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Complete List of Authors:	Bennike, Ole; Geological Survey of Denmark and Greenland, Hedenäs, Lars; Naturhistoriska riksmuseet High, Kirsty; University of York Korshøj, Joakim; GEO Lemdahl, Geoffrey; Linnaeus University, School of Natural Sciences Penkman, Kirsty; University of York Preece, Richard; University of Cambridge, Department of Zoology Rosenlund, Knud; Zoological Museum Viehberg, Finn; University of Cologne, Institut für Umweltgeologie
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New interglacial deposits from Copenhagen, Denmark: Marine Isotope Stage 7

OLE BENNIKE, LARS HEDENÄS, KIRSTY HIGH, JOAKIM STIEL KORSHØJ, GEOFFREY LEMDAHL, KIRSTY PENKMAN, RICHARD C. PREECE, KNUD ROSENLUND AND FINN A. VIEHBERG

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During a pre-site survey and construction of a new metro route and station in Copenhagen, fossiliferous organic-rich sediments were encountered. This paper reports on multidisciplinary investigations of these organic sediments, which occurred beneath a sediment succession with of a lower till, glaciofluvial sand and gravel, an upper till and glaciofluvial sand. The organic sediments were underlain by glaciofluvial sand and gravel. The organic-rich sediments, which were up to 0.5 m thick, accumulated in a low-energy environment, possibly an oxbow lake. They were rich in plant fossils, which included warmth-demanding trees and other species, such as *Najas minor*, indicating slightly higher summer temperatures than at present. Freshwater shells were also frequent. *Bithynia* opercula allowed the sediments to be put into an aminostratigraphical framework. The amino acid racemisation (AAR) ratios indicate that the organic sediments formed during Marine Isotope Stage 7 (MIS 7), which is consistent with optically luminescence dating that gave ages of 206 and 248 ka from the underlying minerogenic deposit. The assemblages from Trianglen are similar to interglacial deposits from the former Free Port (1.4 km away) in Copenhagen, except that *Corbicula* and *Pisidium clessini* were not found at Trianglen. The presence of these bivalves at the Free Port and the ostracod *Scottia tumida* at Triangles indicates a pre-Eemian age. AAR data from archived *Bithynia* opercula from the Free Port were almost identical to those from Trianglen, indicating that the two sites are contemporary. We suggest the Trianglen interglacial be used as a local name for the MIS 7 interglacial deposits in Copenhagen. MIS 7 deposits have rarely been documented from the region, but MIS 7 deposits may have been mistaken for other ages. The use of amino acid racemization ratios in *Bithynia* opercula has a great potential for correlation of interglacial non-marine deposits in mainland northern Europe.

Ole Bennike (obe@geus.dk), Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark; Joakim Stiel Korshøj, GEO, Maglebjergvej 1, DK-2800 Kgs. Lyngby, Denmark; Lars Hedenäs, Swedish Museum of Natural History, Box 50007, S-104 05 Stockholm, Sweden; Kirsty High and Kirsty Penkman, Department of Chemistry, University of York, York, YO10 5DD, UK, Geoffrey Lemdahl, Linnaeus University, SE-391 82, Kalmar, Sweden; Richard C. Preece, Department of Zoology, University of Cambridge, Downing Street, Cambridge CB2 3EJ, UK; Knud Rosenlund, Zoological Museum, Universitetsparken 15, DK-2100 Copenhagen Ø, Denmark; Finn Viehberg, Institute of Geology and Mineralogy, University of Cologne, Zülpicher Str. 49A, 50674 Cologne, Germany

Interglacial deposits occur commonly in Denmark, but most are found in the western parts of the country where erosion by glaciers and meltwater was less intense. Only a few interglacial deposits have been reported from Zealand (Fig. 1). Most of these are marine deposits that have been referred to the Eemian or the Holsteinian, but a few non-marine deposits have also been reported. Interglacial organic sediments were found during excavations for the former Free Port in Copenhagen between 1891 and 1893 (Rosenkjær 1893, 1896). They occurred as large clasts and floes near the base of a till, which was deposited from the north-east (Milthers 1935). Macroscopic plant and animal remains were studied by Rostrup (1895), Sarauw (1897), Johansen (1904) and Hartz (1909) and five samples were analysed for pollen by Jessen (1927). The assemblage included warmth-demanding plants such as *Quercus*, *Tilia*, *Corylus avellana*, *Alnus glutinosa*, *Cornus sanguinea* and *Nymphoides peltata* (Table 1), demonstrating that the fossils came from a temperate stage. Sarauw (1897) suggested that the Free Port deposits should be correlated with the Middle Pleistocene Cromer Forest Bed in East Anglia (England), whereas Johansen (1904) and Milthers (1922) suggested a pre-glacial rather than interglacial age. Jessen (1927) suggested that the Free Port deposit belonged to the oldest Danish interglacial (out of two recognised at that time), a view followed by Milthers (1935). The molluscan fauna from the Free Port includes the bivalve *Corbicula fluminalis* and *Pisidium clessini*. *Corbicula fluminalis* is an extant species, which is unknown from deposits in North-West Europe younger than MIS 7. *Pisidium clessini* is extinct with the last occurrences in MIS 7 deposits; hence these species indicate a pre-Eemian age.

Other non-marine interglacial occurrences on Zealand have been reported from Måløv to the north-west of Copenhagen (Bennike *et al.* 2011; Middle Pleistocene) and from Førslevgaard in the southern part of the island (Johansen 1904). The Førslevgaard fauna includes *Corbicula fluminalis*, *Pisidium clessini* and gastropod *Belgrandia marginata*. The latter species is unknown from other Quaternary deposits in Denmark, but is common in other interglacial deposits in north-western Europe (Preece 1990). Currently, this species is found in France and Spain.

In addition to the interglacial deposit, reworked marine shells were found in the glaciofluvial gravel between two tills; the fauna included "*Tapes aureus* var. *eemiensis*", now *Polititapes aureus* (Gmelin, 1791), which indicated derivation from deposits of Eemian age (Madsen *et al.* 1908). The nearest *in situ* Eemian littoral deposit occurs at Ejby Bro, 45 km west of Copenhagen (Madsen 1968), so it is not surprising that reworked Eemian shells occur in the Copenhagen area. Interglacial peat and gyttja have also been reported from a locality 11.5 km south-east of the centre of Copenhagen (Jørgensen & Frederiksen 2002), but no information on the palaeoecology or age was provided.

