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RESEARCH ARTICLE

Applying geotechnical borehole databases in the search for interglacial deposits in Denmark

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Abstract

Geotechnical investigations conducted in preparation for infrastructure development provide high-quality borehole data in standardised digital formats. In Denmark, such geotechnical borehole data are not required to be reported to the national well database (Jupiter) and are mainly archived in privately owned databases. Accessible interglacial and interstadial terrestrial deposits are rare in Denmark, and these borehole data have the potential to identify interglacial and interstadial deposits, with significant implications for ongoing palaeoclimate, palaeoenvironmental and archaeological research. In this study, we compiled data from six major geotechnical companies, resulting in a database with over 550 000 boreholes. From this database, we identified 1850 boreholes containing samples associated with interglacial and interstadial ages. Through extensive filtering for well-documented lacustrine or palustrine deposits, we selected 161 boreholes and referenced them to 39 different geographical occurrences. Of these 39 occurrences, 36 were either new terrestrial deposits or provided substantial new records to known interglacial and interstadial sites. Our findings demonstrate that access to these privately owned geotechnical borehole data can be a valuable resource for identifying rare near-surface geological deposits, allowing the discovery of several new Pleistocene sedimentary archives that warrant further investigation.

1 Introduction

Over the past 50 years, there has been increasing interest in understanding long-term climatic variations using large-scale geological archives, such as ice sheets, deep-marine sediment beds and loess deposits. As our understanding of palaeoenvironment advances, identifying more high-resolution palaeoenvironmental and palaeoclimate archives is crucial for contemporary efforts to understand past and future climate change and human-environmental interactions. These advances offer new relevance to small-scale terrestrial geological archives, which capture regional and local variations at a high resolution (Moreno *et al.* 2014). Interglacial terrestrial deposits from small lake basins have been used since the early 20th century to establish one of the first terrestrial Quaternary stratigraphies in northern Europe (Jessen & Milthers 1928; Andersen 1965). These deposits became renowned for well-preserved plant macrofossils and pollen, but besides attempts to constrain the Weichselian ice extent (e.g. Hansen 1976), sporadic discoveries (e.g. Gormsen & Hansen 1980; Kronborg & Odgaard 2004; Bennike *et al.* 2019) and a few dedicated studies (Kuneš *et al.* 2013), interglacial terrestrial deposits have received limited attention in recent decades. Advances in dating methods, biomarker analyses and sedimentary ancient DNA (sedaDNA; Parducci *et al.* 2017; Dussex *et al.* 2021) provide promising avenues for gaining new insights into interglacial terrestrial deposits. These advances offer an unprecedented opportunity for a detailed understanding of past ecosystems, climate and glacial erosion history.

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Abbreviations:
aDNA: ancient DNA
b.s.: below surface
GEUS: Geological Survey of Denmark and Greenland
Igls: interglacial and interstadial
MIS: marine isotope stage
Pg: post-glacial
sedaDNA: sedimentary ancient DNA

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Renewed interest in Danish interglacial deposits has recently emerged in the field of archaeology, as palaeolithic research has attempted to establish the limits of past human northward expansion (Nielsen *et al.* 2019). In this context, the focus is primarily on the last interglacial stage and the following interstadials, namely the Eemian interglacial (marine isotope stage [MIS], MIS 5e) and the two following interstadials, Brørup (MIS 5c) and Odderade (MIS 5a). These periods offer favourable conditions owing to their relatively young age and minimal glacial disturbance, providing the best opportunities for preservation and evidence of past human presence. On the North European plain in northern Germany, Eemian and early Weichselian open-air Neanderthal sites have been discovered in lacustrine settings at Schalkholz (Arnold 1978), Lichtenberg (Weiss *et al.* 2022) and Neumark-Nord (Pop *et al.* 2015; Roebroeks *et al.* 2021). At the latter site, a large assemblage of processed megafauna remains was excavated. Earlier occupation of the North European plain is known from the site of Schöningen (Urban *et al.* 2023b), which is correlated with MIS 9 (Urban *et al.* 2023a). The Schöningen site holds the largest assemblage of wooden hunting spears currently known from the Pleistocene. If the aim is to locate new and well-preserved archaeological sites, lake shores offer a suitable habitat for early humans. Adjacent lake sediments may also provide a dateable context for archaeological remains, such as lithics, and hold climate and environmental proxies. To date, the search for such terrestrial interglacial deposits in northern Europe has been opportunistic, using coal and gravel pits, larger infrastructure projects or natural exposures to study interglacial deposits. In the search for traces of Neanderthals who may have occupied the region of southern Scandinavia during MIS 5e (Yaworsky *et al.* 2024), this approach has so far been unsuccessful in Denmark (Nielsen & Riede 2018), and a systematic method for locating interglacial and interstadial (IgIs) deposits is needed.

