



New interglacial deposits from Copenhagen, Denmark: Marine Isotope Stage 7

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4 New interglacial deposits from Copenhagen, Denmark: Marine Isotope Stage 7
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20 During a pre-site survey and construction of a new metro route and station in Copenhagen,
21 fossiliferous organic-rich sediments were encountered. This paper reports on multidisciplinary
22 investigations of these organic sediments, which occurred beneath a sediment succession with of a
23 lower till, glaciofluvial sand and gravel, an upper till and glaciofluvial sand. The organic sediments
24 were underlain by glaciofluvial sand and gravel. The organic-rich sediments, which were up to 0.5
25 m thick, accumulated in a low-energy environment, possibly an oxbow lake. They were rich in
26 plant fossils, which included warmth-demanding trees and other species, such as *Najas minor*,
27 indicating slightly higher summer temperatures than at present. Freshwater shells were also
28 frequent. *Bithynia* opercula allowed the sediments to be put into an aminostratigraphical
29 framework. The amino acid racemisation (AAR) ratios indicate that the organic sediments formed
30 during Marine Isotope Stage 7 (MIS 7), which is consistent with optically luminescence dating that
31 gave ages of 206 and 248 ka from the underlying minerogenic deposit. The assemblages from
32 Trianglen are similar to interglacial deposits from the former Free Port (1.4 km away) in
33 Copenhagen, except that *Corbicula* and *Pisidium clessini* were not found at Trianglen. The
34 presence of these bivalves at the Free Port and the ostracod *Scottia tumida* at Triangles indicates a
35 pre-Eemian age. AAR data from archived *Bithynia* opercula from the Free Port were almost
36 identical to those from Trianglen, indicating that the two sites are contemporary. We suggest the
37 Trianglen interglacial be used as a local name for the MIS 7 interglacial deposits in Copenhagen.
38 MIS 7 deposits have rarely been documented from the region, but MIS 7 deposits may have been
39 mistaken for other ages. The use of amino acid racemization ratios in *Bithynia* opercula has a great
40 potential for correlation of interglacial non-marine deposits in mainland northern Europe.
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20 Interglacial deposits occur commonly in Denmark, but most are found in the western parts of the
21 country where erosion by glaciers and meltwater was less intense. Only a few interglacial deposits
22 have been reported from Zealand (Fig. 1). Most of these are marine deposits that have been referred
23 to the Eemian or the Holsteinian, but a few non-marine deposits have also been reported.
24 Interglacial organic sediments were found during excavations for the former Free Port in
25 Copenhagen between 1891 and 1893 (Rosenkjær 1893, 1896). They occurred as large clasts and
26 floes near the base of a till, which was deposited from the north-east (Milthers 1935). Macroscopic
27 plant and animal remains were studied by Rostrup (1895), Sarauw (1897), Johansen (1904) and
28 Hartz (1909) and five samples were analysed for pollen by Jessen (1927). The assemblage included
29 warmth-demanding plants such as *Quercus*, *Tilia*, *Corylus avellana*, *Alnus glutinosa*, *Cornus*
30 *sanguinea* and *Nymphoides peltata* (Table 1), demonstrating that the fossils came from a temperate
31 stage. Sarauw (1897) suggested that the Free Port deposits should be correlated with the Middle
32 Pleistocene Cromer Forest Bed in East Anglia (England), whereas Johansen (1904) and Milthers
33 (1922) suggested a pre-glacial rather than interglacial age. Jessen (1927) suggested that the Free
34 Port deposit belonged to the oldest Danish interglacial (out of two recognised at that time), a view
35 followed by Milthers (1935). The molluscan fauna from the Free Port includes the bivalve
36 *Corbicula fluminalis* and *Pisidium clessini*. *Corbicula fluminalis* is an extant species, which is
37 unknown from deposits in North-West Europe younger than MIS 7. *Pisidium clessini* is extinct
38 with the last occurrences in MIS 7 deposits; hence these species indicate a pre-Eemian age.
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51 Other non-marine interglacial occurrences on Zealand have been reported from Måløv to the
52 north-west of Copenhagen (Bennike *et al.* 2011; Middle Pleistocene) and from Førslevgaard in the
53 southern part of the island (Johansen 1904). The Førslevgaard fauna includes *Corbicula fluminalis*,
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4 *Pisidium clessini* and gastropod *Belgrandia marginata*. The latter species is unknown from other
5 Quaternary deposits in Denmark, but is common in other interglacial deposits in north-western
6 Europe (Preece 1990). Currently, this species is found in France and Spain.
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9 In addition to the interglacial deposit, reworked marine shells were found in the glaciofluvial
10 gravel between two tills; the fauna included “*Tapes aureus* var. *eemiensis*”, now *Polititapes aureus*
11 (Gmelin, 1791), which indicated derivation from deposits of Eemian age (Madsen *et al.* 1908). The
12 nearest *in situ* Eemian littoral deposit occurs at Ejby Bro, 45 km west of Copenhagen (Madsen
13 1968), so it is not surprising that reworked Eemian shells occur in the Copenhagen area. Interglacial
14 peat and gyttja have also been reported from a locality 11.5 km south-east of the centre of
15 Copenhagen (Jørgensen & Frederiksen 2002), but no information on the palaeoecology or age was
16 provided.
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22 Pleistocene interglacial deposits in Denmark have traditionally been referred to the Eemian,
23 Holsteinian and Cromerian (local name Harreskovian; Andersen 1965), but an interglacial
24 occurrence in eastern Jutland has been referred to a fourth interglacial stage, and correlated with
25 Marine Isotope Stage (MIS) 11, although not with interglacial occurrences referred to the
26 Holsteinian (Kuneš *et al.* 2013). However, the correlation and age of several Danish interglacial
27 occurrences are unknown (Andersen 1967).
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31 In other parts of north-western Europe it is becoming increasingly clear that the Pleistocene
32 successions are much more complex than previously believed (e.g. Urban *et al.* 2011; Penkman *et*
33 *al.* 2013). Interglacial successions in north-western Europe are characterised by climatic conditions
34 similar to the Holocene (e.g. Jessen & Milthers 1928; Andersen 1965), whereas interstadial
35 deposits contain remains of arctic or sub-arctic species (e.g. Bennike *et al.* 1994, 2014).
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40 Prior to the construction of a new metro line in Copenhagen, drilling was undertaken to
41 investigate the geology and the geotechnical properties of the subsurface along the line. Organic-
42 rich sub-till deposits were encountered in a few reconnaissance cores, in particular at Trianglen,
43 where a metro-station was planned. In 2014 excavations for the station were undertaken, allowing
44 photography (Fig. 2) and sampling. The new site at Trianglen is located 1.4 km from the former
45 Free Port in Copenhagen. Here we provide interpretation on the depositional environment of the
46 site and show evidence that the organic sediments at Trianglen and the Free Port accumulated
47 during MIS 7, the first realisation that such sediments occur in Denmark.
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54 Setting
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4 The bedrock geology of the Copenhagen area is dominated by limestone that belongs to the
5 København Kalk Formation, a formal lithostratigraphical unit of Danian age (Stenestad 1976). In
6 some areas the Lellinge Grønsand Formation of Selandian age occurs, and in western Copenhagen
7 Maastrichtian chalk is found at the pre-Quaternary surface (Jakobsen *et al.* 2017). The surface of
8 the pre-Quaternary bedrock usually occurs at depths of 5 to 13 m, but it is deeper in buried valleys
9 (Jørgensen & Frederiksen 2002; Fig. 3). The interglacial deposit reported here occurs at the margin
10 of one of these valleys.
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15 The Pleistocene succession in Copenhagen usually consists of an older unit of glaciofluvial
16 sand and gravel with numerous clasts of limestone and flint, a lower hard and compact till, a
17 younger glaciofluvial unit dominated by sand with some gravel, an upper till and finally an
18 uppermost glaciofluvial unit. The younger inter-till glaciofluvial unit has been dated by
19 thermoluminescence to 22 ka (Frederiksen *et al.* 2002), which indicates that it was deposited just
20 before the last glaciation of the region. Glaciotectionic features and glacial striae on boulders show
21 that the lower till was deposited from the north-east, whereas till fabric analyses and glacial striae
22 on boulders show that the upper till was deposited by a glacier from south-east or south-south-east
23 (Frederiksen *et al.* 2002).
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31 Material and methods

