Lateglacial to Mid-Holocene history of Vasby Mose, eastern Sjælland, Denmark

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We retrieved a sediment core from Vasby Mose, a calcareous fen on eastern Sjælland, Denmark. The record spans the period from *c.* 14 700 to 6800 cal. years BP. During the Lateglacial, Vasby Mose was a lake where minerogenic sandy and clayey sediments accumulated. In the early Lateglacial, from *c.* 14 700 to 13 200 cal. years BP, a tundra-like open, treeless vegetation with *Betula nana* and *Dryas octopetala* was found in the region. During the Younger Dryas, a rich flora of aquatic plants was found in the lake. In the Early to Mid-Holocene, Vasby Mose was a spring-fed calcareous fen, with deposition of peat and tufa. The flora included the sedges *Carex rostrata* and *Carex paniculata*, the aquatic plant *Menyathes trifoliata*, the calciphilous reed plant *Cladium mariscus* and the today nationally extinct bryophyte *Meesia triquetra*. The fauna included aquatic mollusc taxa such as *Pisidium* sp., *Valvata* spp. And *Bithynia tentaculata* and terrestrial or semi-terrestrial species such as *Galba truncatula*, *Euconolus* cf. *alderi*, *Succinea*/*Oxyloma*, *Zonitoides nitidus* and *Vallonia pulchella*. The Preboreal oscillation and other Early Holocene climate events are seen as short-lived, wet intervals.

Keywords: Lateglacial, Holocene, spring-fed fen, tufa, peat, gastropods, macrofossils, palaeoecology.

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Vasby Mose is a mire located in the eastern part of Sjælland, Denmark. Part of the mire is a calcareous fen, with the rare calciphilous vascular plants *Schoenus ferrugineus* and *Primula farinosa*, as well as other rare calciphiles (Hansen 1995). The biodiversity and the extent of the fen have decreased in recent decades due to overgrowing, eutrophication and changing hydrological and hydrogeochemical conditions, which in turn are due to draining, ground water exploitation and impact by nutrients from agricultural fields surrounding the fen. In order to investigate the history of the mire after the last deglaciation and to see if we could find remains of the current rare fen species in the local deposits, we collected a 4.5 m long sediment core from the mire. We conducted macrofossil analyses of the sediments and submitted five samples of terrestrial plant remains for radiocarbon dating.

The coring site was chosen based on a number of cores that had been sampled in the mire in 2015 (Nilsson & Jensen 2015). We cored at the place where the thickest succession of Holocene deposits had been located.

It turned out that part of the succession at the core site consisted of tufa. Previously, tufa was exploited at many places in the eastern parts of Denmark (Esbensen 1999), and several of the medieval churches in the Vasby Mose region are built of tufa. There are only a few Danish studies of tufa deposits and their content of gastropod shells and plant remains (e.g., Elberling 1870, 1876; Ravn 1896; Jessen 1922). These studies were conducted before the introduction of radiocarbon dating and they lack detailed chronologies. The studied deposits were dominated by shells of terrestrial gastropods that live in more or less dry environments. In contrast, the occurrence in Vasby Mose contains shells of species that live in wet or moist places, and the deposit in Vasby Mose can be classified as a spring-fed calcareous fen deposit.

In Skåne in southern Sweden, studies of tufa deposits and their content of terrestrial gastropods were carried out by Gedda *et al.* (1999) and Gedda (2006). Numerous palaeoecological studies of tufa have been conducted in other parts of Europe (e.g., Meyrick & Preece 2001; Davies & Griffiths 2005; Frodlová

& Horsák 2021; Apolinarska *et al.* 2022) but similar modern studies have not been conducted in Denmark. A hundred years ago Jessen (1922) remarked that investigations of tufa in Denmark have been neglected.

The aim of this study was to reconstruct the local development of Vasby Mose after the last deglaciation. We use macrofossils, which are useful in reconstructions of local environments.

Study area

Vasby Mose is located east-north-east of Roskilde and north of the village Sengeløse in eastern Sjælland (Fig. 1). The bedrock in the area consists of Danian limestone with an upper surface at *c.* 20 m below terrain. The limestone is overlain by glaciofluvial sand and clayey till that were deposited during the Weichselian (Houmark-Nielsen & Kjær 2003). The Weichselian deposits are rich in detrital limestone fragments that derive from the bedrock, and clayey till in the region may contain about 20% carbonate (Rørdam 1899).

Vasby Mose is part of a large mire area, together with the neighbouring Sengeløse Mose it covers an area of 109 ha. The present-dayclimate is characterised by a mean July temperature of about 18°C and an annual precipitation about 700 mm. In the northern part of Vasby Mose is the stream Spangå, which was probably straightened out sometime in the 1800s; on a cadastral map from 1869 the stream is depicted as an artificial canal-like feature. The stream was straightened out and presumably also deepened to drain the mire. The mire contains areas of fen, meadows and thickets of *Salix* spp. and *Alnus glutinosa*. There are also several ponds, which were probably dug out by local hunters to attract migrating ducks.