The Danish national well database, Jupiter, is a readily available and accessible resource of borehole data in Denmark maintained by the Geological Survey of Denmark and Greenland (GEUS). The Jupiter database has extensive spatial and temporal coverage; however, it has limitations owing to the heterogeneity of the well data and a lack of context, as it consists primarily of single-point records. Notably, no systematic study has been conducted to identify interglacial deposits within the Jupiter database. Similarly, geotechnical boreholes, which are drilled prior to the construction of buildings and infrastructure, have not been systematically used to identify interglacial deposits. In Denmark, boreholes that are not considered to affect groundwater resources, including boreholes for geotechnical investigation, raw material prospecting or scientific research, are typically excluded from mandatory reporting to Jupiter. Therefore, geotechnical data are commonly stored only by industry actors in private archives, and the findings of interglacial deposits remain publicly unreported. Some sectors of the industry have recently made archived data more available, such as the GeoAtlas Live solution by Geo, where simplified borehole data are displayed and shared between stakeholders and subscribers.

This study aims to assess the capacity of geotechnical borehole data to identify accessible interglacial deposits that may hold traces of early hominin presence in Denmark. Our approach concentrates on compiling data on well-documented interglacial lacustrine deposits from private geotechnical databases. The specific aims are, firstly, to locate glacially undisturbed MIS 5 lacustrine deposits with a focus on southern and southwestern Jylland, and secondly, to demonstrate the potential of large geotechnical data sets. Combined, this draws the contours of the potential of geotechnical data in both Earth and palaeoenvironmental research, provided that general issues of open access and open data can be resolved.

2 Materials and methods

2.1 Geotechnical borehole data

Geotechnical investigations in Denmark follow a common standard formulated by the Danish Geotechnical Society (Felthåndbogen 1999). This means that geotechnical boreholes are commonly drilled with an 8" cased auger, with samples taken every 0.5 m; however, this can differ depending on ground conditions, purpose and companies. Since the late 1990s, borehole data have predominantly been managed within GeoGIS, a database software developed in Denmark and designed for handling geological, geotechnical and water-related data and tasks. The use of the GeoGIS software has facilitated the digitalisation and accumulation of data in large internal databases over time. Borehole data are arranged in 'projects', with referred 'points', with referred 'samples', that again have ascribed attributes, for example, sediment description, depth, moisture content, etc. The sample description follows a common Danish standard (Larsen *et al.* 1995), where the sediment is classified according to its physical appearance by main component(s), grain size, sorting or grading, secondary components, structures, colour and calcareousness. The depositional environment of each sample is interpreted and assigned an age with a code, for example 'Fe Ig' stands for 'freshwater (Fe) environment and interglacial (Ig) age'. The interpretation is based on the geology and the overall stratigraphy. The geotechnical description does not distinguish palustrine sediments, and these would commonly be referred to a freshwater environment. In cases of doubt or redeposition, multiple interpretations can be given, for example 'Fe Pg/Ig' (Pg: Post-glacial). Commonly, the water content of cohesive sediment samples is measured along with the *in situ* ground strength.

With a focus on south and south-west Jylland, six major geotechnical companies were contacted: GeoSyd, Franck Geo-og Miljøteknik, Sweco, Rambøll, NIRAS and Geo. All companies granted access to their databases. The six GeoGIS databases were accessed from September 2022 to May 2023. Ownership and rights regarding the data differ from company to company and are generally informal, with many companies practicing shared ownership with their clients. We did not experience any refusal to share data, but concerns from the six companies were raised, leading to limitations in the display of the data. To protect company clients from third-party intervention, information that could identify clients has been anonymised in this paper. Access to the original data can only be granted by the data owners. Relevant project references are provided in Supplementary File S2 or can be obtained from the corresponding author on request.

2.2 Compilation of geotechnical borehole background data

To evaluate the overall coverage and test geotechnical borehole data against known interglacial sites, all available borehole data from five of the six databases were compiled with an SQL search at the 'point' level. A total of 422 072 points were compiled and evaluated. The raw quantities of the databases are shown in Table 1. The point data were then compiled into one data set at the 'project' level, attributed with the number of boreholes.

There are some inherited differences between the databases where some attributes may not have been entered in every database and coordinates have sometimes been handled separately. All available coordinates were transformed to UTM zone 32N (EPSG: 25832) and plotted in QGIS. In this process, several common errors were identified in the databases, such as erroneous projection, transverse coordinates, decimal and typographical errors. Obvious errors were, to a large degree, corrected manually. Where project coordinates were not available, a coordinate was calculated as a mean of point coordinates. Again, in databases where project titles often resembled addresses, and point coordinates were not available, the project title was georeferenced using the QGIS plugin, Danish Address Tool by ©Septima. One database contained imports from the publicly available data set Jupiter and from municipalities, and these were excluded. Projects identified as being located outside Denmark were excluded from the data set. Due to limitations in manual validation of all project positions, we acknowledge the potential introduction of errors at various stages. Associating all boreholes within a project to a single coordinate can lead to errors, particularly in cases involving multiple locations or referencing a linear shape. During the analysis of various databases, it became evident that certain projects were shared among multiple companies or databases. However, the scale of this issue was assessed to be negligible, and systematic filtering of duplicate background data was not implemented.