32 From core P07.112 only a single small sample was available for analysis, whereas large samples
33 were available from the open sections. Five samples taken through the organic-rich layer were
34 analysed, in addition to some large *ex situ* samples from unknown levels that were lying on the
35 floor of the excavation. Most of the mollusc shells came from a thin shell-rich layer in one of these
36 loose blocks. No difference in floral or faunal composition was apparent, and the samples were
37 treated as one assemblage (Table 1). A total of about 25 kg was analysed. The samples were soaked
38 in a NaOH solution at room temperature for two weeks and wet sieved on a 0.4 mm sieve. Small
39 fractions of the samples were also sieved at 0.2 and 0.1 mm sieves. The residue was analysed using
40 a dissecting microscope. The preservation of plant and animal remains was variable, some were
41 well preserved, whereas others were fragmentary and worn. Some blocks contained the remains of
42 larger shells, possibly unionids, preserved as small areas of white powder. A few ostracod valves
43 were coated with post-mortem pyrite.
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52 Two samples of sandy sediment were collected from a recently cleaned section below the
53 organic-rich sediment by hammering plastic tubes into the sediment. The tubes were then dug out
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4 and capped to retain water and to exclude light. The samples were dated by optically stimulated
5 luminescence using quartz, following the standard procedures at the Nordic Laboratory for
6 Luminescence Dating at Risø (Clemmensen & Murray 2010; Table 2). We assume that the
7 sediment was fully water saturated throughout its history.
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10 Amino acid racemisation (AAR) analyses were undertaken on four individual *Bithynia*
11 *tentaculata* opercula from Trianglen (NEaar 11622–11624, 11654; DTrBto1-4) and on three
12 individual *Bithynia tentaculata* opercula from the Copenhagen Free Port (NEaar 9975–9977;
13 DKoBto1-3; Table 3). The current technique of amino acid analysis developed for
14 geochronological purposes (Penkman *et al.* 2008) combines a reverse-phase high-pressure liquid
15 chromatography (RP-HPLC) method of analysis (Kaufman & Manley 1998) with the isolation of
16 an ‘intra-crystalline’ fraction of amino acids by bleach treatment (Sykes *et al.* 1995). This
17 combination results in the analysis of D/L values of multiple amino acids from the chemically
18 protected (closed system) protein within the biomineral, thereby enabling both decreased sample
19 sizes and increased reliability of the analysis. Amino acid data obtained from the intra-crystalline
20 fraction of the calcitic *Bithynia* opercula indicate that this biomineral is a particularly robust
21 repository for the original protein (Penkman *et al.* 2011, 2013) and therefore it was targeted in this
22 study.
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31 The DL ratios of aspartic acid/asparagine, glutamic acid/glutamine, serine, alanine and valine
32 (D/L Asx, Glx, Ser, Ala, Val) as well as the [Ser]/[Ala] value were assessed to provide an overall
33 estimate of intra-crystalline protein decomposition (IcPD). In a closed system, the amino acid ratios
34 of the FAA and the THAA subsamples should be highly correlated, enabling the recognition of
35 compromised samples (e.g. Preece & Penkman 2005). The D/L ratio of an amino acid will increase
36 with increasing time, whilst the [Ser]/[Ala] value will decrease. Each amino acid racemises at
37 different rates, and therefore is useful over different timescales. The D/L of Ser is less useful as a
38 geochronological tool for interglacial samples, but is presented here as aberrant values are useful
39 indications of contamination. The first analysis of 9977bF showed low Glx concentrations and a
40 high Glx D/L; the second analysis yielded more consistent data and the first replicate is therefore
41 rejected.
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49 The extent of protein decomposition in both the FAA and THAA increases with time, with
50 increased levels of protein breakdown during warm stages and a decrease in the rates of
51 degradation in cold stages. Over a small geographical area, it can be assumed that the integrated
52 temperature histories are effectively the same. Given a similar temperature history, this then allows
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4 an aminostratigraphic framework for an area to be developed, plotting the FAA against the THAA
5 data, with independent geochronology allowing these clusters to be correlated to marine oxygen
6 isotope warm stages; such a framework has been developed for *Bithynia* opercula from England
7 (Penkman *et al.* 2011, 2013).
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10 11 12 Results and discussion