Methods

We used a Russian corer (Jowsey 1966), which was pressed or hammered into the sediment. The corer had a chamber with a diameter of 7.5 cm and a length of 100 cm. Coring was carried out at 55.685°N; 12.239°E, as determined by a hand-held GPS. The terrain surface is about 15 m above sea level. The sediment cores were transferred to plastic tubes, wrapped, and taken to the laboratory, where the cores were carefully cleaned and sub-sampled. Contiguous 3–4 cm thick samples were taken for macrofossil analyses. The samples were wet sieved on 0.4 and 0.2 mm sieves. The residue on the sieves was sorted using a dissecting microscope, and plant and animal remains identified as far as possible. A simplified diagram was constructed using the C2 program that is useful for visualising palaeoenvironmental data (Juggins 2007) and edited in Adobe Illustrator. Remains of terrestrial plants were picked out from selected levels and dried in an oven. Five samples were submitted for radiocarbon dating by accelerator mass spectrometry (AMS) at the Beta laboratory in Miami, Florida and the Radiocarbon dating laboratory in Lund, Sweden. The ages are given in conventional

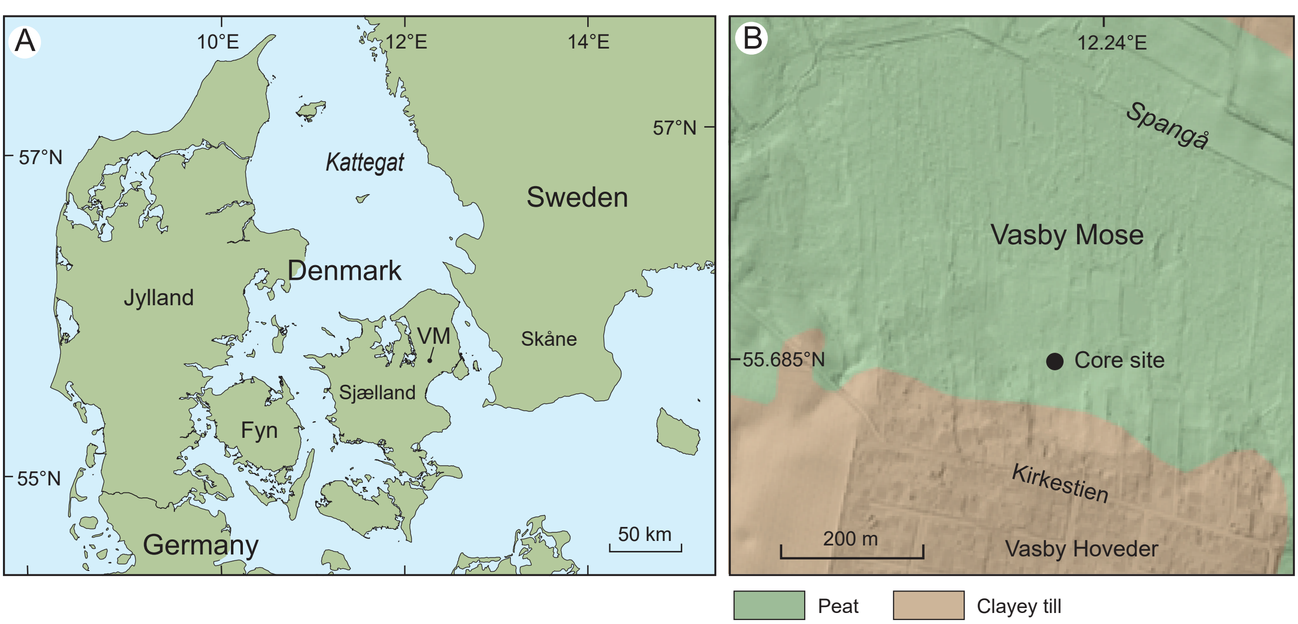

Fig. 1. A. Map of Denmark showing the location of Vasby Mose on Sjælland. VM: Vasby Mose. B. Lidar map of Vasby Mose draped with the surface geology (GEUS Jupiter 2023).

Table 1. Radiocarbon ages from Vasby Mose, eastern Sjælland, Denmark

Depth bct [1] (cm)	Species	Lab. no	Age (^{14}C years BP) [2]	Cal. age (years BP) [3]	Cal. age (yrs BP) [4]
60–64	*Cladium mariscus*	Beta-425412	6690 ± 30	7488–7614	7549
157–160	*M. trifoliata, C. mariscus*	LuS-17297	7915 ± 40	8599–8982	8743
272–276	*Menyanthes trifoliata*	LuS-17298	8950 ± 45	9909–10224	10065
364–368	*Menyanthes trifoliata*	Beta-425413	9740 ± 30	11113–11236	11192
468–472	*Dryas, Betula nana*	LuS-17299	12300 ± 70	14287–14827	14287

[1] bct: below core top.
[2] Radiocarbon ages are reported in conventional radiocarbon years BP (before present = 1950; Stuiver & Polach (1977)).
[3] Calibration to calendar years BP (2 sigma) using IntCal20 (Reimer *et al.* 2020).
[4] Median probability ages.

radiocarbon years before present (BP, Table 1). The radiocarbon ages from Vasby Mose were calibrated to calendar years before present (BP) using the program CALIB with the IntCal20 calibration curve (Reimer et al. 2020). The nomenclature of molluscs follows Anderson & Rowson (2020), but we include some synonyms commonly used in Danish literature.