Pleistocene interglacial deposits in Denmark have traditionally been referred to the Eemian, Holsteinian and Cromerian (local name Harreskovian; Andersen 1965), but an interglacial occurrence in eastern Jutland has been referred to a fourth interglacial stage, and correlated with Marine Isotope Stage (MIS) 11, although not with interglacial occurrences referred to the Holsteinian (Kuneš *et al.* 2013). However, the correlation and age of several Danish interglacial occurrences are unknown (Andersen 1967).

In other parts of north-western Europe it is becoming increasingly clear that the Pleistocene successions are much more complex than previously believed (e.g. Urban *et al.* 2011; Penkman *et al.* 2013). Interglacial successions in north-western Europe are characterised by climatic conditions similar to the Holocene (e.g. Jessen & Milthers 1928; Andersen 1965), whereas interstadial deposits contain remains of arctic or sub-arctic species (e.g. Bennike *et al.* 1994, 2014).

Prior to the construction of a new metro line in Copenhagen, drilling was undertaken to investigate the geology and the geotechnical properties of the subsurface along the line. Organic-rich sub-till deposits were encountered in a few reconnaissance cores, in particular at Trianglen, where a metro-station was planned. In 2014 excavations for the station were undertaken, allowing photography (Fig. 2) and sampling. The new site at Trianglen is located 1.4 km from the former Free Port in Copenhagen. Here we provide interpretation on the depositional environment of the site and show evidence that the organic sediments at Trianglen and the Free Port accumulated during MIS 7, the first realisation that such sediments occur in Denmark.

Setting

The bedrock geology of the Copenhagen area is dominated by limestone that belongs to the København Kalk Formation, a formal lithostratigraphical unit of Danian age (Stenestad 1976). In some areas the Lellinge Grønsand Formation of Selandian age occurs, and in western Copenhagen Maastrichtian chalk is found at the pre-Quaternary surface (Jakobsen *et al.* 2017). The surface of the pre-Quaternary bedrock usually occurs at depths of 5 to 13 m, but it is deeper in buried valleys (Jørgensen & Frederiksen 2002; Fig. 3). The interglacial deposit reported here occurs at the margin of one of these valleys.

The Pleistocene succession in Copenhagen usually consists of an older unit of glaciofluvial sand and gravel with numerous clasts of limestone and flint, a lower hard and compact till, a younger glaciofluvial unit dominated by sand with some gravel, an upper till and finally an uppermost glaciofluvial unit. The younger inter-till glaciofluvial unit has been dated by thermoluminescence to 22 ka (Frederiksen *et al.* 2002), which indicates that it was deposited just before the last glaciation of the region. Glaciotectonic features and glacial striae on boulders show that the lower till was deposited from the north-east, whereas till fabric analyses and glacial striae on boulders show that the upper till was deposited by a glacier from south-east or south-south-east (Frederiksen *et al.* 2002).

Material and methods

From core P07.112 only a single small sample was available for analysis, whereas large samples were available from the open sections. Five samples taken through the organic-rich layer were analysed, in addition to some large *ex situ* samples from unknown levels that were lying on the floor of the excavation. Most of the mollusc shells came from a thin shell-rich layer in one of these loose blocks. No difference in floral or faunal composition was apparent, and the samples were treated as one assemblage (Table 1). A total of about 25 kg was analysed. The samples were soaked in a NaOH solution at room temperature for two weeks and wet sieved on a 0.4 mm sieve. Small fractions of the samples were also sieved at 0.2 and 0.1 mm sieves. The residue was analysed using a dissecting microscope. The preservation of plant and animal remains was variable, some were well preserved, whereas others were fragmentary and worn. Some blocks contained the remains of larger shells, possibly unionids, preserved as small areas of white powder. A few ostracod valves were coated with post-mortem pyrite.

Two samples of sandy sediment were collected from a recently cleaned section below the organic-rich sediment by hammering plastic tubes into the sediment. The tubes were then dug out and capped to retain water and to exclude light. The samples were dated by optically stimulated luminescence using quartz, following the standard procedures at the Nordic Laboratory for Luminescence Dating at Risø (Clemmensen & Murray 2010; Table 2). We assume that the sediment was fully water saturated throughout its history.

Amino acid racemisation (AAR) analyses were undertaken on four individual *Bithynia tentaculata* opercula from Trianglen (NEaar 11622–11624, 11654; DTrBto1-4) and on three individual *Bithynia tentaculata* opercula from the Copenhagen Free Port (NEaar 9975–9977; DKoBto1-3; Table 3). The current technique of amino acid analysis developed for geochronological purposes (Penkman *et al*. 2008) combines a reverse-phase high-pressure liquid chromatography (RP-HPLC) method of analysis (Kaufman & Manley 1998) with the isolation of an 'intra-crystalline' fraction of amino acids by bleach treatment (Sykes *et al.* 1995). This combination results in the analysis of D/L values of multiple amino acids from the chemically protected (closed system) protein within the biomineral, thereby enabling both decreased sample sizes and increased reliability of the analysis. Amino acid data obtained from the intra-crystalline fraction of the calcitic *Bithynia* opercula indicate that this biomineral is a particularly robust repository for the original protein (Penkman *et al*. 2011, 2013) and therefore it was targeted in this study.

The DL ratios of aspartic acid/asparagine, glutamic acid/glutamine, serine, alanine and valine (D/L Asx, Glx, Ser, Ala, Val) as well as the [Ser]/[Ala] value were assessed to provide an overall estimate of intra-crystalline protein decomposition (IcPD). In a closed system, the amino acid ratios of the FAA and the THAA subsamples should be highly correlated, enabling the recognition of compromised samples (e.g. Preece & Penkman 2005). The D/L ratio of an amino acid will increase with increasing time, whilst the [Ser]/[Ala] value will decrease. Each amino acid racemises at different rates, and therefore is useful over different timescales. The D/L of Ser is less useful as a geochronological tool for interglacial samples, but is presented here as aberrant values are useful indications of contamination. The first analysis of 9977bF showed low Glx concentrations and a high Glx D/L; the second analysis yielded more consistent data and the first replicate is therefore rejected.

The extent of protein decomposition in both the FAA and THAA increases with time, with increased levels of protein breakdown during warm stages and a decrease in the rates of degradation in cold stages. Over a small geographical area, it can be assumed that the integrated temperature histories are effectively the same. Given a similar temperature history, this then allows an aminostratigraphic framework for an area to be developed, plotting the FAA against the THAA data, with independent geochronology allowing these clusters to be correlated to marine oxygen isotope warm stages; such a framework has been developed for *Bithynia* opercula from England (Penkman *et al*. 2011, 2013).