13 14 15 *Lithostratigraphy*

16 Descriptions of sediment cores from four sites from Trianglen document the lithostratigraphy (Fig.
17 4), which is similar to the general stratigraphy for the Copenhagen area (Frederiksen *et al.* 2002).
18 The bedrock at Trianglen consists of limestone, which is overlain by sand and gravel rich in
19 limestone and flint. The sediment is poorly sorted and mineralogically immature and interpreted as
20 a glaciofluvial deposit. Two of the cores penetrated organic-rich sediments, which were described
21 as peat in core P07.102 and gyttja in core P07.103. The frequent remains of freshwater organisms
22 show that the sediments can be classified as a coarse-grained detritus gyttja. The organic layer
23 contained a few fragments of compressed pine wood, similar to those observed in deposits at the
24 Free Port. In two cores from Trianglen a hard till occurred above the gyttja. The open section we
25 examined was located close to core P07.102, in the section the transition from gyttja to till was
26 gradual, and small thrusts were observed at the transition. Ice movement was from the NE,
27 consistent with the direction reported from other sites in Copenhagen. The lower till is overlain by
28 glaciofluvial sand and gravel, an upper till, glaciofluvial sand (only seen in one core) and finally
29 fill.
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39 Core P07.112 from a site ~250 m south of Trianglen contains a unit of clay above the
40 bedrock, but such a unit was not encountered at Trianglen (Fig. 4). Apart from that, the
41 lithostratigraphy in core P07.112 is similar to that at Trianglen, with an organic-rich layer at ~10 m
42 below sea level.
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47 48 *Luminescence dating, amino acid analysis, biostratigraphy and age estimate*

49 Two samples from the lower glaciofluvial unit were dated by optically luminescence dating to
50 206±21 and 248±24 ka BP using quartz grains (Table 2). Although 200 ka is old for a quartz date,
51 for these two samples the dose rates are very small, and so the doses are both between 100 and 150
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4 Gy. This is normally thought to be well within the dose range for reliable quartz ages (A.S. Murray,
5 pers. comm., 2017).
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7 Ala is the most useful amino acid for age discrimination over late Middle Pleistocene
8 timescales, and there is no significant difference in racemisation between the two sites in
9 Copenhagen. The aminostratigraphic framework for English sites provides a useful basis with
10 which to compare the new data from the two Danish sites, Trianglen and Copenhagen Free Port
11 (Fig. 5). It is clear that both Danish sites have amino acid values that are similar to, but slightly
12 higher than, those for the same species from sites correlated with the English Ipswichian (and
13 therefore the Eemian and MIS 5e; Bowen 1999), including Trafalgar Square, Bobbitshole, Coston,
14 Shropham, Cropthorne New Inn, Eckington and Tattershall Castle (Penkman *et al.* 2011).
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20 A direct correlation to the marine oxygen isotope stage record based on the amino acid data
21 alone is premature. The temperature history of Copenhagen is likely to have been significantly
22 different to that experienced in England. The mean annual air temperature was 8.4 °C in
23 Copenhagen from 1982 to 2012, and 11.1 °C in London for the same time period, according to
24 <https://da.climate-data.org/>. However, care needs to be taken with recent temperature data
25 comparisons, as metropolitan heat islands mean that the temperatures recorded are not necessarily
26 representative of the pre-city environment. However it is plausible that past temperatures may have
27 been in general slightly higher in England (the region where the core aminostratigraphic framework
28 has been developed) than in Copenhagen. This would result in lower effective diagenetic
29 temperatures (e.g. Wehmiller *et al.* 2012) in Copenhagen, and therefore a slower rate of amino acid
30 racemisation may be assumed for Copenhagen. Using this argument, the ratios from Copenhagen
31 are more compatible with a MIS 7 age than a MIS 5e age.
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39 The organic interglacial sediments from Copenhagen have yielded a few species of
40 biostratigraphical importance. An extinct ostracod, *Scottia tumida*, present at Trianglen is only
41 known from Early and Middle Pleistocene deposits elsewhere in Europe (Fig. 6; Diebel &
42 Pietrzeniuk 1975; Fuhrmann 2013). Two species of mollusc present in sediments from the Free
43 Port also suggest a pre-Eemian age. The first of these is the bivalve *Pisidium clessini*, called *P.*
44 *astartoides* in early literature. In Britain this extinct species is known only from temperate stages
45 and it has a large temporal range extending from the Early Pleistocene to the late Middle
46 Pleistocene (MIS 7; Preece 1995, 2010). It is not known from the Last Interglacial in Britain, and
47 appears to have a similar stratigraphical range elsewhere in north-western Europe (Meijer 1989).
48 The second notable species discovered at the Free Port is the locally extinct *Corbicula fluminalis*.
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4 This species still inhabits rivers in the Middle East but there is some uncertainty as to the true
5 identity of European Pleistocene *Corbicula* and whether it is genuinely conspecific with *fluminalis*
6 (see discussion in Meijer & Preece 2000). Whatever its true identity, *Corbicula* is an important
7 biostratigraphical fossil in the European Pleistocene. Although it has been recorded from Last
8 Interglacial sites in north-western Europe, most, if not all, of these records are now thought to
9 represent shells reworked from older deposits (Meijer & Preece 2000). It appears to have been
10 absent in north-western Europe during the Last Interglacial (Meijer & Preece 2000; Penkman *et al.*
11 2011, 2013), so its occurrence in sediments from the Free Port suggest a pre-Eemian age for them.
12 The absence of *P. clessini* and *Corbicula* at Trianglen can probably be explained by facies
13 differences, as low-energy conditions appear to have prevailed at Trianglen.
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20 It appears that the organic interglacial deposits at Trianglen are broadly contemporary with
21 those recovered from the excavations for the Copenhagen Free Port. Based on the OSL ages, the
22 AAR results and the presence of *Pisidium clessini* and *Corbicula fluminalis*, we suggest that these
23 interglacial deposits formed during MIS 7, which is dated to 243–191 ka (Lisiecki & Raymo 2005).
24 Interglacial deposits referred to MIS 7 have been reported from a number of sites in Britain
25 (Penkman *et al.* 2011, 2013) and have also been reported from a number of sites in mainland
26 Europe. However, MIS 7 deposits have probably often been mistaken for other ages at many sites.
27 None have previously been reported from Denmark. Therefore we suggest a local name, the
28 Trianglen interglacial, for the deposits at Trianglen, at the former Free Port in Copenhagen and in
29 core P07.112.
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38 *Palaeoecology*

