cal yr BP. The cooling around 8200 cal yr BP is observable at numerous locations all over Estonia, for instance, in the pollen-inferred T_{win} and T_{July} reconstructions of Lake Nakri in southern Estonia (Veski et al. 2015), in the T_{ann} curve of Lake Raigastvere in central Estonia, and Lake Viitna and Lake Ruila (Fig. 2), both in northern Estonia (Seppä & Poska 2004), while all reconstructions show a transient cooling of 1.5–2 °C. In the International Holocene Stratigraphic Chart, the Northgrippian lower boundary is detected at annual ultra-high resolution. In Estonian sediment records, such precise chronology and this boundary are determined at 8200 cal yr BP using the datum of the calibrated radiocarbon timescale.

The Middle Holocene is characterized by the Holocene climate optimum. In Estonia, T_{ann} was on average 2.5 °C higher than at present and T_{July} constantly above the present T_{July} normal of 17.4 °C (Seppä & Poska 2004; Seppä et al. 2007, 2009; Holmström et al. 2015; Väliranta et al. 2015; Veski et al. 2015), the expansion of thermophilous broadleaved tree taxa occurred and closed-canopy alder, elm, hazel, lime (*Tilia*), oak (*Quercus*) and ash (*Fraxinus*) dominated forests flourished (Saarse et al. 1995, 1999; Königsson et al. 1998; Saarse & Veski 2001; Blaus et al. 2019).

The Meghalayan Stage/Age, Upper/Late Holocene Subseries/Subepoch (4200 cal yr BP–present)

The uppermost subdivision of the Holocene is defined as the Meghalayan Stage/Age and corresponding to the Upper/Late Holocene Subseries/Subepoch (Walker et al. 2018). The stratotype locality is situated in Mawmluh Cave, Meghalaya, northeast India (25°15′44″N, 91°42′54″E). The GSSP is determined in a cave stalagmite as the strong stable isotope signal, which shows evidence of a pronounced drought and cooling referred to as the 4200-yr event (Walker et al. 2012). The unique characteristics of this isotope record are a combination of precise age control derived through the U–Th dating of the stalagmite, and a sample resolution of less than five years. The Meghalayan GSSP from speleothem is dated to 4200 cal yr BP, with the analytical age uncertainty <30 years in the section of the speleothem spanning the 4200-yr event. However, in order to maintain consistency with the other Holocene GSSPs (the Greenlandian and Northgrippian), which are dated using the ice-core chronology, the age of the Meghalayan GSSP is 4250 yr b2k (Walker et al. 2019). This climatic, almost 250-yr shift appears to involve significant reorganizations of oceanic and atmospheric circulation patterns. In middle and low latitudes the phenomenon of the 4200-yr event is predominantly marked by aridification (Parker et al. 2006), in higher latitudes, however, by climatic cooling (Geirsdóttir et al. 2019). The abrupt climatic shift produced severe disruptions for civilizations around the world, including those of ancient Egypt and Mesopotamia (Weiss 2017).

In the HSCE we determine the Meghalayan lower boundary at 4200 cal yr BP using the datum of the calibrated radiocarbon timescale. There is also a rarely used option of defining this boundary using tephrochronology based at 4260 cal yr BP old Icelandic origin Hekla-4 eruption tephra finds in Estonia (Hang et al. 2006). No indications of an abrupt short-lived climatic reversal at or close to 4200 cal yr BP are present in Estonian terrestrial (lake sediment and peat) records. Instead, pollen-derived temperature reconstruction suggests that the region experienced relatively warm conditions from 8000 to 4500 cal yr BP (i.e. the Holocene Thermal Maximum), followed by a general decrease in temperatures to the present level (Seppä & Poska 2004; Seppä et al. 2009; Holmström et al. 2015; Ilvonen et al. 2016). In general, a well-defined change in the vegetation pattern has been recorded. A gradual drop in nemoral thermophilous tree (lime, hazel, elm, oak and ash) populations and the expansion of boreal trees (pine, birch, willow (*Salix*) and spruce) indicate that forest structure and composition underwent significant changes (Poska & Saarse 2002; Niinemets & Saarse 2007; Reitalu et al. 2013; Blaus et al. 2019). The crop cultivation was introduced to Estonia during the second part of the Northgrippian (Poska & Saarse 2006). The establishment and expansion of permanent agriculture in Estonia took place around 4000 cal yr BP (Poska et al. 2004, 2008) and thereafter human impact became a dominating driver that caused increased landscape openness and affected the floristic species composition (Reitalu et al. 2013; Marquer et al. 2017; Dietze et al. 2018).