Results and discussion

Sediments, ^{14}C ages and sedimentation rates

The succession at the core site consisted, from the bottom upwards, of (1) 20 cm light grey gravelly sand, (2) 90 cm grey calcareous clay with plant remains (Fig. 2). At the top some twigs occurred, (3) 80 cm alternating layers of grey-brown peat and grey-brown, sandy-gravelly tufa with shells, (4) 212 cm layered grey-white sandy-gravelly tufa with some peat layers, especially in the upper part, (5) 44 cm layered sandy-gravelly tufa and dark grey-brown peat, (6) 24 cm layered peat and tufa, (7) 28 cm decomposed, black-brown, slightly sandy peat with a little amount of carbonate.

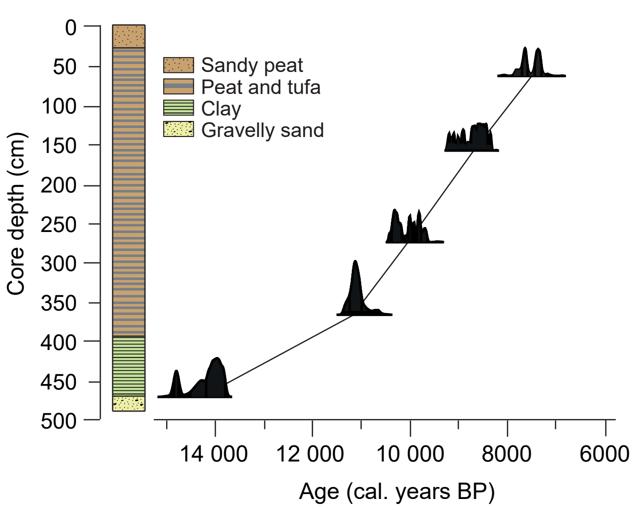

Fig. 2. Calibrated radiocarbon ages plotted against core depth and lithology.

Five samples from the core were dated, yielding median probability ages between 14 287 and 7549 cal. years BP (Table 1). Calibrated ages are plotted versus depth in Fig. 2. According to the age–depth curve the sedimentation rate was *c.* 0.34 mm/year in the lower part of the succession, and *c.* 0.83 mm/year in the middle and upper part. The oldest age corresponds to the Bølling chronozone of Mangerud *et al.* (1974) and the youngest age to the Mid-Holocene (Walker *et al.* 2019).

Macrofossils

The macrofossil diagram was divided into eight macrofossil zones (Fig. 3), which are described and interpreted from bottom upwards.

Zone 1 (12 000–14 700 cal. years BP)

At the bottom of this zone there is sand and gravel with a rare plant remains. The main part of zone 1 consists of clay with remnants of Arctic plants, especially the two dwarf shrubs *Dryas octopetala* and *Betula nana*. Furthermore, there are a few remains of two species of herbs, *Saxifraga oppositifolia* and *Polygonum viviparum*. *Dryas octopetala* and *Saxifraga oppositifolia* are calciphiles; their presence indicates that the local soil was rich in carbonate, and the species assemblage indicate a tundra-like landscape. Two seeds of *Lychnis flos-cuculi* were found; remains of this plant are rare in Lateglacial sediments in Denmark (Bennike & Mortensen 2018; Bennike *et al.* 2020); the species probably grew near the margin of the former lake. In the upper part of the zone, there are only few remains of land plants, but there are many remains of aquatic plant species, including *Chara* sp., *Batrachium* sp., *Myriophyllum spicatum*, *Myriophyllum alterniflorum*, *Potamogeton perfoliatus*, *Potamogeton praelongus*, *Stuckenia filiformis*, *Stuckenia vaginatus*, *Callitriche hermaphroditica* and *Hippurus vul-*