39 The results of the macrofossil analyses from Trianglen, core P07.112 and the Free Port are
40 summarised in Table 1. Overall, the deposits are characterised by species-rich assemblages of
41 vascular plants. Trees are represented by several taxa and there is no doubt that the area was
42 forested. The flora comprises species usually found in climax forests such as *Quercus*, *Ulmus* and
43 *Tilia* but the tree flora also comprises taxa that are typical of open forests and woodland such as
44 *Pinus*, *Betula* and *Populus*. Open ground heliophilous shrubs and herbs are poorly represented but
45 include *Cornus*, *Rubus*, *Empetrum*, *Chenopodium* and *Cerastium*. These plants may have been
46 growing near the shore of rivers, perhaps on sand banks or in bogs. *Cenococcum geophilum* is a
47 fungus that lives in soil.
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4 Wetland plants are represented by many species and bogs and fens were probably widespread.
5 *Alnus* probably grew in swampy areas, but reed beds may also have occupied large areas, perhaps
6 on floodplains. The assemblage of wetland species shows large similarities to Holocene floras from
7 Denmark (e.g. Bennike *et al.* 2004). *Urtica dioica* and *Ranunculus sceleratus* are often found in
8 nutrient-rich areas with high nitrogen levels, which can result from animal faeces and urine, and the
9 fauna may have included large herbivores.

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

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

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

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

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

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

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

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45 The high diversity of plants and animals indicate that the remains were washed together from
46 a fairly large area with different biotopes. This is consistent with the surface topography of the
47 limestone where buried channels can be seen. It is also not surprising that several of the species
48 indicate carbonate-rich soils because the bedrock is limestone, and the sand and gravel found below
49 the organic-rich layer is rich in carbonate. Based on the fossil assemblages from Trianglen and the
50 site location near buried valleys, we suggest that the organic-rich sediments at Trianglen were
51 deposited in a low-energy fluvial environment or an oxbow lake. The occurrence of fluvial species
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4 in the deposits from the Free Port suggests a fluvial environment. The fossil assemblage from the
5 small sample from core P07.112 provide little information on the depositional environment; but the
6 occurrence of aquatic species may indicate a pond or small lake.
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9 Tree taxa such as *Betula pubescens*, *Populus tremula* and *Pinus sylvestris* are typical of the
10 pioneer phase of interglacial development – the protocratic stage, whereas taxa such as *Corylus*,
11 *Quercus*, *Tilia* and *Ulmus* are characteristic elements of the mesocratic stage, corresponding to the
12 thermal maximum with highest temperatures. *Picea* may occur in the mesocratic and oligocratic
13 stages (Birks & Birks 2004). Unfortunately, the data from Copenhagen do not allow the
14 reconstruction of changes in vegetation over time.
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20 *Palaeoclimate*

21 Many of the species in these Copenhagen deposits are warmth-demanding. *Najas minor* is perhaps
22 the most thermophilous with a modern northern geographical range limit in northern Germany.
23 *Najas* spp. are annual plants that require warm summers for their seeds to develop. The summers
24 appear to have been slightly warmer than at present. Most of the beetle species recovered have a
25 predominantly southern distribution in Fennoscandia and Denmark today. *Dyschirius intermedius*
26 is rare and local in northern Europe, but more common in central and southern Europe.
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31 Two interglacial lake deposits have been reported from Zealand, at the Free Port of
32 Copenhagen and at Førslevgaard in southern Zealand (Fig. 1). The molluscan fauna from these
33 deposits includes the bivalve *Corbicula fluminalis* and *Pisidium clessini*, which indicates an Early
34 or Middle Pleistocene age. The Førslevgaard fauna also includes the gastropod *Belgrandia*
35 *marginata*, which is unknown from other Quaternary deposits in Denmark, but is common in other
36 interglacial deposits in north-western Europe (Preece 1990). Currently, this species is found in
37 France and Spain.
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44 *Comparison with other interglacial occurrences in the region*