The Baltic Sea stages

The evidence provided by sedimentary sequences in the Baltic Sea (Andrén et al. 2011 and references therein) and in Estonian offshore and onshore revealed four to five major stages (Yoldia Sea, Ancylus Lake, Initial Litorina Sea and/or Litorina Sea and Limnea Sea) in the Holocene history of the Baltic Sea. They have traditionally been distinguished by the salinity changes caused by the opening/closing of the connection to the ocean. Due to the time-transgressive nature of salinity changes, the geochemical evidence, microfossil (mainly diatoms) and subfossil (mainly mollusc) assemblages in the sediments are often not synchronous among the localities and the chronological definition of the boundaries of these stages along the Baltic coast is ambiguous.

The Baltic Sea deposits in Estonian offshore are more difficult to divide stratigraphically than continental ones, because in many offshore and nearshore sequences unconformities may cover an even longer time interval than preserved strata (Lutt 1985, 1992). Thus, in the thoroughly studied West Estonian Archipelago, the thickness of Holocene bottom sediments is everywhere less than 5 m, locally even less than 5 cm (Lutt 1985). Lutt (1992) described in the Gulf of Finland seven and Kalm et al. (2006) in the Gulf of Riga nine lithological units of the Late Weichselian and Holocene deposits corresponding to six sedimentation stages well reflected in seismoacoustic profiles: the Late Weichselian basal till and waterlain glacial diamicton, laminated clays of the Baltic Ice Lake (BIL), massive silt and clay of the BIL overlaid by clayey silt of the Yoldia Sea, Ancylus Lake clayey silt and clay, Litorina Sea sand and silt capped by Limnea Sea organic mud. Two distinct discontinuity levels below and above the Ancylus Lake sediments reflect the regression events (Kalm et al. 2006).

The conventional practice of classifying deposits according to the Baltic Sea stages breaks the regulations of stratigraphic classification (North American Commission on Stratigraphic Nomenclature 2005; Salvador 2013). Recently, Virtasalo et al. (2014) applied the combined allostratigraphic and lithostratigraphic approach to the stratigraphic division of the Baltic Sea sediments in the Gulf of Finland. This approach is based on regionally significant unconformities, and lower-rank local unconformities and lithological characteristics that are evident in sediment cores and seismoacoustic profiles (Virtasalo et al. 2010). A case study by Tsyrulnikov et al. (2012) in Estonian offshore at the northern Gulf of Riga indicated that allostratigraphic division can be successfully used for stratigraphic correlation across the Baltic Sea basin and comparison of the glacial/postglacial Baltic Sea depositional succession. However, the current state of Estonian geological expertise does not allow formal allostratigraphic/lithostratigraphic definition, description and division of offshore sediments.

Therefore, traditionally stratigraphic studies in Estonia have concentrated on supra-aquatic coastal sediments and the corresponding landforms that emerged as a result of glacioisostatic rebound. Due to moderate land uplift, the terrestrial landscapes and associated coastal sediments have been periodically inundated in connection with the Ancylus Lake (10 700–10 200 cal yr BP) and/or Litorina Sea (8500–7300 cal yr BP) transgressions and occur both below (Nirgi et al. 2020) and above (Veski et al. 2005; Rosentau et al. 2013; Habicht et al. 2016) the present-day sea level. The main focus in those studies has been relative sea-level (RSL) change, including the timing and amplitude of fluctuations and resulting shoreline displacement. In such a background less attention has been paid to the definition of boundaries of the Baltic Sea stages, which usually are incorporated from synoptic publications (Björck 1995; Andrén et al. 2011).

