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A new digital database of Ellen Louise Mertz's 1924 'Overview of late- and postglacial elevation changes in Denmark'

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Abstract

Data from an important historic article on late- and postglacial land-level changes in Denmark and the accompanying map are presented here in a new digital format. The original data were compiled in 1924 by Ellen Louise Mertz and comprise field observations of the marine limit in Denmark made over the late 19th and early 20th centuries. The original tables have been transcribed and expanded into a digital database consisting of 658 entries. The original map sheet has been georeferenced and 392 mapped points have been assigned coordinates. The points are linked to their attributes in the digital data table, making them newly amenable to geospatial analysis in a Geographic Information System. To demonstrate, we briefly present one such application, namely a reproduction and verification of the isolines of raised beach elevation from the original 1924 map.

Tabular abstract

Geographical coverage	Denmark
Temporal coverage	Late- and postglacial (latest Pleistocene and Holocene). Original data were collected 1897–1924.
Subject(s)	Quaternary geology
Data format(s)	Data table of geological observations, including elevation values, with newly extracted coordinates, sourced from an historic study and map, re-tabulated and plotted. Data table provided in .csv and .xlsx formats. Point and line data provided as geopackage (.gpkg) files with attribute tables. Overview map provided in .pdf format.
Sample collection & analysis	Digitisation and GIS processing of historic data.
Parameters	Palaeo-shoreline elevations, strandline elevations, coordinates, deposit and landform types.
Related publications	Mertz (1924) and several volumes of the series DGU Række I–II, as listed in database.
Potential application(s) for these data	Palaeo-shoreline elevations are one of the constraints on relative uplift and subsidence of the Danish landmass over geological time scales. As such they are relevant to studies of glacial isostasy, past sea-level change and as an historical component in calibration of future sea-level change estimates.

Introduction

In 1924, Danish geologist Ellen Louise Mertz compiled a database and map of late- and postglacial land-level changes in Denmark (Mertz 1924). These were based on evidence of the marine limit, that is, the highest elevations of palaeo-shorelines. Her data were extracted from several studies published over the preceding three decades. These studies consist of field observations and measurements made by several Danish geologists mapping the country in the late 19th and early 20th century, principally Axel Jessen,

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Abbreviations:
CRS: coordinate reference system
GDAL: Geospatial Data Abstraction Library
GEUS: Geological Survey of Denmark and Greenland
GIS: Geographic Information System
OCR: optical character recognition
SAGA: System for Automated Geoscientific Analyses
SDFI: Danish Agency for Data Supply and Infrastructure
TPS: thin plate spline
UTM: Universal Transverse Mercator
WMS: web map service

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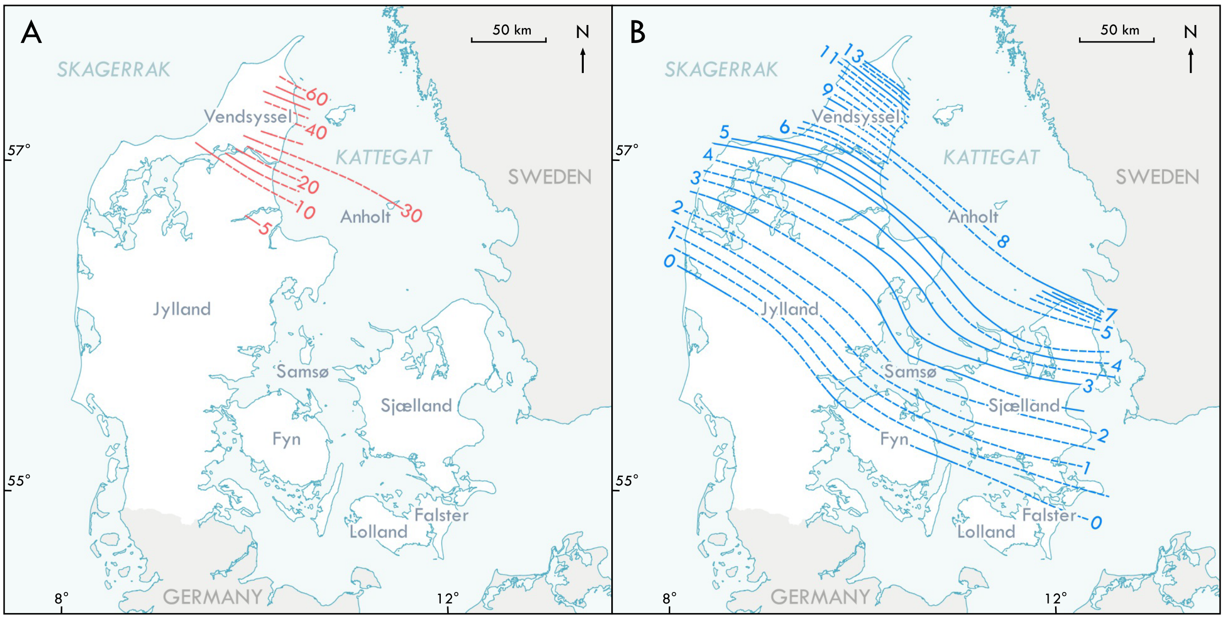