45 The Trianglen site, core P07.112 and the Free Port site occur in the same area and show marked
46 similarities with respect to litho-, bio- and aminostratigraphy. Moreover, the interglacial
47 occurrences are found at a depth of ~10 m below sea level. We believe that the organic deposits
48 accumulated during the same interglacial stage.
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52 As mentioned above, most interglacial deposits in Denmark are referred to the Eemian, the
53 Holsteinian or the Harreskovian, but a lake deposit from eastern Jutland is referred to a fourth
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4 interglacial stage (Kuneš *et al.* 2013). The molluscan fauna from the sites in Copenhagen comprises
5 species suggesting an age older than the Eemian. The Harreskovian pollen record is correlated with
6 the Hunteburg interglacial in Germany and MIS 19, ~780 ka (Odgaard *et al.* 2016). Jessen (1927)
7 reported 8, 20, 22, 30 and 32% *Tilia* pollen in five analysed samples from the Free Port; these
8 values are far higher than found in the Harreskovian. The absence of *Carpinus* pollen in the
9 samples from the Free Port may indicate that it does not correlate with the Holsteinian. The
10 Holsteinian is usually correlated with marine oxygen isotope stage 11, ~400–360 ka, older than
11 indicated by the OSL ages from Trianglen. It is interesting to note that the Trelde Klint interglacial
12 is also characterised by an absence of *Carpinus* but has low *Tilia* percentage values and so probably
13 does not correlate with the Trianglen interglacial. The Trelde Klint interglacial may correlate with
14 MIS 11c based on OSL ages of 350±20 ka. The vegetational succession is different from other
15 Danish sites referred to the Holsteinian, which may correlate with MIS 11a.

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23 The *Nematurella* clay at Gudbjerg on Funen was described by Madsen & Nordmann (1901)
24 and a pre-glacial age was suggested by Rosenkrantz (1942). The molluscan fauna at Gudbjerg,
25 which also appears to represent a fluvial assemblage (Preece 1990), lacks *Corbicula* but includes
26 the extinct gastropod *Tanousia stenostoma*, after which the clay is named (*Nematurella* =
27 *Tanousia*). These components indicate an age much older than the assemblages from Copenhagen,
28 and point to an age within the early part of the ‘Cromerian Complex’ (cf. Andersen 1967; Preece
29 2001).

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35 Interglacial or warm stage deposits in Germany and Britain have been correlated with MIS 7
36 and 9. Open sections in large coal mines in the Schöningen area provide evidence for two
37 interglacials within the Saalian complex (Urban 1997; Urban *et al.* 2011). The younger is the
38 Schöningen Interglacial, which was dated by $^{230}\text{Th}/^{234}\text{U}$ to 180 and 227 ka, indicating a correlation
39 with MIS 7 (Hejnis 1992). The Schöningen Interglacial has been correlated with the Wacken and
40 Dömnitz Interglacials, the Belvédère Interglacial and the Lubavian Interglacial (de Beaulieu *et al.*
41 2001) and is characterised by abundant *Tilia* and almost complete absence of *Abies* and *Fagus*.
42 Wacken and Dömnitz are often described as interstadial deposits rather than interglacials, based on
43 the absence of thermophilous plants such as *Hedera* and *Buxus*. In Britain there are many MIS 7
44 deposits, but no formal type site has been proposed, although the name the Aveley Interglacial has
45 been suggested (Schreve 2001).

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

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23 *Acknowledgements.* – Svend Funder at the Geological Museum in Copenhagen allowed us to
24 analyse *Bithynia* opercula from the Free Port. Amino acid analyses were supported by the
25 Leverhulme Trust. Sheila Taylor is thanked for technical support. We are grateful to Bernd Wagner
26 and Jan Piotrowski for their comments that helped to improve the manuscript.

