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The discovery of the Younger Dryas, and comments on the current meaning and usage of the term

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The Younger Dryas (YD) cold event was discovered in Denmark by Hartz and Mithers in 1904 and the term coined by Hartz in 1912. It was identified as a lacustrine clay bed containing plant macrofossils of an Arctic flora, including *Dryas octopetala*, and lying between Allerød and Holocene gyttjas containing a warmer flora with birch trees. The YD is unique in the sense that it is the largest and most abrupt climate change on Earth since the Last Glacial Maximum and thus within the reach of radiocarbon dating. Yet, I consider it is part of a regular Dansgaard-Oeschger event. The term has been used for a climate event and for lithostratigraphical, biostratigraphical and several other stratigraphical units. I prefer using it as a geochronological and chronostratigraphical unit, i.e. that the YD represents a specific period of geological time and the rocks and sediments formed during this period. In the type area of southern Scandinavia, the YD chron represents the age and duration of the cold event.

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The Younger Dryas (YD) is one of the most studied periods in Quaternary science, and certainly one of the most used stratigraphical terms. A search for 'Younger Dryas' in Google Scholar (1st July 2020) gave more than 46 000 hits. The main reason is that the most abrupt and largest climate changes since the Last Glacial Maximum occurred in and out of the YD, well within the reach of radiocarbon dating. However, in a longer time perspective the YD is, in my opinion, not unique but part of a regular Dansgaard-Oeschger event including the period Bølling-YD (Mangerud *et al.* 2010). However, in this paper, I will not discuss the climate processes that formed the YD but describe how and when the YD was discovered, as a general background for scientists using the term, and give some short comments on current usage and stratigraphical meaning of the term.

The discovery of the YD

The YD is named from *Dryas octopetala* L., a beautiful Arctic flower that is common currently on Svalbard and in the Scandinavian mountains. Nathorst (1870) found leaves of *Dryas octopetala* and other Arctic plants in freshwater clay in Scania, southernmost Sweden. The leaves were not very abundant; Nathorst wrote that if he was able to get out one identifiable leaf per day, he was happy. Japetus Steenstrup then invited Nathorst to Denmark and together they soon found a similar flora in clay pits close to Copenhagen, and later Steenstrup discovered it in a number of clay pits in Denmark whereas Nathorst added 30 sites in Scania (Nathorst 1893). At that time clay pits for production of bricks were, in contrast to the present-day, widespread because bricks are heavy to transport over long distances. Nathorst (1893) used the term 'glacial freshwater deposits' (German: glaziale Süsswasserablagerungen), describing that the lacustrine clay was resting directly on till in shallow depressions and he concluded that the clay was deposited under an Arctic climate soon after the glacial ice melted from the site.

Hartz & Milthers (1901) made a major discovery by finding an up to 30-cm-thick bed of brownish, lacustrine gyttja within the clay in a pit at the village of Allerød, Denmark. They wrote that gyttja, according to their experience, did not form under full Arctic conditions in Denmark and therefore this gyttja bed suggested a climate amelioration. They described an Arctic flora, including *Dryas*, in the clays below and above the gyttja. The flora in the gyttja, which included birch trees and juniper, showed a considerably milder climate than the flora in the clay, and they stated that 'the Allerød Gyttja' indicates a climatic oscillation. They described the lithostratigraphy, the flora and partly the fauna of the Older Dryas-Allerød-YD-Holocene sequence and they inferred the climate evolution. However, they did not introduce the term *Dryas* for the clay or the cold periods.

The term Younger Dryas was first introduced by Hartz when he gave a talk in 1912 to the *Deutsche Geologische Gesellschaft* (the German Geological Society) (Hartz 1912). When describing the stratigraphy in the above-mentioned clay pit at Allerød, he used the term *Younger Dryas Clay* (German: jüngere Dryaston) for the clay between the Allerød gyttja and the Holocene peat, and the *Older Dryas Clay* for the clay below the Allerød-gyttja. He also used the terms Allerød gyttja and the

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Allerød Climatic Oscillation. He used the lithostratigraphy to define the boundaries and the flora and partly the fauna to characterize the palaeoclimate.