Fig. 1 Maps of Denmark (excluding Bornholm) showing isolines of elevation, in metres above sea level, as drawn by Mertz (1924) for **A**: Yoldia Sea beach deposits (**red**) and **B**: Litorina Sea beach deposits (**blue**). Following the original, **solid lines** indicate isolines that are based on field data, while **dashed lines** are inferred. The scanned 1924 original and new digital maps are provided in Jackson *et al*. (2024; Files S3 and S4, respectively).

Vilhelm Milthers, Kristian Rørdam and Victor Madsen. The entries record the height above sea level of raised beach deposits of various late glacial and postglacial marine phases at several hundred localities across Denmark. Additionally, a smaller number of measurements of negative elevations from now submerged localities are included. Mertz tabulated these measurements and drew a map depicting a large subset of the localities with their respective measurements. On this map, Mertz interpolated isolines of elevation for beach deposits of 'Yoldia Sea' age (late glacial) and 'Litorina Sea [sic]' age (postglacial, *c.* 9500 BP–present), respectively (Fig. 1). The original 1924 study, and particularly the set of 'Litorina Sea' isolines, has become a standard reference for late- and postglacial uplift in Denmark. Google Scholar, in 2023, lists 77 citations since 2000, many of which use a version of the Mertz (1924) map as part of a figure (see Christensen & Nielsen 2008; Gregersen & Voss 2010; Hansen *et al.* 2012; Sander *et al.* 2016). Despite still-frequent reproduction and referencing of the isoline map, so far, the original study has only been available as a scan of a physical copy, in which format the data entries are not themselves amenable to computation. In an age of digital analysis, this presents an obstacle to investigation of the data, which this digitisation aims to remove. The 2024 publication centenary is an apt milestone by which to promote the data set and make it more broadly and easily accessible. To this end, we have transcribed the data from Mertz (1924) into a digital open access database (Jackson *et al*. 2024). Here, we present a newly digitised version of the 1924 map (Jackson *et al*. 2024, File S4), the content of which is distilled in Fig. 1. We also demonstrate an example application of modern GIS methods to the data set, namely the generation of new computed isolines for comparison with the manual isolines drawn by Mertz (Fig. 2).

Study aims, terminology and spelling

The intent of this article is simply to present the data contained in Mertz (1924) 'as-is', albeit, we hope, in a format more amenable to modern use and analysis. We are conscious that, as a century-old article, its content has been built upon, and in some instances superseded, by later advances in the field. This article neither aims to evaluate Mertz's 1924 study nor the views of her contemporaries in the light of this later work and no attempt is made to synthesise the current state of knowledge of these topics. For consistency with the source, we retain the place name spellings used by Mertz, even where they have since changed. Although the 'Litorina Sea' and 'Zirphæa Sea' are correctly spelled *Littorina* and *Zirfaea*, respectively, we preserve the original spellings of Mertz (1924) from here on.