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4 Figure captions
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7 *Fig. 1.* Map of Denmark showing the location of interglacial localities on Zealand mentioned in the
8 text. The new occurrence at Trianglen is marked by a star.
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12 *Fig. 2.* Photographs of the excavation at Trianglen in Copenhagen. The excavator is around 20 m
13 below the terrain surface. The following units are seen: Light grey glaciofluvial gravel with a sharp
14 upper boundary, brownish-black organic-rich unit with a gradational upper boundary, and a hard
15 till. The arrows point to the organic-rich unit.
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20 *Fig. 3.* Map of the area north of central Copenhagen, showing the elevation of the surface of the
21 København Kalk Formation. Blue = low elevation; yellow = high elevation. The dashed line shows
22 the track of the new metro line that is under construction. The black dots show the location of sites
23 discussed in the text.
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28 *Fig. 4.* Lithological logs of the cores from Copenhagen. The core names in the geotechnical reports
29 are P07.112, P07.101, P07.100, P07.103 and P07.102. The geographical coordinates are 55°41'42"
30 N, 12°34'42" E (core P07.112) and ~55°41'57" N, 12°34'32" E (the Trianglen cores). Ice movement
31 directions and the 22 ka age are from the literature (see the text). Star = macrofossil samples
32 discussed in this paper.
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38 *Fig. 5.* Total hydrolysable amino acids (THAA) versus Free (FAA) D/L values of Asx, Glx, Ala
39 and Val from bleached *Bithynia tentaculata* opercula from Trianglen and the Copenhagen Free Port
40 compared with opercula from sites in England correlated with MIS 5e (yellow), MIS 7 (green),
41 MIS 9 (blue) and MIS 11 (purple). The data are consistent with a late Middle Pleistocene age, but
42 the different temperature history between England and Copenhagen means that no direct correlation
43 can be made at this stage based on amino acid data alone.
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49 *Fig. 6.* Occurrences of the extinct ostracod species *Scottia tumida* in Europe according to Kempf
50 (1971), Bennike *et al.* (2011) and this study.
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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			
<i>Pinus sylvestris</i> L.	x	x	x
<i>Picea abies</i> (L.) H. Karst	—	—	x
<i>Betula pubescens</i> Ehrh.	x	—	x
<i>Quercus</i> sp.	—	—	x
<i>Ulmus</i> sp.	x	—	p
<i>Tilia</i> sp.	—	—	x
<i>Fraxinus</i> sp.	—	—	p
<i>Corylus avellana</i> L.	—	—	x
<i>Populus tremula</i> L.	x	—	—
<i>Cornus sanguinea</i> L.	—	—	x
<i>Salix</i> sp.	x	—	—
<i>Rubus idaeus</i> L.	—	x	x
<i>Empetrum nigrum</i> L.	x	—	—
<i>Chenopodium</i> sp.	x	—	—
<i>Cerastium</i> sp.	x	—	—
<i>Cenococcum geophilum</i> Fr.	x	—	—
Wetland			
<i>Alnus glutinosa</i> (L.) Gaertn.	x	x	x
<i>Typha</i> sp.	x	—	x
<i>Juncus</i> sp.	x	—	—
<i>Phragmites australis</i> (Cav.) Trin. ex Steud.	x	—	—
<i>Schoenoplectus lacustris</i> (L.) Palla	x	—	—
<i>Schoenoplectus</i> sp. (<i>Scirpus</i> sp.)	—	—	x
<i>Carex rostrata</i> Stokes	x	—	—
<i>Carex</i> sp.	x	x	x
<i>Eriophorum</i> sp.	—	—	x
<i>Alisma plantago-aquatica</i> L.	x	—	—
<i>Filipendula ulmaria</i> (L.) Maxim.	x	—	x
<i>Thalictrum flavum</i> L.	x	—	—
<i>Eupatorium cannabinum</i> L.	—	—	x
<i>Ranunculus sceleratus</i> L.	x	—	—
<i>Ranunculus flammula</i> L.	x	—	—
<i>Ranunculus repens</i> L.	x	—	—
<i>Rumex maritimus</i> L.	x	—	—
<i>Solanum dulchamara</i> L.	x	—	—
<i>Montia fontana</i> L.	x	—	—
<i>Lycopus europaeus</i> L.	x	—	—
<i>Urtica dioica</i> L.	x	x	—
<i>Viola</i> cf. <i>palustris</i> L.	—	—	x
<i>Cirsium</i> sp.	x	—	x