Results and discussion

Lithostratigraphy

Descriptions of sediment cores from four sites from Trianglen document the lithostratigraphy (Fig. 4), which is similar to the general stratigraphy for the Copenhagen area (Frederiksen *et al.* 2002). The bedrock at Trianglen consists of limestone, which is overlain by sand and gravel rich in limestone and flint. The sediment is poorly sorted and mineralogically immature and interpreted as a glaciofluvial deposit. Two of the cores penetrated organic-rich sediments, which were described as peat in core P07.102 and gyttja in core P07.103. The frequent remains of freshwater organisms show that the sediments can be classified as a coarse-grained detritus gyttja. The organic layer contained a few fragments of compressed pine wood, similar to those observed in deposits at the Free Port. In two cores from Trianglen a hard till occurred above the gyttja. The open section we examined was located close to core P07.102, in the section the transition from gyttja to till was gradual, and small thrusts were observed at the transition. Ice movement was from the NE, consistent with the direction reported from other sites in Copenhagen. The lower till is overlain by glaciofluvial sand and gravel, an upper till, glaciofluvial sand (only seen in one core) and finally fill.

Core P07.112 from a site ~250 m south of Trianglen contains a unit of clay above the bedrock, but such a unit was not encountered at Trianglen (Fig. 4). Apart from that, the lithostratigraphy in core P07.112 is similar to that at Trianglen, with an organic-rich layer at ~10 m below sea level.

Luminescence dating, amino acid analysis, biostratigraphy and age estimate

Two samples from the lower glaciofluvial unit were dated by optically luminescence dating to 206±21 and 248±24 ka BP using quartz grains (Table 2). Although 200 ka is old for a quartz date, for these two samples the dose rates are very small, and so the doses are both between 100 and 150

Gy. This is normally thought to be well within the dose range for reliable quartz ages (A.S. Murray, pers. comm., 2017).

Ala is the most useful amino acid for age discrimination over late Middle Pleistocene timescales, and there is no significant difference in racemisation between the two sites in Copenhagen. The aminostratigraphic framework for English sites provides a useful basis with which to compare the new data from the two Danish sites, Trianglen and Copenhagen Free Port (Fig. 5). It is clear that both Danish sites have amino acid values that are similar to, but slightly higher than, those for the same species from sites correlated with the English Ipswichian (and therefore the Eemian and MIS 5e; Bowen 1999), including Trafalgar Square, Bobbitshole, Coston, Shropham, Cropthorne New Inn, Eckington and Tattershall Castle (Penkman *et al*. 2011).

A direct correlation to the marine oxygen isotope stage record based on the amino acid data alone is premature. The temperature history of Copenhagen is likely to have been significantly different to that experienced in England. The mean annual air temperature was 8.4 °C in Copenhagen from 1982 to 2012, and 11.1 °C in London for the same time period, according to https://da.climate-data.org/. However, care needs to be taken with recent temperature data comparisons, as metropolitan heat islands mean that the temperatures recorded are not necessarily representative of the pre-city environment. However it is plausible that past temperatures may have been in general slightly higher in England (the region where the core aminostratigraphic framework has been developed) than in Copenhagen. This would result in lower effective diagenetic temperatures (e.g. Wehmiller *et al.* 2012) in Copenhagen, and therefore a slower rate of amino acid racemisation may be assumed for Copenhagen. Using this argument, the ratios from Copenhagen are more compatible with a MIS 7 age than a MIS 5e age.

The organic interglacial sediments from Copenhagen have yielded a few species of biostratigraphical importance. An extinct ostracod, *Scottia tumida*, present at Trianglen is only known from Early and Middle Pleistocene deposits elsewhere in Europe (Fig. 6; Diebel & Pietrzeniuk 1975; Fuhrmann 2013). Two species of mollusc present in sediments from the Free Port also suggest a pre-Eemian age. The first of these is the bivalve *Pisidium clessini*, called *P. astartoides* in early literature. In Britain this extinct species is known only from temperate stages and it has a large temporal range extending from the Early Pleistocene to the late Middle Pleistocene (MIS 7; Preece 1995, 2010). It is not known from the Last Interglacial in Britain, and appears to have a similar stratigraphical range elsewhere in north-western Europe (Meijer 1989). The second notable species discovered at the Free Port is the locally extinct *Corbicula fluminalis.*

This species still inhabits rivers in the Middle East but there is some uncertainty as to the true identity of European Pleistocene *Corbicula* and whether it is genuinely conspecific with *fluminalis* (see discussion in Meijer & Preece 2000). Whatever its true identity, *Corbicula* is an important biostratigraphical fossil in the European Pleistocene. Although it has been recorded from Last Interglacial sites in north-western Europe, most, if not all, of these records are now thought to represent shells reworked from older deposits (Meijer & Preece 2000). It appears to have been absent in north-western Europe during the Last Interglacial (Meijer & Preece 2000; Penkman *et al.* 2011, 2013), so its occurrence in sediments from the Free Port suggest a pre-Eemian age for them. The absence of *P. clessini* and *Corbicula* at Trianglen can probably be explained by facies differences, as low-energy conditions appear to have prevailed at Trianglen.

It appears that the organic interglacial deposits at Trianglen are broadly contemporary with those recovered from the excavations for the Copenhagen Free Port. Based on the OSL ages, the AAR results and the presence of *Pisidium clessini* and *Corbicula fluminalis*, we suggest that these interglacial deposits formed during MIS 7, which is dated to 243–191 ka (Lisiecki & Raymo 2005). Interglacial deposits referred to MIS 7 have been reported from a number of sites in Britain (Penkman *et al.* 2011, 2013) and have also been reported from a number of sites in mainland Europe. However, MIS 7 deposits have probably often been mistaken for other ages at many sites. None have previously been reported from Denmark. Therefore we suggest a local name, the Trianglen interglacial, for the deposits at Trianglen, at the former Free Port in Copenhagen and in core P07.112.

Palaeoecology

The results of the macrofossil analyses from Trianglen, core P07.112 and the Free Port are summarised in Table 1. Overall, the deposits are characterised by species-rich assemblages of vascular plants. Trees are represented by several taxa and there is no doubt that the area was forested. The flora comprises species usually found in climax forests such as *Quercus*, *Ulmus* and *Tilia* but the tree flora also comprises taxa that are typical of open forests and woodland such as *Pinus*, *Betula* and *Populus*. Open ground heliophilous shrubs and herbs are poorly represented but include *Cornus*, *Rubus*, *Empetrum*, *Chenopodium* and *Cerastium*. These plants may have been growing near the shore of rivers, perhaps on sand banks or in bogs. *Cenococcum geophilum* is a fungus that lives in soil.