All projects were plotted in QGIS, enabling a geographical search, and a density map of all boreholes was generated using a 10-km search radius for each cell and weighing the projects by number of points (boreholes), see Fig. 1. The island of Bornholm was poorly represented in the data and has been excluded from further analyses, together with any offshore boreholes.

2.3 Compilation of interglacial and interstadial samples

In the six geotechnical databases, a separate SQL search was performed to identify all samples with an attributed interglacial or interstadial (IgIs) age. The data were exported to spreadsheets, with a total of more than 11 000 IgIs samples from more than 1800 boreholes. Imported raw quantities are shown in Table 1.

Table 1 Overview of database sizes and the inherent interglacial or interstadial (IgIs) points (boreholes) and samples.

Database	Date of access	Projects		Points		Samples
	(dd.mm.yyyy)	all	IgIs	all	IgIs	IgIs
GeoSyd	16 September 2022	46 838	302	161 426	600	1990
NIRAS	11 November 2022	1750	21	24 598	66	533
Sweco	20 December 2022	7919	75	69 023	170	891
Franck	10 January 2023	10 962	45	59 806	147	1521
Rambøll	31 January 2023	5386	113	107 219	361	2498
Geo[a]	10 May 2023	unknown	144	>147 000	514	4345
Sum		>72 855	700	>569 072	1858	11 778

[a] Access has only been granted to IgIs boreholes.

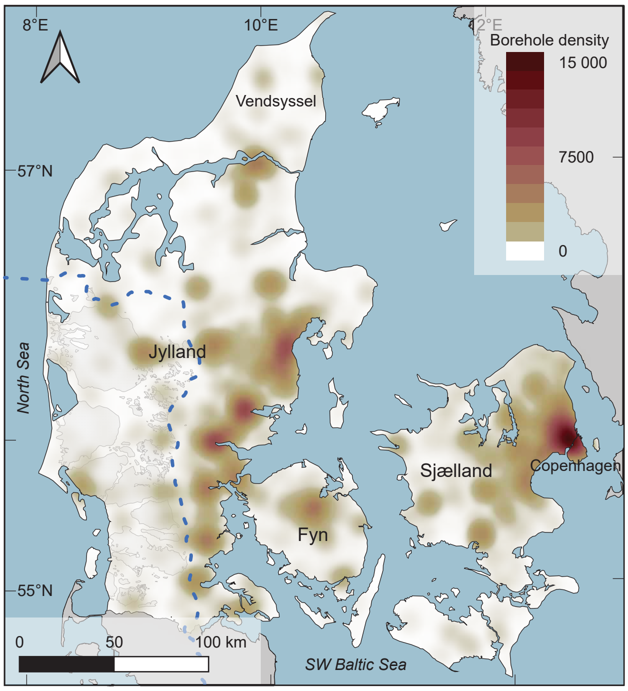

Fig. 1 Density map illustrating the distribution of geotechnical projects, weighted by the number of points (boreholes), showing borehole density within a 10-km radius. The data were sourced from five of the six databases used in this study, encompassing more than 450 000 boreholes from more than 72 000 projects. The map indicates a significant bias in the data set towards urbanised areas, particularly in the Greater Copenhagen area and east Jylland. The main stationary line during the last glacial maximum is depicted by the dashed blue line, while the remnant Pleistocene surface of the Danish hill-islands is represented with a grey mesh, modified from Jakobsen (2022).

All Igls samples were compiled into boreholes (*n* = 1858; 0.33% of total points), georeferenced and plotted in QGIS (see section 'Compilation of geotechnical borehole background data'). All points underwent manual validation; however, eight boreholes could not be georeferenced and were excluded. To identify lacustrine deposits of significant size and reliable data among Igls boreholes (totalling *N* = 1850), a filtering process consisting of four sequential steps was conducted within a spreadsheet. The filtering ascribed the boreholes to five distinct categories listed below. A detailed protocol for the filtration process is accessible in the Supplementary File S1.

1. Category I: Highly unlikely or errors (*n* = 63): This category encompasses boreholes where Igls samples could be classified as first (A) topsoil (*n* = 35) or then (B) duplicates (*n* = 28).
2. Category II: Inconclusive or sparse data (*n* = 912): This category includes boreholes where (A) the majority of samples had a secondary age not being interglacial, interstadial or postglacial (*n* = 437). Additionally, it comprises boreholes with (B) five or fewer samples within a 250 m range (*n* = 252) or (C) two or fewer consecutive samples (*n* = 223).
3. Category III: Few samples or an inorganic context (*n* = 587): This category comprises (A) boreholes with less than 15 samples within a 250 m range (*n* = 169) and (B) boreholes with few or no indications of organic content (*n* = 418).
4. Category IV: Inaccessible or marine deposits (*n* = 127): This category includes boreholes where (A) Igls samples are buried more than 10 m beneath the surface, making them difficult to access (*n* = 71). Additionally, it covers boreholes where (B) the majority of samples have been interpreted as marine (*n* = 56).
5. Category V: Boreholes indicating significantly large deposits of organic-rich freshwater sediment, fairly sure to be of interglacial or interstadial age (*n* = 161).