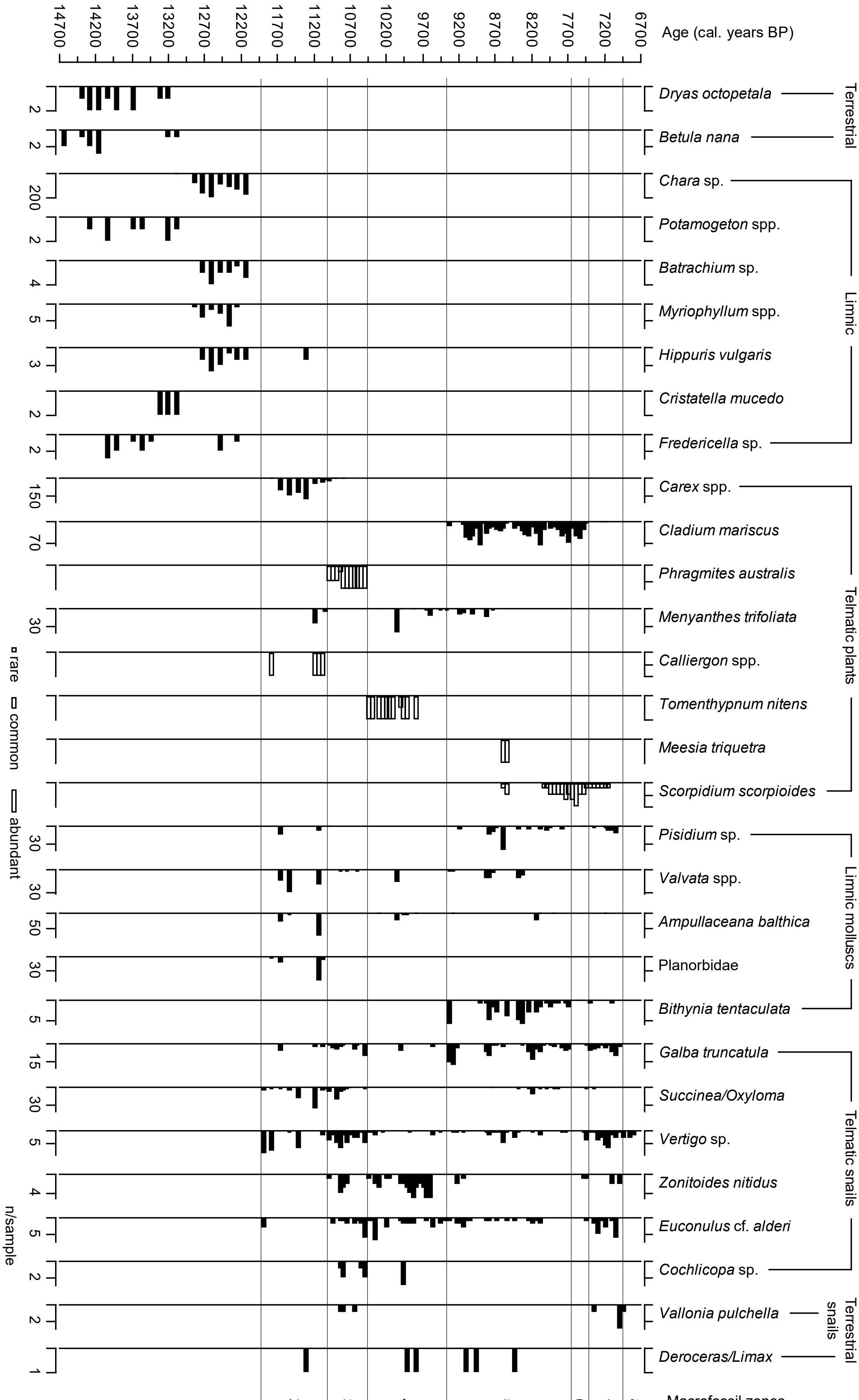

Fig. 3. Macrofossil concentration diagram showing the occurrence of selected plant and animal remains from Vasby Mose.

garis. *Stuckenia vaginatus* is today quite widespread in North America and in Asia; in Europe it is found in Sweden and Finland, where it grows along the shores of the Gulf of Bothnia. Fruit stones of the species have previously been recorded a few times from Lateglacial deposits in Denmark, including Bølling Sø that is a classic site for the study of Lateglacial environmental changes (Stockmarr 1975).

Remains of invertebrates that live in fresh water were common and include Trichoptera, *Sialis* sp., Chironomidae, *Piscicola geometra*, Ostracoda and Bryozoa. The presence of *Piscicola geometra* (fish leach) shows that fishes were also part of the fauna in the lake. The recorded species of small animals are common in Lateglacial lake deposits in Denmark, but one of the species, *Fredericella* sp. has rarely been reported. *Fredericella* is a bryozoan with non-distinct statoblasts that are easily overlooked. The species from Vasby Mose is probably *Fredericella indica*. Despite the name, the species is common in lakes in Europe, and its range extends to northern Norway (Økland & Økland 2001). It is not known from the modern-day fauna of Greenland, but statoblasts of it are quite common in Holocene lake sediments in South-West Greenland (Wagner & Bennike 2012), and the species is probably a member of the present fauna of south-western Greenland.

The sediment was deposited in a Lateglacial lake, and the clay was probably washed out of the local till surrounding the lake. The landscape around the lake was characterised by a sparse vegetation, and maybe there was permafrost in the area (Hartz 1912) which was subject to erosion in the cold climate. In the uppermost part of the zone there was clay without remains of aquatic plants or invertebrates, but with a few twigs of *Salix* sp. or *Betula nana*. The water in the lake may have been too turbid for plant and animal life. Radiocarbon dating of a sample of *Dryas octopetala* and *Betula nana* remains from zone 1 yielded an age of *c.* 14 300 cal. years BP (Table 1).