Danish terms pertaining to the type of deposit in Mertz (1924; referred to as 'Aflejringernes Beskaffenhed') are translated to English (Table 1). Additionally, the concept of 'tanglinie' is an important one that warrants brief elaboration. Mertz explains that accurate measurements of land uplift since the Litorina Sea

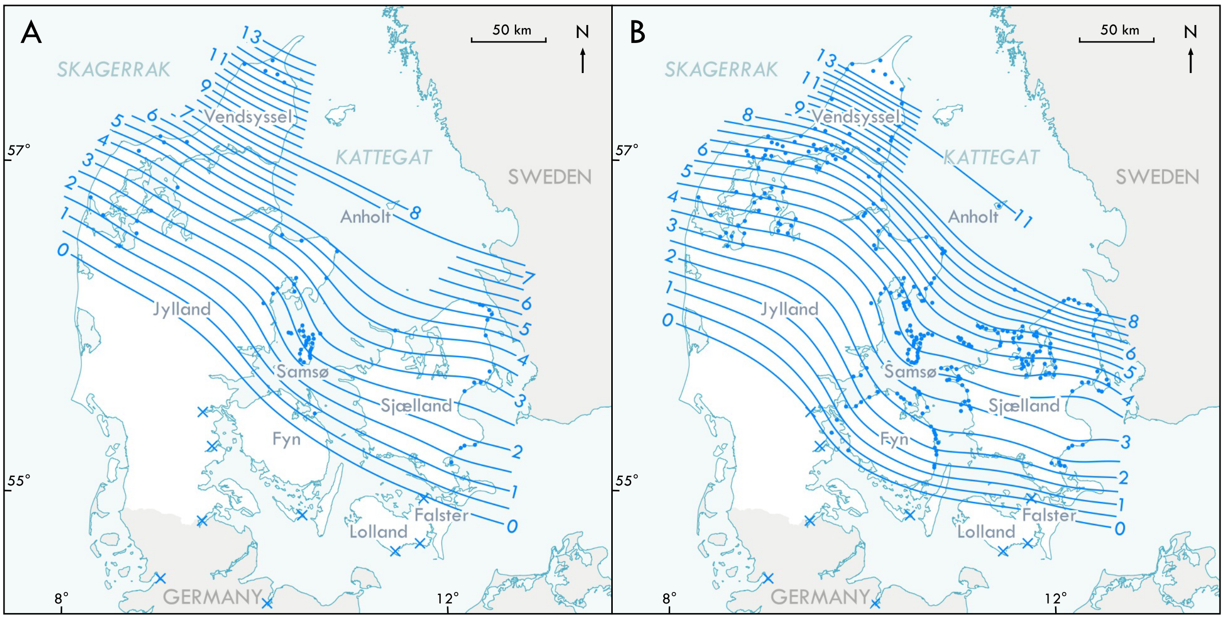

Fig. 2 Maps with new GIS-generated isolines interpolated from Mertz's (1924) Litorina Sea raised beach-elevation point data. The full map is provided in Jackson *et al.* (2024; File S4). The isolines in **A** are interpolated from only 69 strandline-corrected raised beach elevations (**blue dots**), plus nine submerged Stone Age settlements that were used as limiting points (**blue crosses**). The overall shape and zero-line position are in close agreement with the Mertz original, but isolines are more widely spaced towards the north. The alternative map in **B** shows lines interpolated between all 280 Litorina Sea raised beach-elevation values mapped by Mertz, here ignoring strandline correction, plus nine Stone Age settlements as before. This interpolation of the uncorrected data reproduces some features of the Mertz isolines more closely than the corrected data, notably their convergence over north Sjælland and westward curvature over north-west Jylland.

maximum are obtained by subtracting the height of the uppermost ('øverste') tanglinie from the elevation of raised beach deposits. The tanglinie is defined (Mertz 1924, p. 5) as the line of highest wave action. This level is typically marked on an active beach by a conspicuous line of debris, such as seaweed. We suggest 'strandline' to be an appropriate English translation. There can be several such lines on a beach, hence the specification by Mertz of the uppermost strandline. Following Mertz, it is the present-day uppermost strandline, rather than present-day mean sea level, which provides the most appropriate comparison level to former (now raised) beach deposits, when estimating land uplift. This is because raised beach deposits are a better proxy for the former high-wave action-level than they are for the mean sea level at their time of deposition. The new database includes fields from Mertz's original tables and several new fields, all of which are explained in Table 2.