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4	Polypodiaceae ²	X	X	X
5	<i>Campylium stellatum</i> (Hedw.) C.E.O. Jensen	X	—	—
6	<i>Cratoneuron filicinum</i> (Hedw.) Spruce	X	—	—
7	<i>Drepanocladus aduncus</i> (Hedw.) Warnst.	X	—	—
8	<i>Oxyrrhynchium hians</i> (Hedw.) Loeske	X	—	—
9	<i>Sphagnum</i> sp.	X	—	—
10				
11	Aquatic			
12	<i>Menyanthes trifoliata</i> L.	—	X	—
13	<i>Potamogeton gramineus</i> L.	X	—	—
14	<i>Potamogeton perfoliatus</i> L.	X	—	—
15	<i>Potamogeton obtusifolius</i> Mert. & W.D.J. Koch	X	—	—
16	<i>Potamogeton alpinus</i> Balb.	X	—	—
17	<i>Potamogeton crispus</i> L.	X	—	—
18	<i>Potamogeton pusillus</i> L.	X	—	—
19	<i>Stuckenia pectinata</i> (L.) Börner (<i>P. pectinatus</i>)	X	—	—
20	<i>Potamogeton</i> sp.	X	—	X
21	<i>Nymphaea</i> sp.	X	X	X
22	<i>Nuphar</i> sp.	X	—	X
23	<i>Nymphoides peltata</i> (S.G. Gmel.) Kuntze	—	—	X
24	<i>Hippuris vulgaris</i> L.	X	—	X
25	<i>Myriophyllum spicatum</i> L.	X	X	—
26	<i>Sparganium erectum</i> L.	X	—	X
27	<i>Ceratophyllum</i> sp.	—	—	X
28	<i>Najas marina</i> L.	X	—	—
29	<i>Najas minor</i> All.	X	—	—
30	<i>Zannichellia palustris</i> L.	X	—	—
31	<i>Ranunculus</i> sect. <i>Batrachium</i> sp.	X	X	X
32	<i>Chara</i> sp.	X	—	—
33	<i>Nitella</i> sp.	X	—	—
34				
35				
36				
37	Animals			
38				
39	Ectoprocta (freshwater bryozoans)			
40	<i>Cristatella mucedo</i> Cuvier, 1798	X	—	—
41	<i>Plumatella</i> sp.	—	X	—
42				
43				
44	Annelida (worms and leeches)			
45	Lumbricidae indet.	X	—	—
46	<i>Piscicola geometra</i> (Linnaeus, 1761)	X	—	—
47	<i>Erpobdella</i> sp.	X	—	—
48				
49	Crustacea, Branchiopoda			
50	<i>Chydorus</i> cf. <i>sphaericus</i> (O.F. Müller, 1776)	—	X	—
51	<i>Alona</i> sp.	X	—	—
52	<i>Leydigia</i> sp.	X	X	—
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55	Crustacea, Ostracoda			
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4	<i>Scottia tumida</i> (Jones, 1850)	x	—	—
5				
6	Insecta, Coleoptera (beetles)			
7	<i>Dyschirius intermedius</i> Putzeys, 1846	x	—	—
8	<i>Trechus quadristriatus</i> (Schrank, 1781)	x	—	—
9	<i>Agonum obscurum</i> (Herbst, 1784)	x	—	—
10	<i>Pterostichus strenuus</i> (Panzer, 1796)	x	—	—
11	<i>Limnius volkmari</i> (Panzer, 1793)	x	—	—
12	<i>Bledius</i> sp.	x	—	—
13	<i>Otiorhynchus</i> sp.	x	—	—
14	<i>Hydraena gracilis</i> Germar, 1824	x	—	—
15				
16	Megaloptera (alderflies)			
17	<i>Sialis</i> sp.	—	—	—
18				
19	Trichoptera (caddis-flies)			
20	Limnephilidae indet.	x	—	—
21				
22	Diptera (flies)			
23	Cyclorrhapha indet.	x	—	—
24	Chironomidae indet.	x	x	—
25				
26	Oribatida (mites)			
27	Oribatida indet.	x	—	—
28				
29	Mollusca (molluscs)			
30	Terrestrial			
31	<i>Deroceras</i> sp.	x	—	—
32	<i>Clausilia</i> sp.	—	—	x
33	<i>Fruticicola fruticum</i> (O.F. Müller, 1774)	—	—	x
34	<i>Zonitoides nitidus</i> (O.F. Müller, 1774)	—	—	x
35	Aquatic			
36	<i>Valvata cristata</i> O.F. Müller, 1774	—	—	x
37	<i>Valvata piscinalis</i> (O.F. Müller, 1774)	x	—	x
38	<i>Gyraulus crista</i> (Linnaeus, 1758)	x	—	—
39	<i>Radix balthica</i> (Linnaeus, 1758; <i>L. peregra</i>)	—	—	x
40	<i>Lymnaea stagnalis</i> (Linnaeus, 1758)	x	—	x
41	<i>Bithynia leachi</i> (Sheppard, 1823) ³	—	—	x
42	<i>Bithynia troschelii</i> (Paasch, 1842)	x	—	?
43	<i>Bithynia tentaculata</i> (Linnaeus, 1758)	x	—	x
44	<i>Planorbis planorbis</i> (Linnaeus, 1758)	—	—	x
45	<i>Pisidium supinum</i> Schmidt, 1850	x	—	—
46	<i>Pisidium moitessierianum</i> Paladihe, 1866	x	—	—
47	<i>Pisidium amnicum</i> (O.F. Müller, 1774)	—	—	x
48	<i>Pisidium clessini</i> Neumayr, 1875 (<i>P. astartoides</i>)	—	—	x
49	<i>Pisidium subtruncatum</i> (Malm, 1855)	x	—	—
50	<i>Pisidium henslowanum</i> (Sheppard, 1825)	x	—	—
51	<i>Pisidium casertanum</i> (Poli, 1791)	x	—	x
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4	<i>Sphaerium corneum</i> (Linnaeus, 1758)	—	—	x
5	<i>Sphaerium</i> sp.	x	—	—
6	<i>Corbicula fluminalis</i> (O.F. Müller, 1774)	—	—	x
7				
8	Vertebrata (vertebrates)			
9	<i>Perca fluviatilis</i> (Linnaeus, 1758)	x	—	—
10	Cyprinidae	x	x	—
11	<i>Apodemus</i> sp.	—	—	x
12	Rodentia indet.	x	—	—
13				

¹Data from Hartz (1909)

²Probably *Thelypteris confluens* (Thunb.) C.V. Morton

³Could be *Bithynia troschelii*

p = pollen grains

For Review Only

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

For Review Only

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

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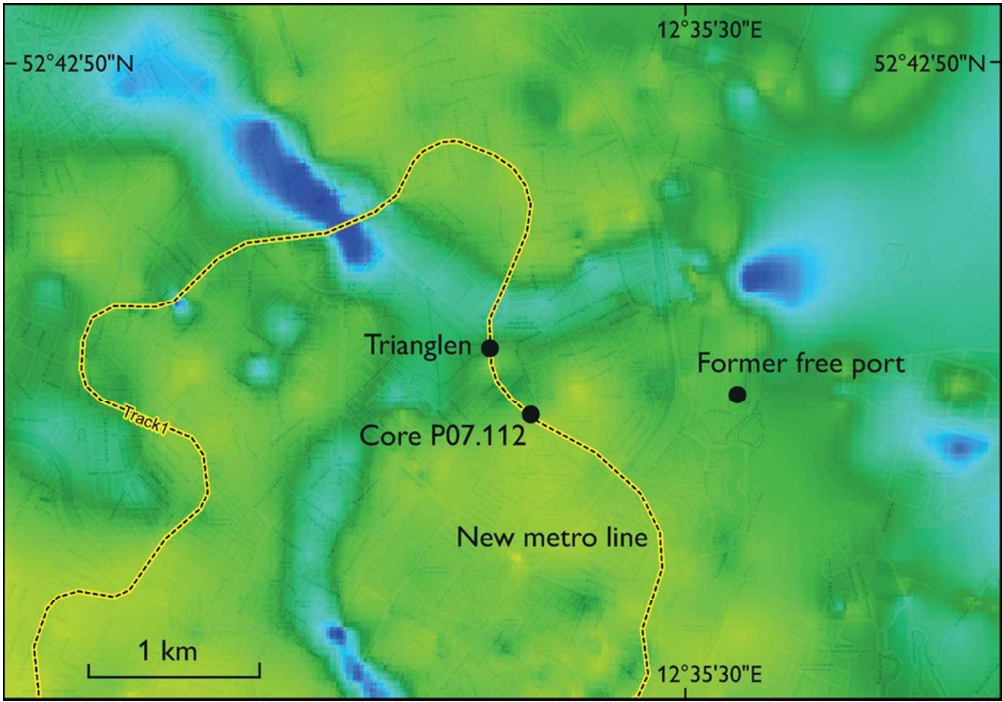
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61x20mm (300 x 300 DPI)