Zone 2 (11 000–12 000 cal. years BP)

This zone shows rapid changes. There are two layers with shells of the small bivalve *Pisidium* spp. and freshwater gastropods: *Valvata* spp. (mainly *Valvata cristata* but also a few *Valvata piscinalis*), *Ampullaceana balthica* (syn. *Lymnaea peregra*), *Bathyomphalus contortus* (syn. *Anisus contortus*), *Anisus vortex*, *Anisus leucostoma*, *Gyraulus crista* (syn. *Armiger crista*) and *Hippeutis complanatus*. The presence of these species indicates small water bodies such as fen pools or peaty pools. Otherwise, zone 2 is characterised by remains of the bryophytes *Calliergon giganteum*, *Calliergon stramineum* and *Calliergon trifarium*, by fruits of *Carex rostrata* and *Carex paniculata* and by seeds of *Menyanthes trifoliata*. The zone contains a fairly rich fauna of terrestrial hygrophilous gastropods that live in wet, swampy habitats, such as *Succinea*/*Oxyloma* and *Euconulus* cf. *alderi* as well as the semiterrestrial amphibious *Galba truncatula* (syn. *Lymnaea truncatula*). Furthermore, a single shell of *Pupilla muscorum* was found; this species usually lives in more dry places, but it can also live in calcareous wetlands.

A single sample from zone 2 contained numerous seeds of *Menyanthes trifoliata*; the seeds were dated yielding a median probability age of 11 192 cal. years BP (Table 1), which may correspond to the Preboreal oscillation – a short period of high δ^{18}O values around 11 220 cal. years BP seen in the Greenland ice cores (Rasmussen *et al.* 2007). This may have been a short-lived phase with wet conditions in Vasby Mose. The Early Holocene was characterised by several short-term climatic fluctuations in north-west Europe (e.g. Bos *et al*. 2007), and these climate fluctuations would probably affect water levels, temperature and vegetation in Vasby Mose. The local environment alternated between a shallow lake and a bryophyte-rich fen.

Zone 3 (10 400–11 000 cal. years BP)

In this zone there are many remains of the reed plant *Phragmites australis* and shells of terrestrial gastropods, mostly of the same species as in zone 2 (*Galba truncatula*, *Succinea*/*Oxyloma*, *Vertigo* sp. and *Euconulus* cf. *alderi*) that indicate wet habitats. Moreover, the sediment contains shells of the gastropods *Zonitoides nitidus*, *Cochlicopa* sp. and *Vallonia pulchella*, which indicate somewhat more dry conditions than in zone 2. The area was likely covered by reed beds. *Phragmites australis* can spread by vegetative propagation and the species can form dense populations where other plants have difficulties gaining a foothold.

Zone 4 (9300–10 400 cal. years BP)

This zone begins with a long interval with the bryophyte *Tomenthymnum nitens*, which is a peat-forming species. In the upper part of the zone the only identified plant remains are seeds of *Menyanthes trifoliata*. This zone comprises a single sample with shells of fresh-water gastropods (*Valvata cristata* and *Ampullaceana balthica*), as well as shells of ostracods. The remains of these invertebrates show that there was a brief period of open water; in the same sample, there are also many seeds of *Menyanthes trifoliata*. The sample is dated to *c.* 10 070 cal. years BP; it may correspond to an accumulation anomaly observed in Greenland ice cores at around 10 020 cal. years BP (Rasmussen *et al.* (2007). There is a shift in the fauna of gastropods: *Galba truncatula*, *Succinea*/*Oxyloma* and *Vertigo* sp. are rarer than in Zone 3, whereas *Zonitoides nitidus* is more common. This shift may reflect that the vegetation changes in character from reed beds to a bryophyte-rich fen. In the upper part of zone 4, there are only few plant remains and the sediment consists almost entirely of sandy tufa. The sediment was soft and easy to the sample with the Russian corer.

Zone 5 (7700–9300 cal. years BP)

Plant remains in this zone are dominated by fruits and vegetative remains of *Cladium mariscus*. In the upper part there are remnants of the bryophyte *Scorpidium scorpioides*; in the lower part, there are some seeds of *Menyanthes trifoliata*. Both *Cladium mariscus* and *Scorpidium scorpioides* are calciphilous species.

Two samples contained frequent remains of the bryophyte *Meesia triquetra*, which is a circumpolar boreo-arctic peat-forming moss growing in fens, for example, in calcareous fens which are periodically flooded. Remains of the species are frequent in Holocene deposits from Europe (Dickson 1973). Live specimens of the species have been recorded from two sites in eastern Denmark, but it is many years ago and the species is probably now extinct in Denmark (Den danske Rødliste 2023). Remains of *Meesia triquetra* in Holocene deposits have previously been reported from two sites in northern Sjælland (Odgaard 1988). One of the finds is dated to the Mid-Holocene, whereas the age of the other find is more uncertain – it is probably of Early or Mid-Holocene age. The species has been regarded as a glacial relict, but its former occurrence in deposits from the Mid-Holocene, when temperatures were higher than today, indicates that the decline and disappearance of the species from Denmark was caused by drainage and human alteration of the sites rather than climatic changes.