Growth and development of the term

In the following decades, the stratigraphical subdivision by Hartz was extensively used in Scandinavia, and the use gradually spread into most of Europe. At that time, scientists did not discriminate strictly between different stratigraphical classifications and the terms were used for lithostratigraphy, biostratigraphy, chronostratigraphy and climatostratigraphy. With the introduction of pollen analyses by von Post in 1916 (Birks & Berglund 2018) the number of studies of lake sediments increased. In lacustrine sediments in Scandinavia, and indeed in most of NW Europe, the units defined by Hartz are easily identified by litho- and pollen stratigraphy, and it is fascinating that the lithological boundaries currently used for the YD in lacustrine sediments in Scandinavia are exactly the same as those originally described by Harz (Fig. 1). Iversen (1942) discovered a warm event that is older than the Allerød and called it Bølling from the name of the lake he studied. Accordingly, he redefined the Oldest and Older Dryas to be below and above the Bølling, respectively.

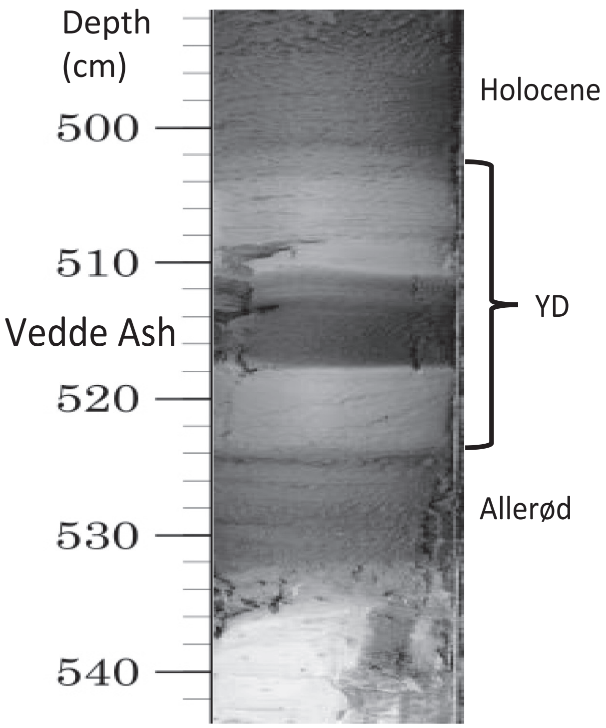

Fig. 1. Photograph of a lake core from western Norway (Svartatjørna, south of Bergen) that shows an example of the minerogenic Younger Dryas (YD) silt between more organic (gyttja) Allerød and Holocene sediments. In this basin there is a thick Vedde Ash in the middle of the YD silt. Photograph Carl Regnéll.

The boundaries of the YD soon became targets for radiocarbon dating when this method was introduced and the lower and upper boundaries were dated to about 11 000 and 10 000 radiocarbon years BP, respectively (Mangerud *et al.* 1974). Now, when the age was established, scientists started to search for what happened during the YD in different environments and over the entire Earth.

Current meaning and usage

Scientists currently use the YD almost exclusively as the name for a climate event, a time period or a combination of the two, in most cases referring directly or indirectly to lake stratigraphy in Scandinavia, although in the last few decades sometimes referring to the Greenland Stadial 1 (GS1) event in ice-cores. Most scientists in practice used it as a geochronological unit, although often informally, as they examined the geological or climatic development in a geographical area, or in a specific environment, during the time period of the YD in Scandinavia. The boundaries are identified by sedimentological, biological, physical or chemical proxies, although biostratigraphical units are most often named after fossils. Kristiansen *et al.* (1988) also named formal lacustrine lithostratigraphical units for the YD, Allerød, etc. But these have not been widely used.