A graphical presentation of the filtration and classification for this study is shown in Fig. 2.

All 161 category V Igls points were combined into 39 Igls occurrences together with neighbouring Igls points. A map of the occurrences is shown in Fig. 3. The localities were crosschecked with localities known from literature and nearby Jupiter boreholes. All sites were attributed an occurrence number, occurrence name and (1) source information: number of category V and II–IV boreholes; (2) Spatial information: UTM32N coordinate, maximal and minimal elevation and maximal and minimal depth; (3) short comment with characteristics, observations and related geomorphology; (4) references to relevant literature, relevant nearby Jupiter boreholes and references to the geotechnical database and adjoining project number. The attributes for all 39 occurrences are shown in Supplementary File S2.

2.4 Jupiter data

For comparison, borehole data from the Jupiter database have been assessed. A search of the boreholes with digitised lithology, June 2024, revealed 1820 boreholes containing interglacial deposits, 514 of which contained interglacial freshwater sediments of likely terrestrial origin. When filtered similarly to the GeoGIS data, with a depth less than 10 m, total thickness of interglacial layers greater than 0.5 m and sediment to be of gyttja or peat, only 58 boreholes remain. Due to the huge difference in recorded parameters between the geotechnical and Jupiter databases, however, boreholes from Jupiter have not been included in this study and have not been filtered for the concentration criteria (more than 15 Igls samples within a 250 m range).

3 Results and discussion

3.1 Marine deposits

Three well-known marine interglacial deposits (Knudsen 1995) appear frequently in the databases. These are (1)

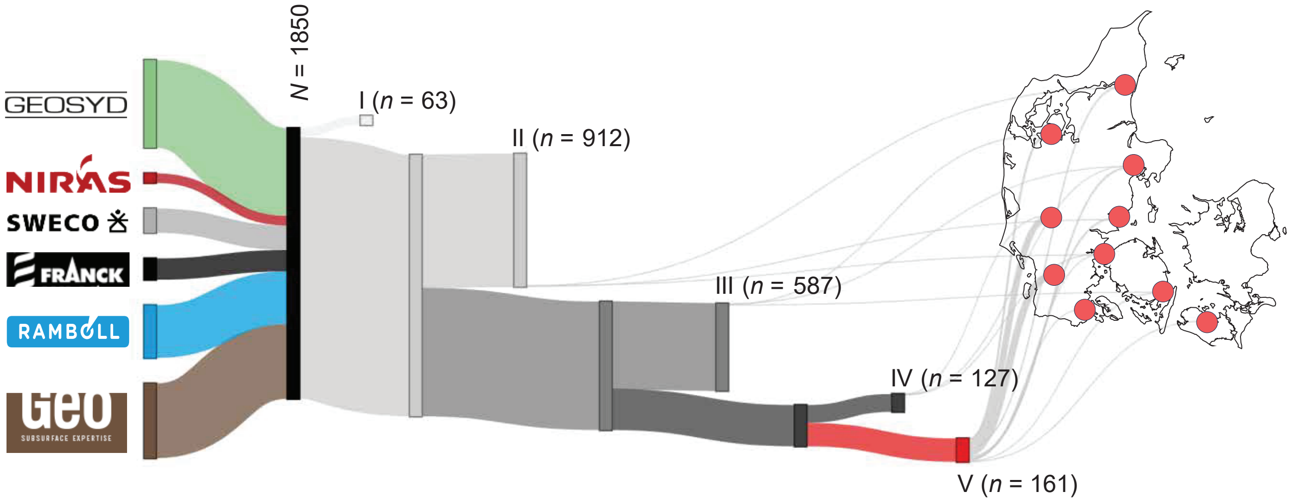

Fig. 2 Flow diagram illustrating the filtration of boreholes into categories I–V, based on sediment descriptions, quantity, interconnectivity, accessibility and more. A total of 161 boreholes were identified as containing significantly large deposits of organic-rich freshwater sediment with interglacial or interstadial age. These were grouped into 39 occurrences, incorporating neighbouring boreholes from the categories II–IV. Diagram created using SankeyMATIC.

the Eemian Cyprina Clay (Kristensen & Knudsen 2008), familiar to the south-western Baltic Sea, and often found incorporated in Weichselian tills in the Aabenraa, Haderslev and south Fyn area. In some company records, this organic-rich marine clay is referred to as "*Eemler*", Eemian clay. (2) The marine Eemian and Early Weichselian *Skærumhede* Series known from northern Jylland (Pedersen 2005), also referred to as the "Older Yoldia Clay". This deep marine deposit is found in the Vendsyssel area in outcrops and deep boreholes. (3) Marine deposits are also known from older interglacial stages, especially in south-western Jylland, where the likely Elsterian "Oldest Yoldia Clay" and subsequent Holsteinian marine deposits are found in many boreholes around the city of Esbjerg and have been described from former clay pits there.