The mollusc fauna in zone 5 is represented by *Pisidium* sp., the gastropod *Bithynia tentaculata* and more sparingly *Valvata cristata*, *Valvata piscinalis* and *Ampullaceana balthica*. These species indicate that there was open water, at least periodically. There are also many shells of the semiterrestrial gastropods *Galba truncatula* and *Succinea/Oxyloma* (in the upper part of the zone), as well as the terrestrial *Vertigo* sp. and *Euconulus* cf. *alderi*. The sediments in this zone were mainly deposited in reed beds with *Cladium mariscus*, but for a short period, the vegetation was a brown-moss fen with *Meesia triquetra* and *Scorpidium scorpioides*. In the upper part, there is evidence for both moss-rich fen vegetation with *Scorpidium scorpioides* and reed bed vegetation with *Cladium mariscus*.

It is striking that *Bithynia tentaculata* first appears in zone 5. This species is today one of the most common and widespread freshwater gastropods in Denmark, but apparently the species immigrated relatively late to Denmark. The species is missing or very rare in Lateglacial and earliest Holocene sediments in Denmark (Johansen 1904). However, it is also possible that the local environment did not suite this species that is characteristic of permanent water bodies.

Zone 5 begins with a distinct *Bithynia tentaculata* peak, which is dated to 9340 cal. years BP, according to the age-depth model. This peak, which indicate a wet period in Vasby Mose may correspond to the cold 9.3 ka event recorded in the Greenland ice cores. The event is dated to *c.* 9250 cal. years BP in the ice cores (Rasmussen *et al.* 2007).

Zone 6 (7400–7700 cal. years BP)

This zone resembles zone 5; it is dominated by *Cladium mariscus* and *Scorpidium scorpioides*. The zone is separated out because shells of freshwater molluscs are missing, indicating more dry conditions in Vasby Mose. A sample of *Cladium mariscus* remains was radiocarbon dated to *c.* 7500 cal. years BP (Table 1). This corresponds to the Mid-Holocene, which was the warmest period in Denmark after the last deglaciation. The Mid-Holocene was characterised by summer temperatures a few degrees higher than today (Brown *et al.* 2011).

Cladium mariscus is today a rare plant in Denmark, but remains of the species are common in Early and Mid-Holocene deposits. The species is warmth-demanding, and the relatively high summer temperatures have undoubtedly favoured it. It is also a calciphilous plant, and it has undoubtedly lost ground in Denmark as leaching of the soils progressed during the Holocene. Also, oligotrophication of wetlands may have contributed to its decline.

Zone 7 (7000–7400 cal. years BP)

In this zone there are remains of *Scorpidium scorpioides* and *Pisidium* spp. – especially in the upper part of the zone, indicating that flooding became more frequent than in zone 6. Of gastropods from wet or moist soil can be mentioned common shells of *Galba truncatula*, *Euconolus* cf. *alderi* and rare shells of *Succinea/Oxyloma*, *Zonitoides nitidus* and *Vallonia pulchella*. The sediment was probably deposited in a wet fen that was periodically flooded.

Zone 8 (6800–7000 cal. years BP)

In this zone there were egg capsules of earthworms. A few shells of *Vertigo* sp. and also individual seeds of plants that often occur as weeds such as *Cerastium* sp., *Chenopodium* sp. and *Rumex* sp. as well as plants that grow in moist areas such as *Filipendula ulmaria*. In addition, there are remains of plants that have hard fruit stones that may be preserved even in decomposed peat such as *Rubus idaeus* and *Sambubus nigra*. The sediment consists of decomposed, soil-like peat. The absence of sediments younger than about 6800 cal. years BP indicates that peat was excavated in the area.

Further discussion

The sediments in Vasby Mose and their content of plant and animal remains tell a story of dramatic shifts in environment and climate. The layer of clay in the basal part of the succession was deposited during the Lateglacial and the remains of terrestrial plants indicate a tree-less tundra-like landscape with Arctic dwarf shrub heaths. Sedimentation continued in the Early and Mid-Holocene with deposition of peat and tufa.

One may wonder why the sediments in Vasby Mose are so rich in calcium carbonate. However, the bedrock in the area consists of Danian limestone, and the bedrock surface is located close to the terrain surface. Just a few kilometres north of Vasby Mose there are old pits where one can see that Danian limestone is found near the terrain surface. The local clayey till and glaciofluvial sand are also rich in carbonate. As the ice melted away from the area during the last deglaciation it probably left a landscape with light-coloured, carbonate-rich soils.