When using the YD as a climatostratigraphical unit (a climate event) the boundaries are inherently asynchronous, and the unit can geographically be mapped only as far as the specific climate event can be identified. Cooler summers have been the classical interpretation in Scandinavia, but in other areas the response might be quite different, for example wetter, drier or colder climate.

I prefer to use YD as a geochronological (chron) and chronostratigraphical unit (chronozone; should formally be Upper Dryas) (Salvador 1994), i.e. that the Younger Dryas represents a specific period of geological time and the rocks and sediments formed during this time period. This was first proposed by Mangerud *et al.* (1974) and I follow their concept that the boundaries are defined by the major climatic changes in southern Scandinavia – although they gave absolute ages for the boundaries. Mangerud *et al.* (1974) postulated that there was no significant time-lag in climate change within the small area of southern Scandinavia, but they assumed that the transition lasted some time, partly because of time-lags in the environmental response of different proxies. Muschitiello & Wohlfarth (2015) for example, found time differences in pollen response at the onset of the YD. The basic assumption is that the ages of the geochronological and climatostratigraphical units should be the same in southern Scandinavia, but even if the climate changes were synchronous, the synchronicity will depend on which proxy is selected to determine the boundary. The strength in defining the YD as a chronozone is that it can be delineated in sediments anywhere on Earth, even at places where no climatic change is seen. The weakness is currently that the boundaries are yet not very precisely defined; there are no decisions or even proposals for boundary stratotypes.

Another problem is that in the Nordic countries (Mangerud *et al.* 1974), and partly world-wide, the YD/Preboreal boundary has been considered to represent the Pleistocene/Holocene boundary. However, the internationally accepted boundary stratotype (Walker *et al.* 2009) places the Pleistocene/Holocene boundary slightly before the end of the YD (Lohne *et al.* 2013; Obreht *et al.* 2020).

A recently much-discussed question in palaeoclimatology is geographical time-lags in climate change (Lane *et al.* 2013), and closely related to this, time-lags in the response by different proxies. I consider that the fact that some scientists use YD as the name for a climate event and other scientists use it for a time period is unlikely to have much influence on this discussion. However, it should always be spelled out how the term is used. Such discussions of time-lags must be performed by comparing ages directly in years for changes at different sites, or relative to volcanic ash beds, or as stratigraphically different responses of proxies in the same section or core.

In a core from the Kråkenes Lake, western Norway, 118 AMS C-14 dates have been obtained across the relevant time interval and the ages 12 737±31 and 11 535±58 cal. years BP were concluded for the lower and upper boundaries for the YD, respectively (Lohne *et al.* 2013, 2014) using the lithostratigraphical boundaries and the IntCal13 calibration (Reimer *et al.* 2013). In northern Germany, several lakes with annual varves through the YD are well dated (Zolitschka *et al.* 2000; Neugebauer *et al.* 2012; Obreht *et al.* 2020). The lakes are located up to 700 km south of Scandinavia and there may be some time-lags compared to Scandinavia. However, most radiocarbon ages of the YD boundaries correspond within dating errors with the ages from Kråkenes (Lohne *et al.* 2013). Yet, by counting varves they obtained a duration of maximum 1090 varve years for the YD in the German lakes (Brauer *et al.* 2001), compared to 1200 calibrated C-14 years at Kråkenes.

Comparison with Greenland ice-core stratigraphy

The Greenland ice-core stratigraphy has, for obvious reasons, become the most used yardstick for palaeoclimate studies of the last deglaciation (Rasmussen *et al.* 2014; Lowe *et al.* 2019); ice-cores contain a continuous, high-resolution snow/ice stratigraphy, which for the younger part can be dated precisely by counting annual varves and climate properties can be measured directly in the snow, without any delay in response of environmental or depositional processes. Weaknesses with ice-cores for boundary stratotypes are that common geological tools such as litho- and biostratigraphy cannot be used for correlation, and that the ice-core and radiocarbon time scales are not identical. Some of the problems can be overcome by using volcanic ash layers, for the YD especially the Vedde Ash (Mangerud *et al.* 1984; Obreht *et al.* 2020).