Historic data and mapping

The original data are found in the now discontinued titles published by the Geological Survey of Denmark (Danmarks Geologiske Undersøgelse I–V. Række; *www.geusjournals.org*) between 1897 and Mertz's publication in 1924 (see references in Jackson *et al*. 2024, Files S1 and S2). Many of the volumes consist of map descriptions covering parts of Denmark and include folded maps. Data tables are also often included. The volumes describe a wide range of landforms and geological features, of which beach-ridge systems are one part. In compiling her data table, Mertz evidently extracted data from both the original tables and from the long-form text of the sources. It seems likely that in most, if not all cases, the authors were reporting measurements they themselves had made. In the absence of 'methods' sections or equivalent descriptions of exact methods in the texts, however, we are not able to quantify the uncertainties involved, and we therefore limit ourselves to presenting the measurements as they are compiled in Mertz (1924).

Data extraction

From the original tables

Table entries were read from page scans of Mertz (1924) and initially written into a Microsoft Excel (.xlsx) spreadsheet. Adobe optical character recognition (OCR) facilitated the copying of text data (locality names and comments), with manual corrections as necessary. Numerical data were entered manually but drag-copied where repeated over several rows. Danish text is preserved as it appears in Mertz (1924), including archaisms and older locality names.

Table 1 Summary table providing an overview of the database.

ID[1]	Mertz source table	No. of entries in database[2]	No. of mapped entries[3]	Descriptive categories[4]		
				Original Danish term	Suggested English translation	*n*
2501–2623	Yoldia Sea	97	63	Erosionsterrasse	Wave-cut terrace	46
				Terrassehak	Wave-cut notch	16
				Strandvold	Beach ridge	11
				Accumulationsterrasse	Washover terrace	8
				Strandgrus	Beach gravel	7
				Marine Grænse	Marine limit	2
				Grusrevle	Gravel shoal	1
				Unspecified	-	6
2701–2711	Zirphæa Sea	11	9	Skallag	Shell bed	5
				Kystlinie	Shoreline	4
				Erosionsterrasse	Wave-cut terrace	1
				Kystskrænt	Coastal scarp	1
2801–3301	Ancylus Lake	41	24	Tørv	Peat	37
				Stubbe og Stammer	Relict tree stumps	4
0101–2409	Litorina Sea	493	280	Strandvold	Beach ridge	284
				Havstok	Beach face	40
				Strandgrus	Beach gravel	29
				Terrassehak	Wave-cut notch	26
				Terrasse	Terrace	20
				Marine Grænse	Marine limit	20
				Erosionsterrasse	Wave-cut terrace	16
				Kystlinie	Shoreline	14
				Strandvold og Havstok	Beach ridge and beach face	10
				Kystskrænt	Coastal scarp	8
				Skallag	Shell bed	8
				Grusrevle	Gravel shoal	6
				Tørv	Peat	5
				Accumulationsterrasse	Washover terrace	4
				Unspecified	-	3
0001–0016	Submerged Stone Age settlements	16	16	-	-	-
	Total:	*658*	*392*			

Field names[5]			Origin
Locality	Find_type	DGU_ref	Carried over from original database
Dep_abbr	Note_1924		
Region	Elev_max	SL_range	Expanded from original database
Division	Elev_range	SL_is_appx	
Deposit	E_is_appx	DGU_Vol	
Dep_Eng	SL_min	DGU_page	
Elev_min	SL_max		
Table	X_Coord	Elev_map	Newly assigned or calculated
ID	Y_Coord	E_minus_SL	
Map_point	Note_2024	Mertz_page	

[1]ID number ranges of original entries in the new data set. [2]Tally of entries from respective data tables in Mertz (1924). [3]Subset of entries represented by points on the original map. [4]Breakdown of the descriptive categories assigned to each entry in the original paper, generally a landform or facies. [5]Breakdown of fields in the data set by origin. The first five fields (Locality, Dep_abbr, Find_type, Note_1924, DGU_ref) correspond directly to columns in the original tables, whilst all others either break down the data from a single column over several new columns, or provide information not presented in the original tables.