The lower part of the succession in Vasby Mose mainly consists of Lateglacial clay, which is found in many lakes in Denmark. A dated sample of plant remains gave the oldest age of Lateglacial plant remains yet reported from Sjælland (Table 2; Fig. 4). However, sediment cores with Lateglacial remains of terrestrial plants collected close to Sjælland have provided somewhat older ages of plant remains. The oldest age obtained so far comes from Køge Bugt, from where a sample of *Salix polaris* leaves gave an age of *c.* 15 400 cal. years BP. A bone of a *Pusa hispida* (ringed seal) from North-East Sjælland gave an older age of *c.* 16 900 cal. years BP. From Jylland, which was deglaciated earlier than Sjælland, dating of plant remains or shells of marine bivalves yielded still older ages, up to *c.* 17 600 cal. years BP (Fig. 4). Dating of bones or antlers of *Rangifer tarandus* (reindeer) gave ages somewhat younger than ages of plant remains (Table 2; Aaris-Sørensen *et al.* 2007).

In the Early and early Mid-Holocene, alternating layers of peat and tufa were deposited in Vasby Mose, indicating an alkaline spring-fed fen. This type of wetland was probably more common in Denmark in the Early and Mid-Holocene than in the Late Holocene. Upwelling groundwater rich in dissolved calcium carbonate led to formation of tufa. Several authors have concluded that deposition of calcareous tufa culminated in the Mid-Holocene (e.g. Pietruczuk *et al.* 2018) but in Vasby Mose tufa deposition began already in the Early Holocene. However, tufa was replaced by

Table 2. Oldest radiocarbon ages of Lateglacial plant or animal remains from Denmark

Site	Species	Lab. no	Age (^{14}C years BP) [1]	Cal. age (years BP) [2]	Reference
Kattegat	*Elphidium clavatum*	ETH-62243	15145 ± 145	17696	1
N. Jylland	Marine shells	K-2670	14650 ± 190	17582	2
NE Sjælland	*Pusa hispida*	Ua-1023	14510 ± 250	16913	3
S. Jylland	Twigs	Ua-19217	14180 ± 165	17249	4
Kattegat	*Hiatella arctica*	AAR-4526	14000 ± 120	16279	5
Arkona Basin	*B. nana, S. polaris*	AAR-2637	12700 ± 110	15132	6
C. Jylland	*S. pol, Dyas, Sax, Dist.* [3]	AAR-7443	12590 ± 80	14961	7
S. Jylland	*Rangifer tarandus*	AAR-906	12520 ± 190	14717	8
Faxe Bugt	*Salix polaris*	AAR-1313	12440 ± 150	14605	9
Mors	*Salix polaris*	Ua-16600	12420 ± 120	14572	10
Storebælt	*Betula nana*	Beta-481723	12310 ± 40	14256	11
Vasby Mose	*D. octopetala, B. nana*	LuS-17299	12300 ± 70	14287	TS
Falster	*Dryas octopetala*	AAR-15014	12226 ± 44	14134	12
Køge Bugt	*Salix polaris*	Ua-57758	12863 ± 47	15373	13
Køge Bugt	*Rangifer tarandus*	AAR-1036	12140 ± 110	14047	8

[1] Radiocarbon ages are reported in conventional radiocarbon years BP (before present = 1950; Stuiver & Polach (1977)).
[2] Calibration to calendar years BP (median probability ages) using IntCal20 and Marine20 (Reimer *et al.* 2020; Heaton *et al.* 2020).
[3] *Salix polaris, Dryas octopetala, Saxifraga oppositifolia, Distichium* sp.
References 1: Hyttinen *et al.* 2021, 2: Knudsen 1978, 3: Lagerlund & Houmark-Nielsen 1993, 4: Mortensen *et al.* 2011 5: Jensen *et al.* 2002, 6: Jensen *et al.* 1997, 7: Bennike *et al.* 2004, 8: Aaris-Sørensen *et al.* 2007, 9: Bennike & Jensen 1995, 10: Korsager *et al.* 2003, 11: Bennike *et al.* 2019, 12: Mortensen *et al.* 2014, 13: Bennike unpublished data, TS: this study.