Wetland plants are represented by many species and bogs and fens were probably widespread. *Alnus* probably grew in swampy areas, but reed beds may also have occupied large areas, perhaps on floodplains. The assemblage of wetland species shows large similarities to Holocene floras from Denmark (e.g. Bennike *et al.* 2004). *Urtica dioica* and *Ranunculus sceleratus* are often found in nutrient-rich areas with high nitrogen levels, which can result from animal faeces and urine, and the fauna may have included large herbivores.

Only a few fragments of bryophytes were encountered, which is a typical feature of interglacial assemblages from forested environments (Dickson 1973). All the identified bryophyte species are typical of base-rich to carbonate-rich environments (although not necessarily calcareous). *Drepanocladus aduncus* and *Oxyrrhynchium hians* are usually found in more or less nutrient-rich habitats. *Campylium stellatum* and *D. aduncus* are wetland species, *Cratoneuron filicinum* is mostly found in wetlands but is also frequent on wet soil or rocks (often springs or with seeping water), whereas *O. hians* grows on bare soil or sometimes on base-rich rocks in humid sites. *Oxyrrhynchium hians* is rare as a fossil in Denmark, but there is a single record from the Eemian (Odgaard 1981; originally recorded as *O. swartzii*).

The ground beetle *Dyschirius intermedius* lives on steep banks bordering the sea and lake margins, where it preys on *Bledius* spp. *Agonum obscurum* and *Ptrerostichus strenuus* are species characteristic of damp, shaded sites in deciduous or mixed forests, whereas *Trechus quadristriatus* is confined to open, sandy and dry ground with sparse vegetation.

Aquatic plants and animals are also well represented. Many of the species are typical of shallow water, such as ponds, lakes or streams with slow-flowing water and with mesotrophic to eutrophic, carbonate-rich waters. The molluscan assemblage from Trianglen was dominated by *Valvata piscinalis*, *Bithynia tentaculata* and *Pisidium*, mostly *P. casertanum*, *P. henslowanum* and *P. moitessierianum.* This assemblage is characteristic of moving water, a conclusion supported by the thickened shells of many of the *P. casertanum* (form *ponderosa*) and the fact that *Bithynia* opercula vastly outnumber *Bithynia* shells. The bivalves *Pisidium clessini*, *Pisidium amnicum* and *Corbicula fluminalis* recorded from the Free Port are fluvial species. *Bithynia troschelii* is new to the fossil fauna of Denmark, the species occurs in most interglacial stages before the Holocene in Britain and on the continent (Meijer 1990; Preece 2010). The Trianglen molluscan fauna is characterised by a rather low diversity. Indeed only a dozen or so species were recovered, far lower than most molluscan assemblages from full interglacial contexts – perhaps a consequence of the particular facies. The water scavenger beetle *Hydraena gracilis* and the riffle beetle *Limnius* *volkmari* are found in running water, such as streams and brooks. The pondweed *Potamogeton crispus* is characteristic of highly eutrophic waters and *Nymphoides peltata* is also found in eutrophic water. The pondweed *Stuckenia pectinata* is often found in brackish-water environments, but it also grows in ion-rich freshwater. The same applies to *Najas marina* and *Najas minor*. Both species were common in Denmark during the Early Holocene, but *N. marina* is now extremely rare and *N. minor* no longer lives in Denmark (Bennike *et al.* 2001). The presence of the charophytes *Chara* and *Nitella* also indicates carbonate-rich or ion-rich waters.

Nymphoides peltata was identified by Rostrup (1895) from the Free Port, but was not found at Trianglen. Rostrup (1895) and Hartz (1909) called it *Limnanthemum nymphæoides*. The plant has not been recorded from other interglacial or Holocene deposits in Denmark, but it has been re-introduced by man and thrives well.

Freshwater animals comprise the fish leach *Piscicola geometra* and some remains of fishes but only perch *Perca fluviatilis* could be identified to species. The bryozoans *Cristatella mucedo* and *Plumatella* sp. and caddis-fly larvae of the family Limnephilidae are common in lakes, ponds and streams. Only a few cladocerans were identified due to poor preservation; surprisingly no ephippia of *Daphnia* were found.

In the samples from the Free Port, several species of terrestrial gastropods were reported, but only one terrestrial species was recovered from Trianglen, a single slug plate (*Deroceras* sp.). However, several species of freshwater molluscs were recorded. Some of them may have lived in lakes or ponds in the area, but as mentioned above some of them indicate a fluvial environment. Overall, the aquatic species indicate a slow-flowing river or stream with abundant vegetation.

Finally, some small bone and teeth fragments of rodents were found in the samples from Trianglen, but the fragments could not be identified to species. Johansen (1904) and Hartz (1909) reported *Mus sylvaticus* from the Free Port based on an incisor that was identified by Herluf Winge. We refer this fossil to *Apodemus* sp. (Table 1).

The high diversity of plants and animals indicate that the remains were washed together from a fairly large area with different biotopes. This is consistent with the surface topography of the limestone where buried channels can be seen. It is also not surprising that several of the species indicate carbonate-rich soils because the bedrock is limestone, and the sand and gravel found below the organic-rich layer is rich in carbonate. Based on the fossil assemblages from Trianglen and the site location near buried valleys, we suggest that the organic-rich sediments at Trianglen were deposited in a low-energy fluvial environment or an oxbow lake. The occurrence of fluvial species in the deposits from the Free Port suggests a fluvial environment. The fossil assemblage from the small sample from core P07.112 provide little information on the depositional environment; but the occurrence of aquatic species may indicate a pond or small lake.

Tree taxa such as *Betula pubescens*, *Populus tremula* and *Pinus sylvestris* are typical of the pioneer phase of interglacial development – the protocratic stage, whereas taxa such as *Corylus*, *Quercus*, *Tilia* and *Ulmus* are characteristic elements of the mesocratic stage, corresponding to the thermal maximum with highest temperatures. *Picea* may occur in the mesocratic and oligocratic stages (Birks & Birks 2004). Unfortunately, the data from Copenhagen do not allow the reconstruction of changes in vegetation over time.

Palaeoclimate

Many of the species in these Copenhagen deposits are warmth-demanding. *Najas minor* is perhaps the most thermophilous with a modern northern geographical range limit in northern Germany. *Najas* spp. are annual plants that require warm summers for their seeds to develop. The summers appear to have been slightly warmer than at present. Most of the beetle species recovered have a predominantly southern distribution in Fennoscandia and Denmark today. *Dyschirius intermedius* is rare and local in northern Europe, but more common in central and southern Europe.

Two interglacial lake deposits have been reported from Zealand, at the Free Port of Copenhagen and at Førslevgaard in southern Zealand (Fig. 1). The molluscan fauna from these deposits includes the bivalve *Corbicula fluminalis* and *Pisidium clessini*, which indicates an Early or Middle Pleistocene age. The Førslevgaard fauna also includes the gastropod *Belgrandia marginata*, which is unknown from other Quaternary deposits in Denmark, but is common in other interglacial deposits in north-western Europe (Preece 1990). Currently, this species is found in France and Spain.