From the original map

GIS work was carried out in QGIS (version 3.22.0; QGIS Development Team 2021). A digital scan of the Mertz 1:1 000 000 paper map was georeferenced against web map service (WMS) layers published by the Danish Agency for Data Supply and Infrastructure (SDFI). Georeferencing and all subsequent analysis was performed in the Universal Transverse Mercator (UTM) 32N (EPSG:25832) coordinate reference system (CRS) as used by SDFI. Georeferencing features were identified from the content of the base map used by Mertz (issued originally by Generalstabens topografiske Afdeling – General staff topographic department 1925). Both artificial features (e.g. railway bridges) and natural features (e.g. river mouths) were used. A third-order polynomial transformation was necessary to achieve a satisfactory fit of the paper map to the modern reference layers. A total of 100 control points were used for georeferencing. Three reference layers were used:

Table 2 Data fields as they appear in the new digital database, alongside an explanation of their meaning.

Field name	Description
Table	Specifies source table in Mertz (1924): Yoldia, Zirphæa, Ancylus, Litorina, Settlements
ID	Unique identifier. The first two digits identify the table and region.
Region	Broadest locality specification
Division	Intermediate locality specification
Locality	Narrowest locality specification
Map_point	Number to indicate that the entry is represented with a point on the original map. If not, this cell is empty. Numbers are sequential per table, but not unique overall
X_Coord	New value extracted from digitised point geometries
Y_Coord	New value extracted from digitised point geometries
Dep_abbr	Abbreviation for deposit type as recorded by Mertz
Deposit	Danish text transcribed from 'Aflejringernes beskaffenhed' ('Nature of the deposit'). Descriptive categories for facies or landforms recorded at the given elevation.
Dep_Eng	Suggested English translation of descriptive categories (see also Table 1).
Find_type	Applies to archaeological finds only
Note_1924	'Andre oplysninger' (other information) field transcribed from Mertz
Note_2024	Authors' notes
Elev_min	Minimum elevation (Højde over havet) value if original table gives a range. Otherwise, this cell is empty.
Elev_max	Maximum elevation value if original table gives a range. Otherwise, the sole value.
Elev_range	The maximum minus the minimum elevation value.
E_is_appx	Binary field, where '1' indicates that the elevation value for the record is marked as approximate (*c.*) in the original table. Otherwise, this cell is empty.
Elev_map	The elevation value as recorded on the original map. In most cases the same as Elev_max.
SL_min	Minimum strandline (tanglinie) value if original table gives a range. Otherwise, this cell is empty.
SL_max	Maximum strandline value if original table gives a range. Otherwise, the sole value.
SL_range	The maximum minus the minimum strandline value
SL_is_appx	Binary field, where '1' indicates that the elevation value for the record is marked as approximate (*c.*) in the original table. Otherwise, this cell is empty.
E_minus_SL	New, calculated field for raised beach elevation minus strandline. Only applies to cases where both values are available. Otherwise, this cell is blank. The new isolines presented in this article are based on these values.
Mertz_page	Page number of entry in original Mertz table
DGU_ref	Original source reference as listed by Mertz
DGU_Ser	Original reference series
DGU_Vol	Original reference volume
DGU_page	Original reference page

1. The most recent topographic map layer for Denmark (Danmarks Topografiske Kortværk 1:25 000), used for orientation and identification of features by place name and geometry (SDFI 2022a).
2. The most recent orthophoto layer for Denmark (Ortofoto forår, GeoDanmark), for precise placement of control points (SDFI 2022b).
3. A historic topographic map layer for Denmark (Lave målbordsblade 1901–1971), to check, where necessary, that control point features have been stable over the past century (SDFI 2022c).