3.2 Significant interglacial and interstadial occurrences

All 39 identified Igls occurrences are shown on the map in Fig. 3 and listed in Supplementary File S2. In some cases, additional data were obtained from the companies in the form of full geotechnical or excavation reports although this was not always possible.

Of the 39 occurrences identified in this study, two were already known and described in the literature: the Brørup Stationsby deposit (occurrence (occ.) 25; Hartz 1909) and the Kollund lake deposit at Lind (occ. 15; Kronborg & Odgaard 2004; Odgaard & Møbjerg 2009). Five occurrences are in proximity to, or can be correlated with, known deposits, yet the added observations are substantial (occ. 18, 20, 21, 24 and 35). A total of 32 of the identified occurrences appear to be new findings of Igls deposits. Nine of the 39 occurrences are selected and described below to illustrate and discuss the potential of the identified Igls deposits.

3.2.1 Hvorup (occ. 1)

Located just north of Nørresundby, North Jylland, this is the northernmost site with an interglacial freshwater deposit found in this study and known from the literature. The deposit is located under the gently sloping surface of late glacial Younger Yoldia sand (Berthelsen 1987) on the eastern flank of Hvorup Hill. The deposit is buried 3.5–4.5 m below the surface (b.s.) and is more than 8.5 m thick. It is recorded in six boreholes within a 30 × 30 m quadrant and may correlate with two Jupiter boreholes within 130 m. Samples are described mainly as peaty gyttja, with more clayey horizons towards the base. No similar freshwater interglacial deposits have been reported from this area, and the age of the deposit remains unresolved.

3.2.2 Ans (occ. 2)

The Ans Igls deposit is located 10 km north of Silkeborg, in Central Jylland. The interglacial deposit was encountered during the development of a new residential area. Identified by two separate companies in three different projects, the deposit consists mainly of gyttja with diatomite, up to 6 m thick. One investigation recorded high calcareous content, which is generally rare for interglacial deposits. The deposit is situated within an area of 100 × 100 m on a gentle slope within the extended south-eastern course of a buried valley, identified as area AAR44 in Sandersen and Jørgensen (2016). The age of the deposit is unresolved, but if it is found to be an infill of the buried valley, it would likely be pre-Eemian.