Comparison with other interglacial occurrences in the region

The Trianglen site, core P07.112 and the Free Port site occur in the same area and show marked similarities with respect to litho-, bio- and aminostratigraphy. Moreover, the interglacial occurrences are found at a depth of ~10 m below sea level. We believe that the organic deposits accumulated during the same interglacial stage.

As mentioned above, most interglacial deposits in Denmark are referred to the Eemian, the Holsteinian or the Harreskovian, but a lake deposit from eastern Jutland is referred to a fourth interglacial stage (Kuneš *et al.* 2013). The molluscan fauna from the sites in Copenhagen comprises species suggesting an age older than the Eemian. The Harreskovian pollen record is correlated with the Hunteburg interglacial in Germany and MIS 19, ~780 ka (Odgaard *et al.* 2016). Jessen (1927) reported 8, 20, 22, 30 and 32% *Tilia* pollen in five analysed samples from the Free Port; these values are far higher than found in the Harreskovian. The absence of *Carpinus* pollen in the samples from the Free Port may indicate that it does not correlate with the Holsteinian. The Holsteinian is usually correlated with marine oxygen isotope stage 11, ~400–360 ka, older than indicated by the OSL ages from Trianglen. It is interesting to note that the Trelde Klint interglacial is also characterised by an absence of *Carpinus* but has low *Tilia* percentage values and so probably does not correlate with the Trianglen interglacial. The Trelde Klint interglacial may correlate with MIS 11c based on OSL ages of 350±20 ka. The vegetational succession is different from other Danish sites referred to the Holsteinian, which may correlate with MIS 11a.

The Nematurella clay at Gudbjerg on Funen was described by Madsen & Nordmann (1901) and a pre-glacial age was suggested by Rosenkrantz (1942). The molluscan fauna at Gudbjerg, which also appears to represent a fluvial assemblage (Preece 1990), lacks *Corbicula* but includes the extinct gastropod *Tanousia stenostoma,* after which the clay is named *(Nematurella* = *Tanousia*). These components indicate an age much older than the assemblages from Copenhagen, and point to an age within the early part of the 'Cromerian Complex' (cf. Andersen 1967; Preece 2001).

Interglacial or warm stage deposits in Germany and Britain have been correlated with MIS 7 and 9. Open sections in large coal mines in the Schöningen area provide evidence for two interglacials within the Saalian complex (Urban 1997; Urban *et al.* 2011). The younger is the Schöningen Interglacial, which was dated by $^{230}Th/^{234}U$ to 180 and 227 ka, indicating a correlation with MIS 7 (Heijnis 1992). The Schöningen Interglacial has been correlated with the Wacken and Dömnitz Interglacials, the Belvédere Interglacial and the Lubavian Interglacial (de Beaulieu *et al.* 2001) and is characterised by abundant *Tilia* and almost complete absence of *Abies* and *Fagus*. Wacken and Dömnitz are often described as interstadial deposits rather than interglacials, based on the absence of thermophilous plants such as *Hedera* and *Buxus*. In Britain there are many MIS 7 deposits, but no formal type site has been proposed, although the name the Aveley Interglacial has been suggested (Schreve 2001).

Conclusions

We conclude that the organic-rich sediments at Trianglen were deposited in a low-energy fluvial environment, perhaps an oxbow lake. The water was rich in carbonate and nutrients. The depositional environment represented by sediments excavated at the Free Port appears to have been similar but perhaps characterised by slightly higher-energy conditions. This is reflected by the occurrence of several fluvial molluscs, such as *Pisidium clessini* and *Corbicula fluminalis*, not recovered at Trianglen. The occurrence of these species suggests a pre-Eemian age for the Free Port sediments, which in combination with amino acid analyses of *Bithynia* opercula from both sites, suggests a MIS 7 age for both. This conclusion is supported by OSL dating of two samples of sand from below the organic-rich layer at Trianglen. Summer temperatures appear to have been slightly higher than in Denmark at the present. The region was forested, but the forest included some light-demanding species such as *Betula*, *Populus* and *Pinus*.

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Figure captions

Fig. 1. Map of Denmark showing the location of interglacial localities on Zealand mentioned in the text. The new occurrence at Trianglen is marked by a star.

Fig. 2. Photographs of the excavation at Trianglen in Copenhagen. The excavator is around 20 m below the terrain surface. The following units are seen: Light grey glaciofluvial gravel with a sharp upper boundary, brownish-black organic-rich unit with a gradational upper boundary, and a hard till. The arrows point to the organic-rich unit.

Fig. 3. Map of the area north of central Copenhagen, showing the elevation of the surface of the København Kalk Formation. Blue = low elevation; yellow = high elevation. The dashed line shows the track of the new metro line that is under construction. The black dots show the location of sites discussed in the text.

Fig. 4. Lithological logs of the cores from Copenhagen. The core names in the geotechnical reports are P07.112, P07.101, P07.100, P07.103 and P07.102. The geographical coordinates are 55°41'42" N, 12°34'42" E (core P07.112) and ~55°41'57" N, 12°34'32" E (the Trianglen cores). Ice movement directions and the 22 ka age are from the literature (see the text). Star = macrofossil samples discussed in this paper.

Fig. 5. Total hydrolysable amino acids (THAA) versus Free (FAA) D/L values of Asx, Glx, Ala and Val from bleached *Bithynia tentaculata* opercula from Trianglen and the Copenhagen Free Port compared with opercula from sites in England correlated with MIS 5e (yellow), MIS 7 (green), MIS 9 (blue) and MIS 11 (purple). The data are consistent with a late Middle Pleistocene age, but the different temperature history between England and Copenhagen means that no direct correlation can be made at this stage based on amino acid data alone.

Fig. 6. Occurrences of the extinct ostracod species *Scottia tumida* in Europe according to Kempf (1971), Bennike *et al.* (2011) and this study.

Table 1. Remains of plants and animals from interglacial deposits from Copenhagen, Denmark. Some synonyms are listed in parentheses.