Supra-aquatic coastal sediments and geomorphological evidence along the Estonian coast suggest that the

BIL shoreline prior to the Billingen drainage event at around 11 700 cal yr BP was *ca* 35 m a.s.l. in SW Estonia and *ca* 70 m a.s.l. in N Estonia (Rosentau et al. 2009; Vassiljev & Saarse 2013). Terrestrial sediments of the Yoldia Sea are rare in Estonia due to the following transgressive Ancylus Lake. Recent findings (Nirgi et al. 2020) in the Pärnu area, SW Estonia, report the lowest Yoldia Sea water-level at an altitude of *ca* –5.5 m, while in northern Estonia, due to uneven land uplift, the Yoldia Sea lowstand water-level remained below 24 m a.s.l. (Heinsalu & Veski 2007).

The onset of the following Ancylus Lake (10 700–9800 cal yr BP) is displayed by an almost simultaneous switch in relative water-level change in southern and central Baltic coasts (Andrén et al. 2011). This, so-called Ancylus Lake transgression culminated in Estonia at around 10 200 cal yr BP (Veski et al. 2005; Rosentau et al. 2013; Nirgi et al. 2020), leaving behind clearly defined raised beaches. The amplitude of the Ancylus Lake transgression in western Estonia was around 18 m with an average rate of rise about 35 mm yr^{-1}. In NE Estonia the respective values were 9 m and 13 mm yr^{-1}.

About 9800 cal yr BP saline waters started to enter slowly the Baltic Sea Basin, marking the onset of the Initial Litorina Sea (Andrén et al. 2000; Berglund et al. 2005). During the Initial Litorina Sea, earlier described also as the Mastogloia Sea (Hyvärinen 1984), RSL dropped in SW Estonia *ca* 16 m to an altitude of at least –4 m a.s.l. and in NE Estonia *ca* 10 m to about 2 m a.s.l. (Rosentau et al. 2013; Nirgi et al. 2020). Due to the lack of clear biostratigraphic evidence of salinity change with almost a balance between eustasy and isostatic rebound along the Estonian coast, this transitional period has been inconsistently addressed in the history of the Baltic Sea research in Estonia and was linked to the subsequent Litorina Sea in the previous HSCE. Considering this, we support the distinction of one brackish-water stage following the Ancylus Lake from 9800 to 4500 cal yr BP in the new stratigraphic chart (Fig. 1).

Rising sea level is believed to be the main mechanism behind the onset of the Litorina Sea transgression, which in Estonia started at *ca* 8500 cal yr BP and culminated at *ca* 7300 cal yr BP (Rosentau et al. 2013; Nirgi et al. 2020). The RSL records show a rise of the Litorina Sea about 14 m in the SW and about 8 m in the NE Estonian coast. Since 7300 cal yr BP, RSL in Estonia has been regressive. So-called Litorina Sea transgressions (Berglund et al. 2005), caused by eustatic sea-level fluctuations due to episodic melting events of large ice sheets, have not been recognized in Estonian RSL records. Mollusc fauna, the isotopic composition of shells and diatom stratigraphy of offshore sediments demonstrate the maximum postglacial salinities in the Baltic basin around 6000 cal yr BP (Hyvärinen et al. 1988; Punning et al. 1988; Westman & Sohlenius 1999). Due to decrease in the outlet area through Danish straits, coupled with increase in climate-driven freshwater discharge (Gustafsson & Westman 2002; Zillén et al. 2008), the salinity in the Baltic Sea basin started to decline gradually from around 4500 cal yr BP, which is proposed to mark the boundary between the Litorina Sea and the subsequent Limnea Sea in Estonia and Finland (Hyvärinen et al. 1988).