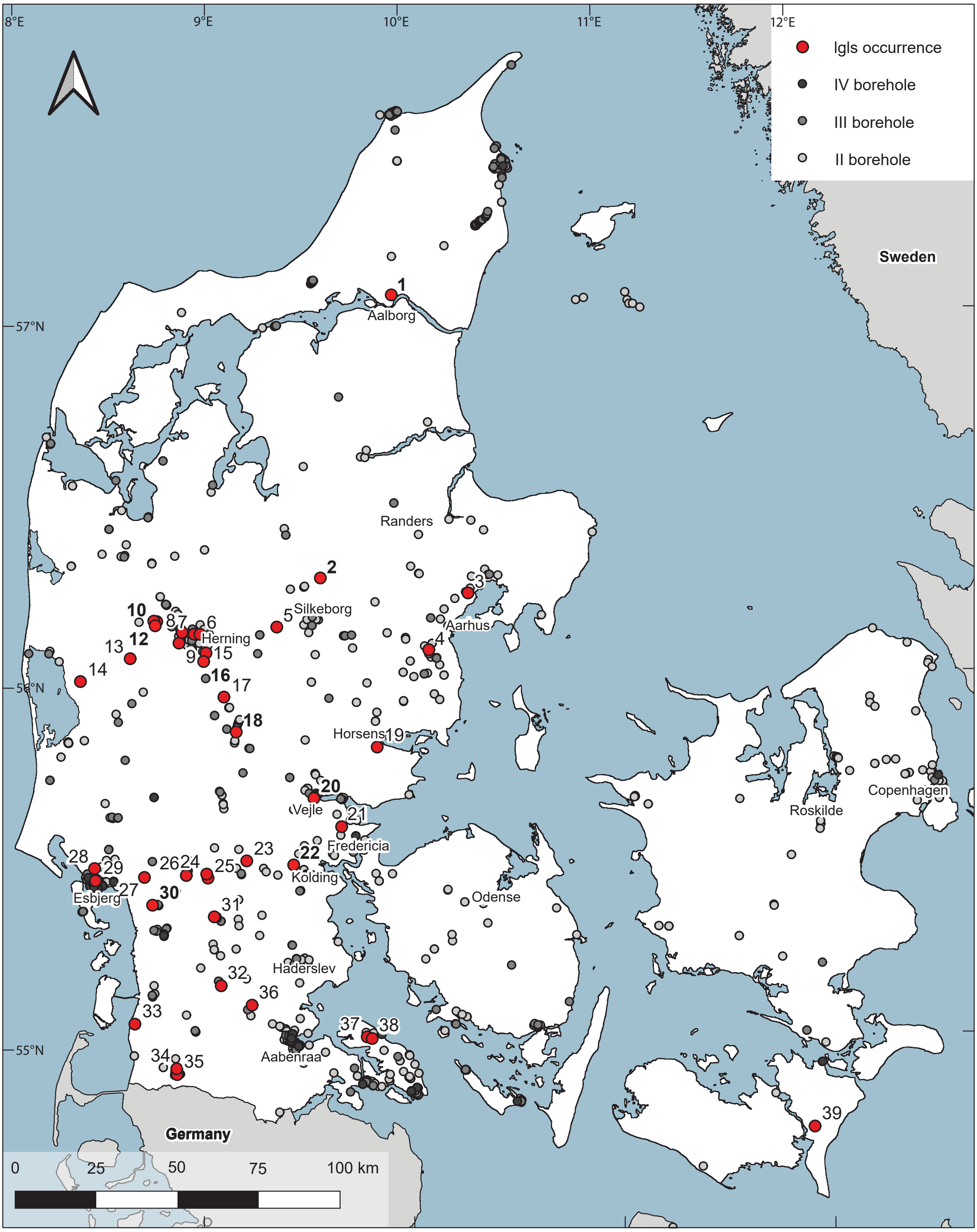

Fig. 3 The distribution of boreholes categorised as II, III and IV is shown in greyscale. Identified interglacial and interstadial (IgIs) occurrences are highlighted in red, and locations discussed in the text are labelled in bold. Details for all 39 occurrences are provided in Supplementary File S2. The labelled occurrences are: **1: Hvorup**, **2: Ans**, 3: Engskovgård, 4: Birkemose, 5: Engesvang, 6: Holing, 7: Fuglsang, 8: Gødstrup, 9: Snejbjerg, **10: Vildbjerg I**, 11: Vildbjerg II, **12: Møltrup**, 13: Videbæk, 14: Lem I, 15: Kollund Sø, **16: Elmholt**, 17: Flø, 18: Risbanke II, 19: Dagnæs, **20: Mølholm Valley**, 21: Karensdal, **22: Kolding V**, 23: Gesten, 24: Brørup N, 25: Brørup Stationsby, 26: Holsted Stationsby, 27: Bramming I, 28: Kjersing, 29: Rørkjær, **30: Gredstedbro**, 31: Møgelmose, Rødding, 32: Toftlund I, 33: Bådsbøl, 34: Tønder N, 35: Tønder, 36: Horsbyg, 37: Havnbjerg, 38: Nordborg, 39: Sdr. Vedby.

3.2.3 Vildbjerg I (occ. 10)

A concentration of 12 boreholes from four different projects is located south-west of Vildbjerg, Central Jylland. Here, interglacial freshwater gyttja and peat are found within an area of approximately 200 × 400 m situated on a gentle valley slope. The deposit is found at 3.5–21.5 m b.s. and is up to 16.5 m thick. It appears homogeneous with a moisture content typically ranging from 50 to 100% and with a few peat layers reaching 200%. The deposit is not recorded in nearby Jupiter boreholes. The age is unknown, but based on a geomorphological assessment, a pre-Eemian age is suggested.

3.2.4 Møltrup (occ. 12)

Initial observations from geotechnical boreholes and reports indicated highly irregular deposits of thin peat layers, thick layers of gyttja, clay and silt, among sorted sand with variable organic content. Part of the site development project was apparently abandoned in areas with the most organic soils. However, a subsequent excavation unveiled significant deformation with organic-rich soil A and B horizons, exhibiting a sub-vertical orientation in the profile. The combined findings strongly suggest the presence of a glaciotectonically disturbed soil surface with a thick podzol, with a combined thickness of O-A-E-Bh-Bs-horizons exceeding 1.5 m, developed from glacially derived parent material. No published examples of Pleistocene palaeosols from south-west Scandinavia (Sjørring & Frederiksen 1980; Stephan 2014; Nielsen *et al.* 2019; Houmark-Nielsen 2021), nor from Pliocene or Miocene deposits in Denmark (Rasmussen 2017), contain such 'giant' podzols. In this regard, the Møltrup site represents an anomalous and complex interglacial deposit that merits further investigation.

3.2.5 Elmholt (occ. 16)

Situated on the Skovbjerg hill-island, this interglacial deposit was encountered prior to the construction of a highway south of Herning, Central Jylland. The deposit has a thickness of more than 12 m and extends for 400 m in a north–south direction, while its east–west extent remains unknown. It consists mainly of non-calcareous diatomic peat and gyttja with water content of 80–110% and is overlain by clay with a high moisture content, approximately 35%. The age is undetermined, but similar deposits in the area have been correlated to MIS 11 (Odgaard *et al.* 2016) and a pre-Eemian age aligns well with the geomorphology at the site.

3.2.6 Risbanke II (occ. 18)

A single deep borehole penetrated a thick series of apparently undisturbed glacial and interglacial lake sediments. The bottom of the series starts at 17 m b.s. with slightly organic and slightly calcareous, then non-calcareous clay, shifting to a varved, very calcareous silt at 13 m b.s., followed by gyttja, which becomes non-calcareous. At 8.5 m b.s., the deposit consists of laminated clay, which is followed by gyttja at 5 m b.s. and then by clay. The IgIs deposit is within 500 m of a known interglacial site, Risbanke (I), ascribed to the Eemian interglacial (Milthers 1939), but the deposits cannot be directly correlated.