	Trianglen	Core 112	Free Port[1]
Plants			
Terrestrial			
Pinus sylvestris L.	x	x	x
Picea abies (L.) H. Karst	–	–	x
Betula pubescens Ehrh.	x	–	x
Quercus sp.	–	–	x
Ulmus sp.	x	–	p
Tilia sp.	–	–	x
Fraxinus sp.	–		p
Corylus avellana L.	–	–	x
Populus tremula L.	x	–	–
Cornus sanguinea L.	–	–	x
Salix sp.	x	–	–
Rubus idaeus L.	–	x	x
Empetrum nigrum L.	x	–	–
Chenopodium sp.	x	–	–
Cerastium sp.	x	–	–
Cenococcum geophilum Fr.	x	–	–
Wetland			
Alnus glutinosa (L.) Gaertn.	x	x	x
Typha sp.	x	–	x
Juncus sp.	x	–	–
Phragmites australis (Cav.) Trin. ex Steud.	x	–	–
Schoenoplectus lacustris (L.) Palla	x	–	–
Schoenoplectus sp. (*Scirpus* sp.)	–	–	x
Carex rostrata Stokes	x	–	–
Carex sp.	x	x	x
Eriophorum sp.	–	–	x
Alisma plantago-aquatica L.	x	–	–
Filipendula ulmaria (L.) Maxim.	x	–	x
Thalictrum flavum L.	x	–	–
Eupatorium cannabinum L.	–	–	x
Ranunculus sceleratus L.	x	–	–
Ranunculus flammula L.	x	–	–
Ranunculus repens L.	x	–	–
Rumex maritimus L.	x	–	–
Solanum dulchamara L.	x	–	–
Montia fontana L.	x	–	–
Lycopus europaeus L.	x	–	–
Urtica dioica L.	x	x	–
Viola cf. *palustris* L.	–	–	x
Cirsium sp.	x	–	x

Polypodiaceae[2]	x	x	x
Campylium stellatum (Hedw.) C.E.O. Jensen	x	–	–
Cratoneuron filicinum (Hedw.) Spruce	x	–	–
Drepanocladus aduncus (Hedw.) Warnst.	x	–	–
Oxyrrhynchium hians (Hedw.) Loeske	x	–	–
Sphagnum sp.	x	–	–
Aquatic			
Menyanthes trifoliata L.	–	x	–
Potamogeton gramineus L.	x	–	–
Potamogeton perfoliatus L.	x	–	–
Potamogeton obtusifolius Mert. & W.D.J. Koch	x	–	–
Potamogeton alpinus Balb.	x	–	–
Potamogeton crispus L.	x	–	–
Potamogeton pusillus L.	x	–	–
Stuckenia pectinata (L.) Börner (*P. pectinatus*)	x	–	–
Potamogeton sp.	x	–	x
Nymphaea sp.	x	x	x
Nuphar sp.	x	–	x
Nymphoides peltata (S.G. Gmel.) Kuntze	–	–	x
Hippuris vulgaris L.	x	–	x
Myriophyllum spicatum L.	x	x	–
Sparganium erectum L.	x	–	x
Ceratophyllum sp.	–	–	x
Najas marina L.	x	–	–
Najas minor All.	x	–	–
Zannichellia palustris L.	x	–	–
Ranunculus sect. *Batrachium* sp.	x	x	x
Chara sp.	x	–	–
Nitella sp.	x	–	–
Animals			
Ectoprocta (freshwater bryozoans)			
Cristatella mucedo Cuvier, 1798	x	–	–
Plumatella sp.	–	x	–
Annelida (worms and leeches)			
Lumbricidae indet.	x	–	–
Piscicola geometra (Linnaeus, 1761)	x	–	–
Erpobdella sp.	x	–	–
Crustacea, Branchiopoda			
Chydorus cf. *sphaericus* (O.F. Müller, 1776)	–	x	–
Alona sp.	x	–	–
Leydigia sp.	x	x	–
Crustacea, Ostracoda			

Scottia tumida (Jones, 1850)	x	–	–
Insecta, Coleoptera (beetles)			
Dyschirius intermedius Putzeys, 1846	x	–	–
Trechus quadristriatus (Schrank, 1781)	x	–	–
Agonum obscurum (Herbst, 1784)	x	–	–
Pterostichus strenuus (Panzer, 1796)	x	–	–
Limnius volkmari (Panzer, 1793)	x	–	–
Bledius sp.	x	–	–
Otiorhynchus sp.	x	–	–
Hydraena gracilis Germar, 1824	x	–	–
Megaloptera (alderfies)			
Sialis sp.	–	–	–
Trichoptera (caddis-flies)			
Limnephilidae indet.	x	–	–
Diptera (flies)			
Cyclorrhapha indet.	x	–	–
Chironomidae indet.	x	x	–
Oribatida (mites)			
Oribatida indet.	x	–	–
Mollusca (molluscs)			
Terrestrial			
Deroceras sp.	x	–	–
Clausilia sp.	–	–	x
Fruticicola fruticum (O.F. Müller, 1774)	–	–	x
Zonitoides nitidus (O.F. Müller, 1774)	–	–	x
Aquatic			
Valvata cristata O.F. Müller, 1774	–	–	x
Valvata piscinalis (O.F. Müller, 1774)	x	–	x
Gyraulus crista (Linnaeus, 1758)	x	–	–
Radix balthica (Linnaeus, 1758; *L. peregra*)	–	–	x
Lymnaea stagnalis (Linnaeus, 1758)	x	–	x
Bithynia leachi (Sheppard, 1823)[3]	–	–	x
Bithynia troschelii (Paasch, 1842)	x	–	?
Bithynia tentaculata (Linnaeus, 1758)	x	–	x
Planorbis planorbis (Linnaeus, 1758)	–	–	x
Pisidium supinum Schmidt, 1850	x	–	–
Pisidium moitessierianum Paladihe, 1866	x	–	–
Pisidium amnicum (O.F. Müller, 1774)	–	–	x
Pisidium clessini Neumayr, 1875 (*P. astartoides*)	–	–	x
Pisidium subtruncatum (Malm, 1855)	x	–	–
Pisidium henslowanum (Sheppard, 1825)	x	–	–
Pisidium casertanum (Poli, 1791)	x	–	x

Sphaerium corneum (Linnaeus, 1758)	–	–	x
Sphaerium sp.	x	–	–
Corbicula fluminalis (O.F. Müller, 1774)	–	–	x
Vertebrata (vertebrates)			
Perca fluviatilis (Linnaeus, 1758)	x	–	–
Cyprinidae	x	x	–
Apodemus sp.	–	–	x
Rodentia indet.	x	–	–

[1]Data from Hartz (1909)
[2]Probably *Thelypteris confluens* (Thunb.) C.V. Morton
[3]Could be *Bithynia troschelii*
p = pollen grains

Table 2. Optically stimulated luminescence age determinations from Trianglen, Copenhagen.