The Allerød, YD, etc. can be easily identified in the Greenland ice-core stratigraphy, and this was done in the very first paper on the $\delta^{18}O$ stratigraphy in Greenland (Camp Century) ice-cores (Dansgaard *et al.* 1969) and more recently by Rasmussen *et al.* (2006). However, precise time correlations of the boundaries are more difficult, partly due to the different proxies measured; Obreht *et al.* (2020) showed that the onset of the YD at Meerfelder Maar was delayed by 185 years relative to the start of the GS1 in Greenland. The present precision in comparing ages requires a corresponding precision in the way which proxies and their palaeoclimatical meaning are compared, for example in terms of summer temperature, distance to sea ice, wind, winter precipitation, etc.

Here I note that in Greenland ice-cores the $\delta^{18}O$ curves for GI1 to GS1 and GI8 to GS8 are almost identical, except for an offset of 2‰ (Mangerud *et al.* 2010), suggesting that the Bølling-YD (=GI1–GS1) is a regular Dansgaard-Oeschger (D-O) event (Fig. 2). This implies

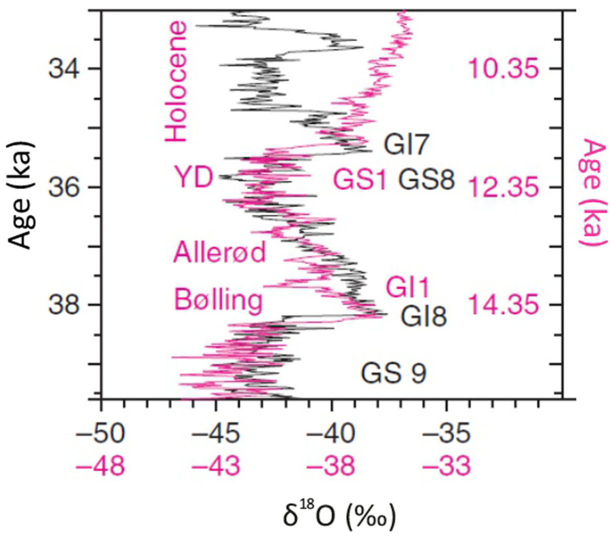

Fig. 2. Comparison between Greenland (NGRIP) $\delta^{18}O$ curves (Svensson *et al.* 2008) for the period 39–33 ka (black curve, numbers and letters) and the period 15.5–9.35 ka BP (pink curve, letters and ages). Ages are given in the GICC05 time scale shifted 50 years to use 1950 zero year. Note that the time and $\delta^{18}O$ scales are identical for the two curves, except that the $\delta^{18}O$ scale is shifted 2‰ and the age scale 23 650 years between the two curves. Slightly modified from Mangerud *et al.* (2010). The point here is that the curve for the Bølling-YD is similar to the curve through a typical Dansgaard-Oeschger event. [Colour figure can be viewed at www.boreas.dk]

that any process proposed to explain the climate change during the YD should be valid also for older D-O events, a point often overlooked.

Conclusions

In practice, the classical subdivision of the Lateglacial into Oldest Dryas-Bølling-Older Dryas-Allerød-Younger Dryas works reasonably well in Scandinavia and adjacent areas and I propose to retain this classification and subsequently correlate with the Greenland ice-core stratigraphy. The scientific community should also improve the definitions of the units, so that they become even more precise than at present.

I propose to use the names as geochronological and chronostratigraphical units (chrons and chronozones). Currently, until more sites are better dated, I use rounded boundary ages for the YD at 12 800 and 11 600 cal. years BP (i.e. before 1950). Some scientists will probably still use the YD as a purely climatostratigraphical (event) unit, but the different usage is unlikely to produce any unsurmountable problems as long as scientists are clear about their stratigraphical criteria. The issue of interchanging climatostratigraphy with geochronological and chronostratigraphical units is common to many parts of Quaternary stratigraphy (Gibbard & West 2000). In the present case the connection is obvious: the YD chron expresses the age and duration of the cold YD event in southern Scandinavia.

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