Subdivision of Estonian Prehistory

The periodization of Estonian Prehistory from the initiation of the scientific archaeology in the second half of the 19th century has been based on more general division systems that have been developed on the basis of studies in other European areas as well as on the systematization of local find assemblages. In the course of time only the three-age system, the Stone, Bronze and Iron Age, created by Thomsen (1836) and based on the main raw materials used for making tools, has remained unchanged. However, the subdivision of periods into subperiods and further into cultural phases has evolved gradually along with research progresses and advances in chronological methods and has thus been repeatedly corrected. It has been a cyclical process where, for a certain time, the subperiods and phases with their chronology have been formalized by archaeologists until the coupling of more recent data led to changes in the understanding and corresponding advances in periodization. The latest update in the periodization of Estonian Prehistory was provided almost 20 years ago (Lang & Kriiska 2001) and a number of improvements have been made to it since then. In the case of the Bronze and Iron ages, the changes have been derived from more precise age estimations. The amendments to the Stone Age have been caused by the surge in the number of radiocarbon dates, the differences recorded in material culture and the involvement of socio-economic processes in the differentiation of subperiods and phases. Alongside with the new HSCE, the subdivision of the longest, Stone Age Period is more thoroughly presented in the periodization of Estonian Prehistory, while for the Bronze and Iron ages, only the chronology of their boundaries is defined.

The Estonian Stone Age is divided into two larger subperiods, the Mesolithic and the Neolithic. The differentiation of these two subperiods was previously based on the beginning of pottery making (Jaanits et al. 1982; Lang & Kriiska 2001). Modern periodization is based on the combination of technological, social, cultural and economic changes and the earliest pottery which is connected to the Mesolithic Subperiod. The chronology of all the phases and the phase boundaries of the Stone Age is based on the calibrated radiocarbon timescale with the mean error of single age estimations being calculated to be around ±50 yrs.

The Mesolithic in Estonia starts from the beginning of the habitation (*ca* 11 000 cal yr BP) and lasts until large-scale transformations in the material culture caused by a demic diffusion and the changes in society and social networks around 5900 cal yr BP. Based on the paramount changes in settlement and social networks, subsistence and material culture, the Mesolithic can be divided into four phases named after the settlement sites and Narva region, where the first excavated Narva culture settlements in Narva Joaorg and Riigiküla are located: (1) the Pulli Cultural Phase that started with the first settlers and belonged to large-scale social networks in the forest zone of eastern and northern Europe (*ca* 11 000–10 500 cal yr BP), (2) the Kunda Cultural Phase during which the habitation stabilized and local networks developed (*ca* 10 500–9000 cal yr BP), (3) the Sindi-Lodja Cultural Phase when the differences in coastal and inland settlements started to emerge and the marine economy developed (*ca* 9000–7200 cal yr BP) and (4) the Narva Cultural Phase, which is the period of the onset of pottery in Estonia (*ca* 7200–5900 cal yr BP).

The Neolithic Subperiod is divided into two cultural phases that existed in tandem during several centuries at the end of the Stone Age. The initial, Comb Ware Cultural Phase of the Neolithic is distinguished by a marked change in material culture including pottery, lithic technology, introduction of new materials, etc. This was triggered by the arrival of a new population group on the territory of Estonia around 5900 cal yr BP (Saag et al. 2017; Kriiska et al. 2020). In archaeological literature the Comb Ware Cultural Phase has inconsistently been divided into two stages: typical Comb Ware culture (5900–5500 cal yr BP) and Late Comb Ware culture (5500–3800 cal yr BP), based mostly on differences in pottery and lithic material (Kriiska et al. 2020). According to recent aDNA studies (Saag et al. 2017), another population carrying new material culture arrived on the Estonian territory around 4800 cal yr BP. This so-called Corded Ware culture (4800–4000 cal yr BP) existed parallel to the Comb Ware culture until 4000 cal yr BP. In addition to hunting, the livelihood of Corded Ware people was fishing, gathering and also animal husbandry with farming.