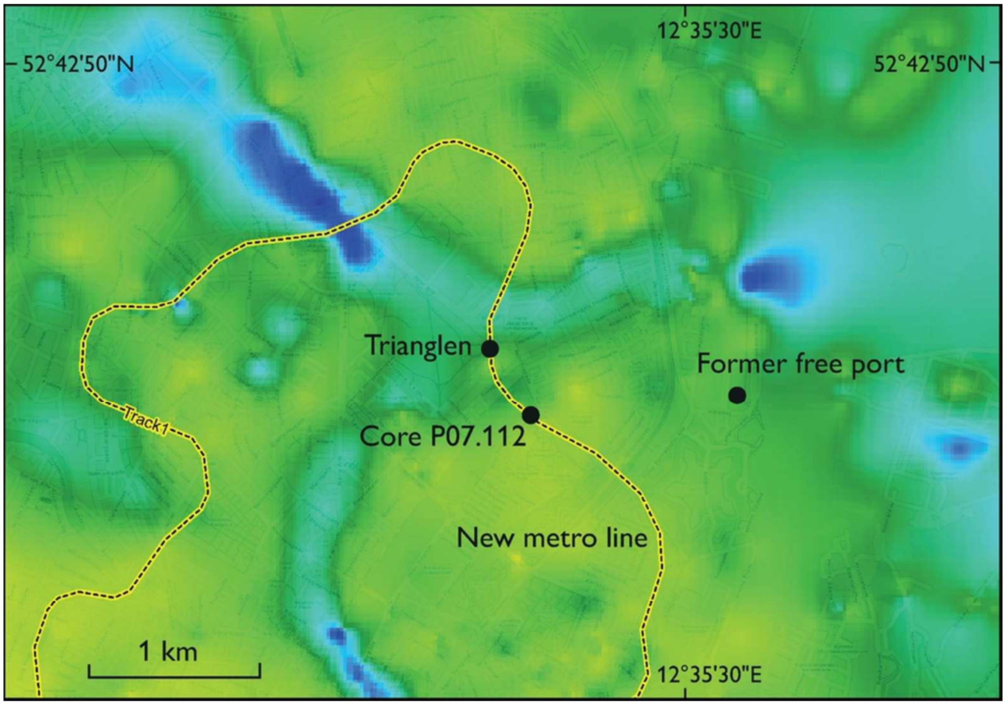
Risø no.	Depth (m)	Age (ka)	Dose (Gy)	(n)	Dose rate (Gy ka^{-1})	Water content (%)
15 05 01	20	206±21	118±9	16	0.57±0.04	21
15 05 02	20	248±24	125±8	18	0.50±0.04	25

Table 3. Amino acid ratios in opercula of *Bithynia tentaculata* from Trianglen and the Free Port, Copenhagen, Denmark. Error terms represent one standard deviation about the mean for the duplicate analyses for an individual sample. F = free amino acid fraction; H = total hydrolysable fraction; ND = not detectable. Each sample was bleached.

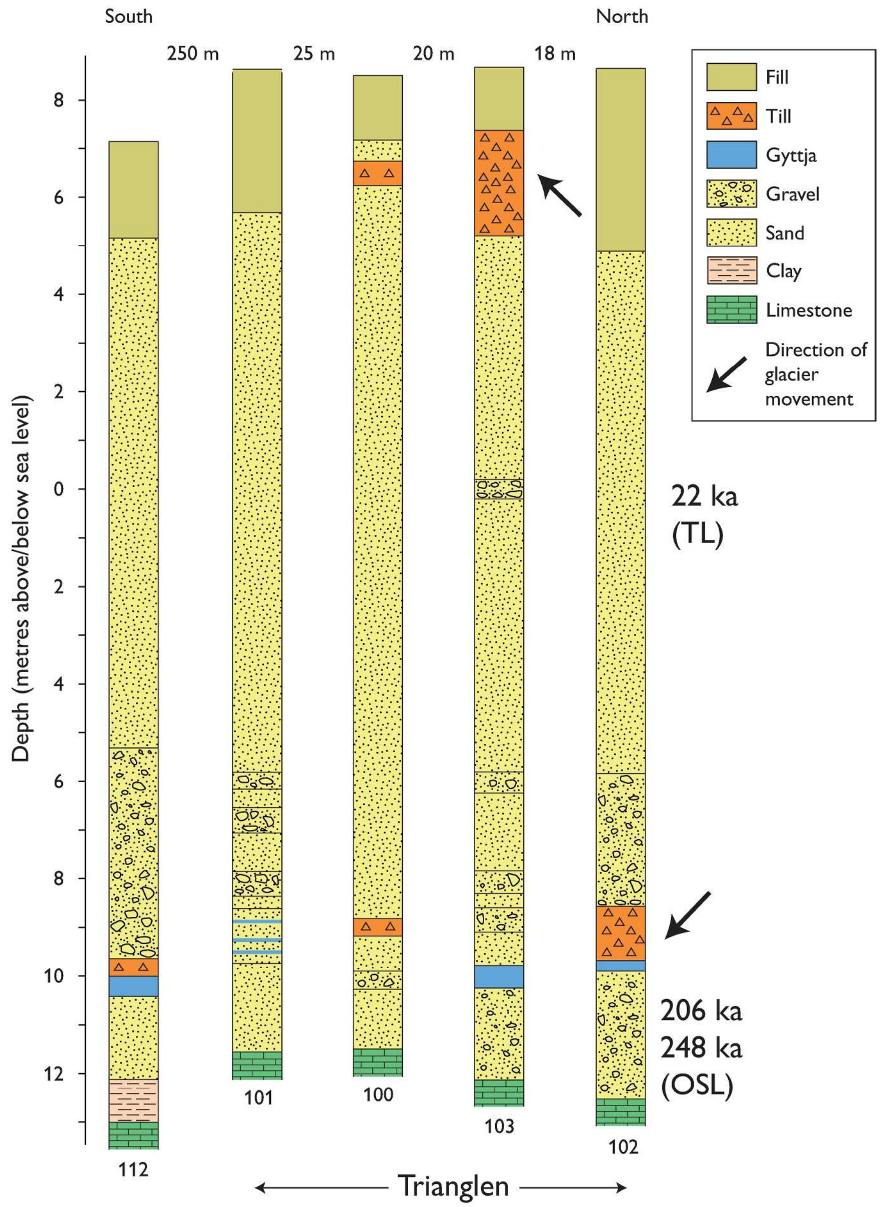
NEaar no.	Asx D/L	Glx D/L	Ser D/L	Ala D/L	Val D/L
Trianglen					
11622F	0.655±0.002	ND	0.932±0.015	0.315±0.001	0.187±0.018
11622H	0.569±0.001	0.157±0.002	0.677±0.006	0.225±0.001	0.125±0.001
11623F	0.634±0.003	ND	0.917±0.007	0.264±0.002	0.147±0.002
11623H	0.553±0.010	0.129±0.006	0.642±0.022	0.211±0.005	0.112±0.002
11624F	0.640±0.011	0.165	0.905±0.010	0.275±0.000	0.153±0.007
11624H	0.564±0.004	0.136±0.002	0.680±0.003	0.209±0.003	0.111±0.003
11654F	0.650±0.003	0.163	0.946±0.020	0.283±0.002	0.160±0.004
11654H	0.566±0.001	0.150±0.000	0.658±0.003	0.222±0.004	0.118±0.000
Free Port					
9975F	0.671±0.003	0.171±0.012	0.964±0.001	0.296±0.001	0.166±0.003
9975H	0.536±0.003	0.146±0.001	0.613±0.021	0.213±0.008	0.118±0.000
9976F	0.641±0.004	0.144±0.005	0.906±0.003	0.282±0.000	0.163±0.002
9976H	0.536±0.000	0.155±0.001	0.632±0.021	0.206±0.008	0.126±0.000
9977F	0.657±0.014	0.149	0.900±0.047	0.297±0.005	0.148±0.002
9977H	0.492±0.003	0.168±0.003	0.552±0.001	0.221±0.004	0.150±0.011