3.2.7 Mølholm Valley (occ. 20)

Within and in front of Mølholm Valley, a side valley to Vejle Fjord Valley, east Jylland, several boreholes have encountered a deposit of freshwater sediments. The deposit consists of homogeneous diatom gyttja, which is more than 31 m thick. It is situated within the buried valley of Randsfjord (RIB17; Sandersen & Jørgensen 2016), stretching nearly 25 km from Vejle south-east to Fredericia. The interglacial site of Vejlby within this valley is ascribed to the Holsteinian interglacial (Andersen 1965). The deposit at Mølholm Valley might not be novel, but it represents the thickest section found so far and could provide a high-resolution archive of the Holsteinian Interglacial.

3.2.8 Kolding V (occ. 22)

The deposit is located within the 'Kolding V' (Kolding west) highway intersection, but the exact location has not been georeferenced, as the data originate from an investigation carried out in 1968. The data have since been digitised by the company Geo. Five boreholes penetrated interglacial gyttja, which appeared near the surface or buried 5 m below, with a thickness of up to 7.5 m. The deposit consists of clay at the base, overlain by gyttja. The upper part consists of gyttja, silt and sand layers. The age of the deposit is unknown.

3.2.9 Gredstedbro (occ. 30)

The IgIs deposit at Gredstedbro is documented by single investigation and situated on a high-lying terrace on the western side of the Holsted hill-island, to the north-east of Gredstedbro. Here, five boreholes revealed an interglacial deposit primarily composed of homogeneous sand and interbedded freshwater gyttja, at depths ranging from 1.3 to 4.9 m b.s. The gyttja, likely lacustrine in origin, is described as having coal-like sections and exhibits a high moisture content of approximately 100–150%. This gyttja layer overlays well-sorted sand with plant remains and is covered by well-sorted medium-fine sand. The age of the deposit remains undetermined.

3.3 Poor coverage of Pleistocene basins

The borehole distribution map, Fig. 1, reveals a clear bias towards developed areas around Denmark's larger cities. In contrast, west Jylland, west of the main stationary line of the Last Glacial Maximum, shows relatively sparse coverage of geotechnical boreholes. This likely reflects the limited recent development following low population density in the region. The low degree of urban development especially applies to present-day depressions, which are left undeveloped where possible.

A notable example is the Eemian palaeolake at the Herning clay pit, first described by Jessen and Milthers (1928). Situated in a weak depression measuring approximately 250 × 800 m, this palaeolake is now located within a densely populated area. The area has been maintained as a recreational area, with football fields and only a few roads and a railroad line crossing it. This tendency to avoid developing basins on the remnant Pleistocene surface in urban areas appears to be common and reflects an avoidance of wetlands and additional cost associated with constructing deeper foundation. The site of Herning clay pit also highlights a general reluctance to ascribe deposits to IgIs ages when organic layers are not buried by subsequent glaciogenic deposits. In 2018, a geotechnical investigation in the south-eastern corner of the Herning clay pit (Madsen 2018a) initially misinterpreted the dark organic-rich layers as fill, glaciogenic or of other origins. Only upon deeper reinvestigation were these deposits correctly identified as interglacial (Madsen 2018b).

3.4 Limitations of geotechnical data

In filtering relevant boreholes (Fig. 2), we set a high threshold for boreholes, leading to the exclusion of some promising boreholes with limited neighbouring IgIs boreholes. This threshold, especially the criterion of more than 15 samples within a 250 m range, presents issues for large infrastructure projects where borehole density is low and often aligned in transects rather than clusters. To address this, we could prioritise the thickness of IgIs layers in individual boreholes over the number of neighbouring samples. However, for this initial study, we considered the spatial extent obtained from multiple boreholes more important for characterising the deposits.

Another potential improvement involves expanding the data set beyond the six geotechnical databases accessed for this study, particularly focusing on west Jylland. Including other GeoGIS databases or Jupiter data or addressing other research questions could enhance our understanding and utilisation of these data.

3.5 Catching false negatives

The accuracy of sediment classification and geological interpretation by technicians heavily influences our methodology. As illustrated by the Herning clay pit example (section 'Poor coverage of Pleistocene basins'), we suspect that many organic-rich interglacial deposits, especially those not overtly covered by glaciogenic sediments, are mistakenly attributed a postglacial age. This misattribution often arises from reliance on stratigraphy, where interglacial age assignment depends on the presence of overlying glaciogenic deposits. This issue is particularly pronounced when IgIs deposits are buried beneath Holocene lacustrine deposits, where there is only a subtle transition between the postglacial and interglacial layers.