The boundary between the Stone Age and the Bronze Age is dated to *ca* 3800 cal yr BP. With certain concessions, the Bronze Age could be divided into three phases: the Early Bronze Age (starting at 3800/3700 cal yr BP), the Middle Bronze Age (starting at 3200 cal yr BP) and the Late Bronze Age (starting at 2800 cal yr BP), depending on the change in material culture and beginning of the stone-cist graves and enclosed settlement sites (Kriiska et al. 2020). As the chronology of the boundaries of these phases still needs to be confirmed, we did not use this subdivision in the new HSCE (Fig. 1). The beginning of the Iron Age is defined at 2500 (2450) cal yr BP and the end is marked by the crusades and the German and Danish invasions to Estonia that started eight centuries ago (the border between Prehistory and the Middle Ages has been dated inconsistently to AD 1200, AD 1225, AD 1227 and/or AD 1250) (e.g. Lang & Kriiska 2001; Kala et al. 2012; Kriiska et al. 2020).

SUMMARY

In the current paper a new HSCE was presented. The new chart, like the international one, is climatostratigraphic with tripartite subdivision. It is based on changes in mean July temperatures (T_{July}) reconstructed from terrestrial pollen data. The data show an increase in T_{July} during the Early Holocene Subepoch or the Greenlandian Age (11 700–8200 cal yr BP), until the cooling event at *ca* 8200 cal yr BP. The Middle Holocene Subepoch or the Northgrippian Age (8200–4200 cal yr BP) is characterized by a climate optimum with T_{July} constantly above the present Estonian T_{July} normal of 17.4 °C. In the Late Holocene Subepoch or the Meghalayan Age (from 4200 cal yr BP), T_{July} has generally decreasing but volatile values.

The chronological boundaries in the new HSCE have been aligned with the International Holocene Stratigraphic Chart. The correlation is achieved using highly characteristic, synchronous and significant global climatic oscillation events, which are preserved in Estonian Holocene sedimentary climatic proxy archives and directly AMS ^{14}C dated. The subdivision of the Baltic Sea sediments in the new HSCE is based on the internationally recognized stages in the Baltic Sea history and the chronology of their boundaries.

The periodization of Estonian Prehistory is added to the new HSCE. Such an approach was considered reasonable because of the close cooperation between archaeologists and Earth scientists in Estonia, which requires common understanding of the chronological background.

In the new HSCE, the subdivision and chronology of both terrestrial and the Baltic Sea sediments are not based on the specific unit and boundary stratotypes. These result from the generalization of studies into a large number of Holocene sedimentary sections, which is a common strategy in Quaternary studies in many regions.

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Eesti uus Holotseeni stratigraafiline skeem

Tiit Hang, Siim Veski, Jüri Vassiljev, Anneli Poska, Aivar Kriiska ja Atko Heinsalu

On esitatud uus Eesti Stratigraafia Komisjoni poolt jaanuaris 2020 kinnitatud Eesti Holotseeni stratigraafiline skeem. Uus skeem põhineb kiirend-mass-spektromeetri (AMS) radiosüsinikumeetodi dateeringute põhisel kalibreeritud (kal a) ajaskaalal ja vastava andmestiku rööbistamisel Rahvusvahelise Stratigraafia Komisjoni poolt hiljuti vastu võetud vastava stratigraafilise skeemiga. Rööbistamine baseerub globaalsetes piiristratotüüpides dateeritud kliimasündmustel, mis on tuvastatavad ka Eesti Holotseeni setteläbilõigetes. Holotseeni ladestiku kolmikjaotuse kronoloogilised piirid ja stratotüüpidele toetuvad nimed on Grööni, Northgripi ning Meghalaya (ingl Greenlandian, Northgrippian, Meghalayan).