77x66mm (300 x 300 DPI)

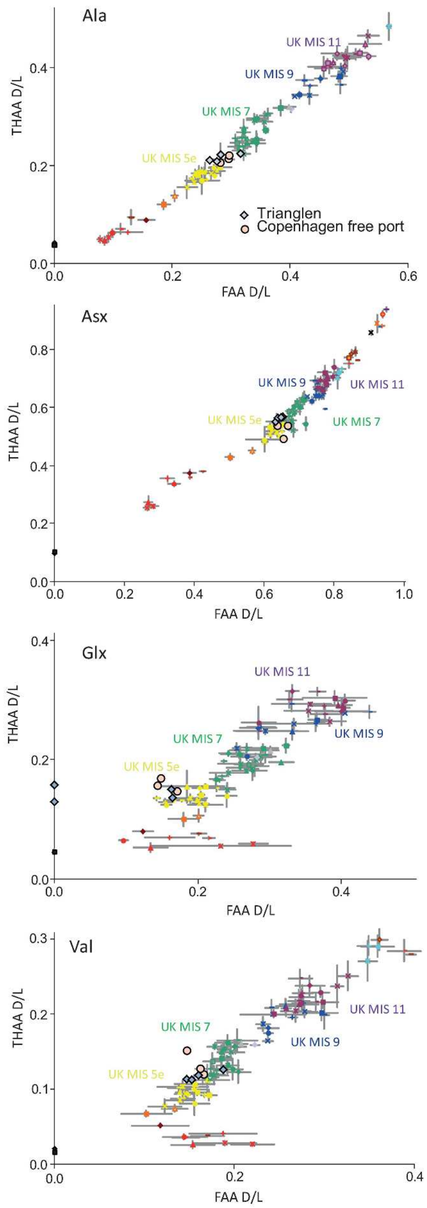
61x20mm (300 x 300 DPI)



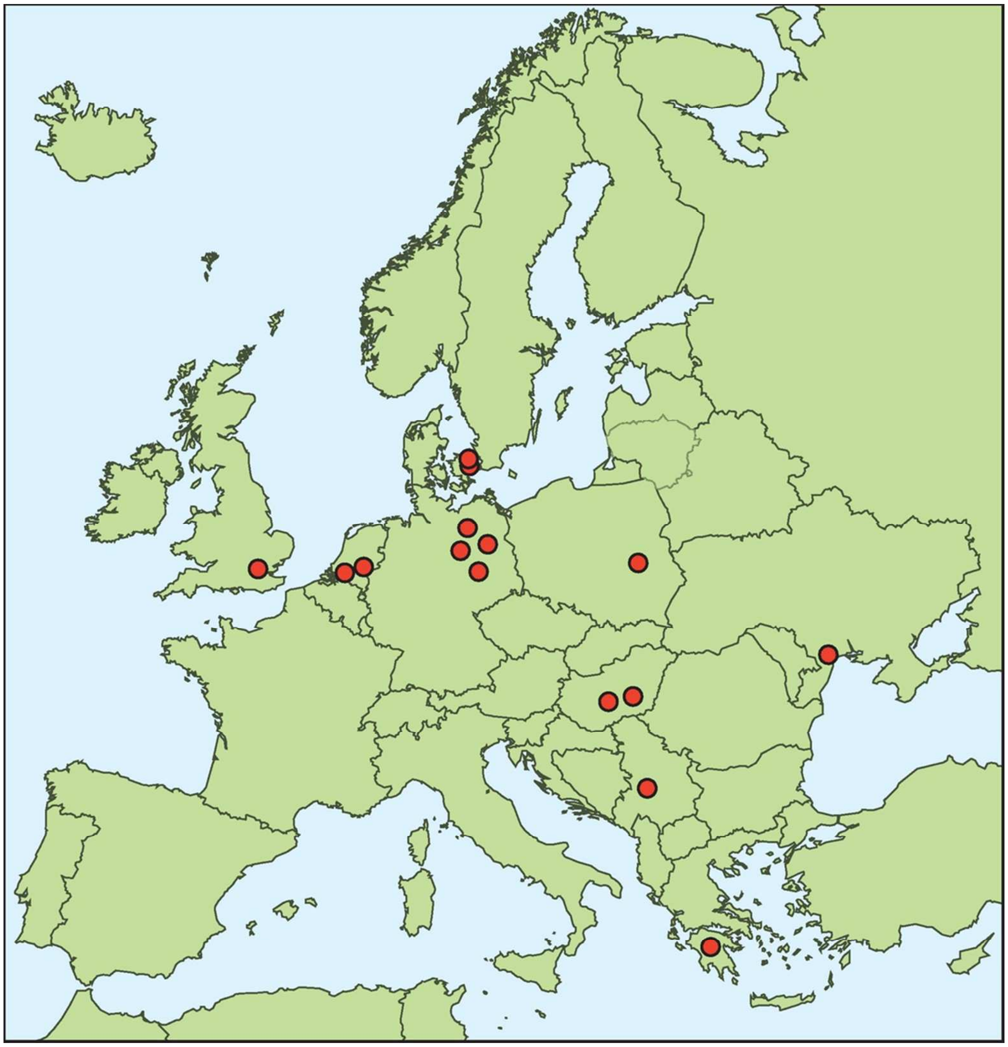
82x57mm (300 x 300 DPI)



207x286mm (300 x 300 DPI)



224x639mm (300 x 300 DPI)



93x96mm (300 x 300 DPI)