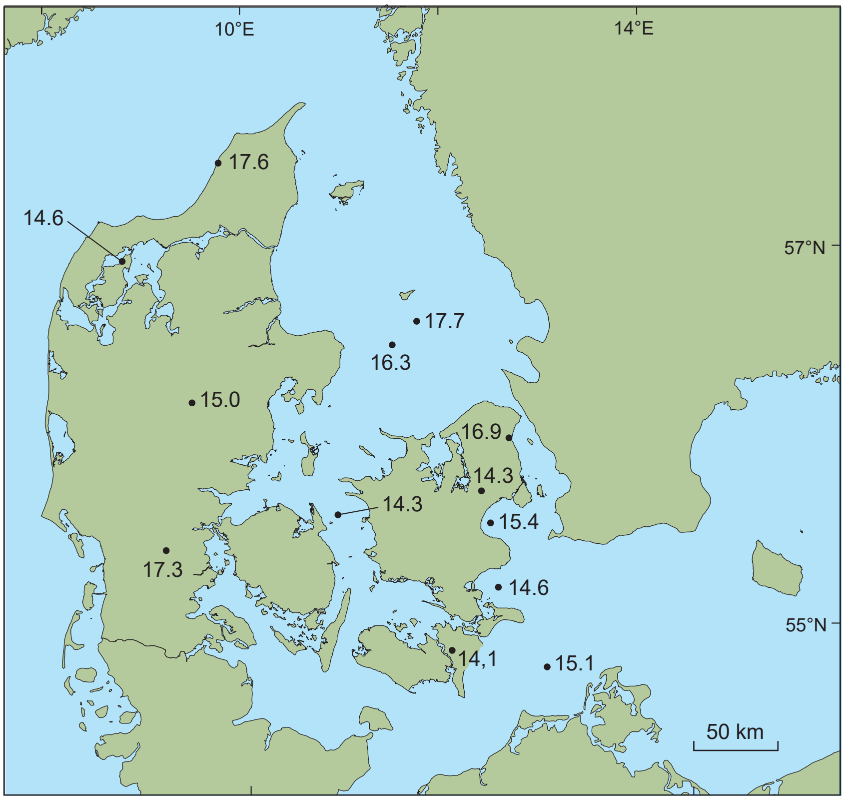

Fig. 4. Map of Denmark showing oldest Lateglacial radiocarbon ages in calibrated kilo-years BP.

a *Menyanthes*-rich peat during the cold Preboreal oscillation. The presence of aquatic molluscs shows that the fen was periodically flooded. Finally, the area turned into a peat-forming fen, probably because of sediment accumulation, infilling and overgrowing of the basin. We suggest that younger peat was once present but has been removed by peat digging. The youngest age from the succession was *c.* 7500 cal. years BP.

In the field we were in doubt about how to classify the Holocene calcareous sediments. At first, we believed it to be calcareous gyttja, but the calcareous layers from Vasby Mose usually do not contain remains of water plants or aquatic invertebrates. Therefore, the calcareous layers cannot be classified as gyttja or lake marl. Instead, the layers contain remains of plants and animals that live in calcareous fens, marshes or reed swamps and should be classified as tufa, which can be difficult to distinguish from calcareous gyttja (Milthers 1935). Peat-like or gyttja-like layers may alternate with tufa and all transitions between carbonate-free peat and tufa without organic remains can be found (Jessen 1922). It should also be noted that the sediments are much more sandy and gravelly than calcareous gyttja.

The results of this study can be compared with studies of tufa deposits in Fyledalen, Skåne, southern Sweden. However, the tufa in Fyledalen was deposited in an oxidising environment that caused problems with analyses of non-calcareous organic remains, which had decomposed or were strongly corroded (Gedda *et al.* 1999; Gedda 2006). The molluscan faunas in Fyledalen also indicated drier habitats than the fauna from Vasby Mose. The occurrences in Fyledalen are relatively small spring-fed deposits, whereas the deposits in Vasby Mose cover a large area. Other studies of tufa deposits in the UK and the USA show similar results to the results from Vasby Mose (e.g., Meyrick & Preece 2001; Davies & Griffiths 2005; Meyrick & Karrow 2007).

Modern palaeoecological studies of alkaline spring-fed fens are fairly rare. Gałka *et al.* (2021) investigated a Holocene calcareous spring-fed fen in Latvia. The fossil assemblages in Latvia are somewhat similar to the assemblages from Vasby Mose, but the deposit in Latvia was more dominated by peat. Dobrowolski *et al.* (2016, 2019), Pietruczuk *et al.* (2018) and Apolinarska *et al.* (2022) have conducted detailed studies of the development of spring-fed fens in Poland and Frodlová & Horsák (2021) studied a tufa record from Slovakia.

The studies of the sediments from Vasby Mose show that there have been major changes in the local environment, long before man intervened. The mires, fens and meadows, which today are found in Vasby Mose, are a result of peat cutting and grazing. The present flora of calciphilous plants is probably dependent on peat removal exposing the old tufa layers.

Conclusions

The succession from Vasby Mose comprise Lateglacial clay with remains of the dwarf shrubs *Dryas octopetala* and *Betula nana*, which were dated to *c.* 14.3 cal. ka BP. This is so far the oldest dated Lateglacial plant remains from Sjælland, but older Lateglacial plant and animal remains have been recorded from other sites in Denmark, especially in Jylland. Alternating layers of tufa and peat accumulated in Vasby Mose during the period from *c.* 11 200 to *c.* 7500 cal. ka BP, in an alkaline spring-fed fen that was periodically flooded. The flora in the Holocene sediments comprises the calciphilous bryophyte *Meesia triquetra*, which probably does not grow in Denmark anymore. The Holocene mollusc fauna comprises aquatic, semiterrestrial and terrestrial species.

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