During this study, we considered using moisture content as a proxy for age, based on the idea that sediment compacts over time due to burial, permafrost processes and organic material decomposition. However, the heterogeneous nature of the parent material, coupled with other variables such as overlay pressure, drainage patterns and decomposition, renders moisture content an unreliable proxy for age.

3.6 Potential for preservation in regions

The preservation of organic material is essential to establish a robust archive to reconstruct palaeoenvironments. Organic deposits typically indicate an anoxic environment, which protects them from microbial decay. Although comprehensive evaluations of organic degradation are challenging, insights can sometimes be gleaned from sample descriptions, especially when macrofossils are identified. For peat, the DGF standard (Larsen *et al.* 1995) outlines four levels of degradation, yet these are not consistently applied in sediment descriptions.

Another crucial factor affecting preservation is the pH level, which directly impacts bone preservation – a key consideration in fauna studies and archaeological investigations involving cutmarks and bone modifications. High pH levels are also known to support ancient DNA (aDNA) preservation (Giguet-Covex *et al.* 2019). While geotechnical sediment descriptions do not include pH measurements, HCl testing can determine the presence of calcareous minerals. Likewise, the presence of shells can provide clues regarding a neutral or alkaline environment. Among the 39 occurrences found in the survey, 10 have recorded calcareousness, with just two sites – Ans (2) and Risbanke II (18) – documenting partially calcareous organic deposits.

In some cases, subsequent glaciations have influenced interglacial deposits to varying degrees.

Glaciotectonic disturbances can significantly disrupt these deposits, compromising their structural integrity. Detecting glaciotectonic structures through geotechnical boreholes alone is challenging, as exemplified by the Møltrup site (occ. 12), see Section 3.2.4.

3.7 MIS 5 or older deposit

Most interglacial sites in Denmark have been referred to either the Eemian (MIS 5e) or the Holsteinian (MIS 11c) stages, but other interglacial periods are also represented. Although dating of the identified IgIs deposits is beyond the scope of this study, we evaluated the 39 occurrences based on the present geomorphology, historical topographic maps, overall descriptions and related literature. From this evaluation, we believe that it is unlikely any deposits relate to the late glacial interstadials Bølling-Allerød. Our criteria – more than two consecutive samples and a minimum of 15 samples within close proximity – appear effective in this regard. None of the 39 localities could be directly linked to depressions in the Pleistocene surface, unlike several known examples of MIS 5 deposits, such as the Brørup Bogs (Jessen *et al.* 1918) or the Herning clay pit (Jessen & Milthers 1928). This could be due to terrain alterations following construction. However, several deposits present at current terrain levels and located at the Pleistocene surface are likely of Eemian age, including occurrence 5–9, 13–14, 17 and 23–32. A few occurrences correlate with known deposits older than the Eemian, this being occurrences 15 and 20–21. Some deposits appear in thicknesses and distributions hitherto unprecedented in an Eemian context, suggesting a pre-Eemian age, including occurrence 10–11, 16 and 18. Due to limited information, we refrain from ascribing any age estimates to the remaining localities. As for all localities, reliable dates should be obtained with suitable methods if further studied.

4 Conclusion

This study identified 39 new interglacial sites, many of interest to the scientific community. The method of querying private databases has proven particularly effective in locating IgIs deposits, with evident glacial overprints. These sites require further study to fully explore their potential and to date these deposits properly.

Our data set included many marine deposits, which were not discussed here, but could be crucial climate archives and lead to a better understanding of historical sea-level fluctuations. Supplementing this data set with additional GeoGIS databases is feasible, and new data are continuously produced. Thus, this approach offers significant promise for identifying unknown interglacial sites in the future.

However, this approach is limited in identifying sites suitable for exploring early hominin evidence. Determining highly attractive campsites requires an understanding of the interconnectivity to the broader palaeolandscape. The identified sites generally lack geomorphological context. To address biases in geotechnical borehole data away from Pleistocene depressions (see section 'Poor coverage of Pleistocene basins') and avoid false postglacial attributions (see section 'Catching false negatives'), new strategies are necessary to locate undisturbed Eemian deposits on a large scale.

This study demonstrates, for the first time in Denmark, how privately owned geotechnical databases can be used for scientific inquiries when made accessible. Many more applications are conceivable. Open access to archived and ongoing geotechnical data would benefit various fields, including archaeology, Quaternary geology, groundwater mapping and environmental risk and geohazard assessment. A model that respects owner rights could include only sediment descriptions, groundwater tables and layer boundaries, while omitting quantitative data on the soil geotechnical properties.

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Author contributions

EMSN: Conceptualisation, resources, data curation, formal analysis, investigation, methodology, validation, visualisation, writing – original draft, writing – review and editing; SMK and TKN: Conceptualisation, supervision, writing – review and editing; TKN: Funding acquisition, project administration.

Competing interests

The authors declare no competing interests

Additional files

Three supplementary files are available at *https://doi.org/10.22008/FK2/48HRA5*. These include: (1) A readme file. (2) Supplementary File S1: Protocol of data processing and filtration of IgIs boreholes. (3) Supplementary File S2: Table of 39 IgIs occurrences.

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