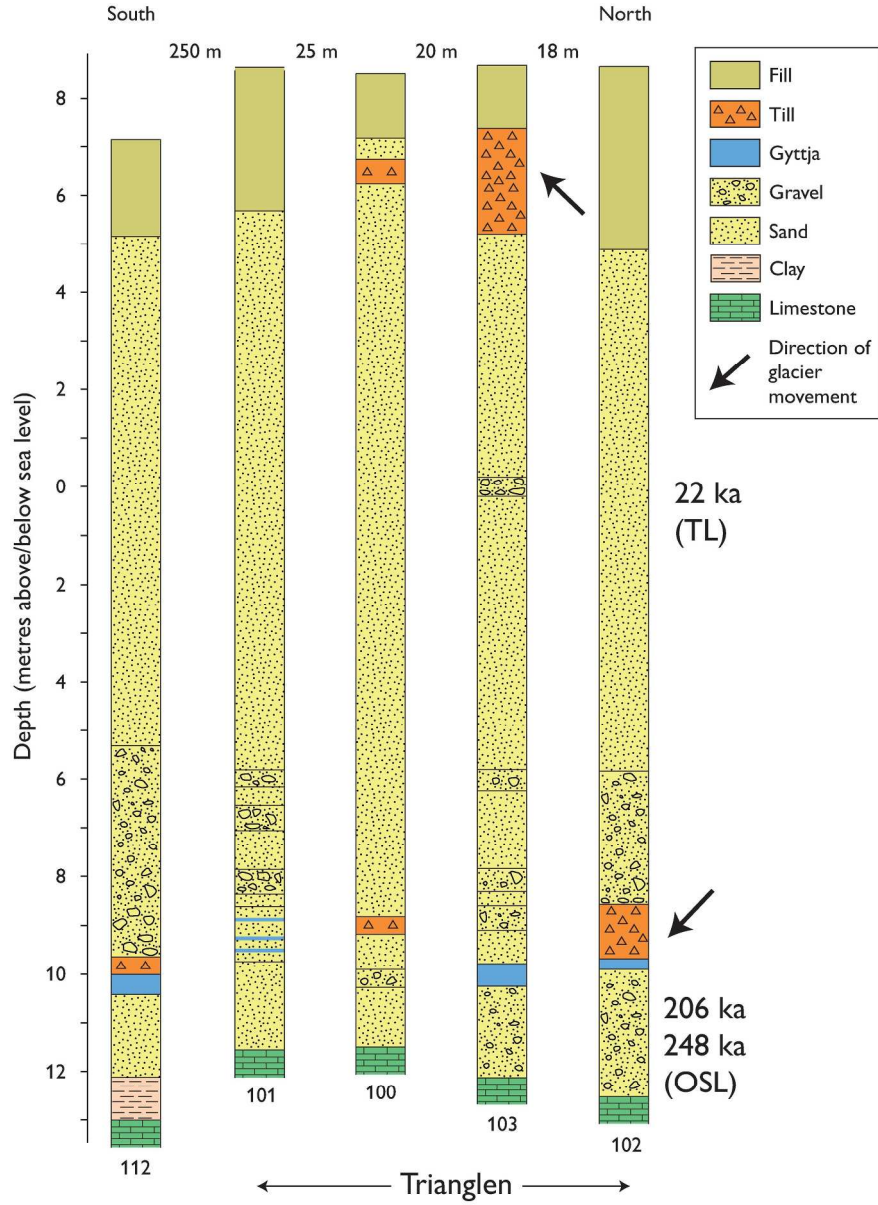
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82x57mm (300 x 300 DPI)

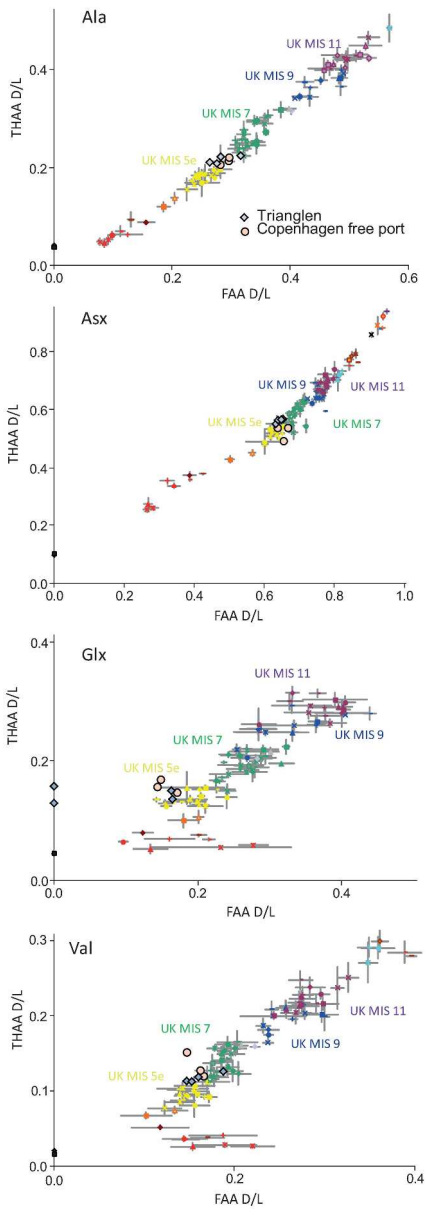
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207x286mm (300 x 300 DPI)

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93x96mm (300 x 300 DPI)