The geographical coordinates of the locations on the map are based on the scanned, georeferenced map, with a pixel size of approximately 125 m. We estimate the precision of the mapped points to be at best about an order of magnitude coarser, given that each point is about 8–10 pixels wide, or roughly 1 km at scale. Further uncertainty arises from the fact that the placement of points on the original map was based on textual descriptions of their location from the source references. These consist, in some cases, of a cardinal bearing from a named feature (e.g. SW of landmark 'x'), in other cases of a bearing plus an approximate distance (e.g. 1000 m SW of landmark 'x'), and in yet others of a simple indication of proximity (e.g. by landmark 'x'). The size of this uncertainty depends on both the level of detail in the textual description and the level of detail on the base map. This is not straightforward to quantify, but is plausibly at least 1–3 km.

Data processing

Generation of new table

Tabular data were mostly handled in Microsoft Excel. The data in Mertz (1924) are presented in five separate tables, each containing records pertaining to a different phase in the late- and postglacial timeline of Denmark. The new database (Files S1 and S2, Jackson *et al*. 2024) can be viewed either as a single combined table or filtered on the 'Table' column for separate viewing of each table. Each entry was assigned a unique four-digit ID, in which the first two digits identify the geographic subdivision of a given table and the last two identify the specific entry within the same. Some of the fields from Mertz's tables were expanded into more than one field in the new table to ensure consistent information hierarchy and allow filtering of the data. For example, in Mertz's original table, the 'Locality' field contains nested sub-headings for regions, regional subdivisions and individual localities, as well as asterisks to indicate which localities are plotted on the map. These were each allocated their own field in the new table (Jackson *et al*. 2024). Similarly, Mertz's field 'Publiceret I D.G.U. Skrifter' (meaning 'published in Geological Survey of Denmark [DGU] series') lists reference information that was supplemented in the new database with separate fields for series, volume and page number, to make filtering easier. On the original Mertz map (File S3, Jackson *et al*. 2024) all points have only a single value shown adjacent to them, even where the table includes a range of values for a given entry. A new field was added for the elevation value as it is displayed next to the points on the original map, which in most cases corresponds to either the table value or the maximum value of a range, but in a few cases corresponds to the minimum value. The determination as to which value is appropriate for the map was made by Mertz and is simply carried over. Mertz's 'højde over havet' (height above sea level) and 'nutidens øverste tanglinie' (uppermost present-day strandline) fields have been expanded to several fields to provide minimum, maximum and range values where relevant. A further new field gives the calculated difference between the height above sea level and present-day strandline at those localities for which both values are provided in the original table. This field supplies the elevation values used to produce a new GIS version of the isolines (Fig. 2). The elevation values used by Mertz in drawing lines were corrected with respect to strandline elevation, as described by Mertz (1924, pp. 16–18). Our method of isoline contouring differs slightly in that it uses, where possible, the actual georeferenced coordinates and strandline-corrected elevation values of points on the map, rather than the more generally defined areas of the original article. Two comment fields are included: the first transcribes, without alteration, the text from Mertz's 'Andre Oplysninger' (other information) field; the second lists the current authors' notes and is mainly used to acknowledge minor apparent ambiguities in the source tables. New fields were added for the X and Y coordinates of the map points (in m, UTM zone 32N), obtained by georeferencing of the Mertz map as described in the next section.

Generation of the new digital map

Localities marked on the Mertz (1924) map were digitised as points placed at the visually estimated centre of the dots on the original map, generally while zoomed to between 1:100 000 and 1:10 000 scale. They were saved as a points layer in geopackage (.gpkg) format. To facilitate matching the points to the corresponding table records, they were digitised in the same order as they appear on the original tables. For the Litorina table, the points were too numerous for this to be manageable in one sitting, so the map was first sectored manually into smaller geographical areas which, for convenience, followed the pre-existing subdivisions of Mertz's 'Locality' field. Once all points had been mapped, a table join was performed, linking point geometries to all other data fields. X and Y coordinates were extracted and added to the table. Mertz's original isolines (Fig. 1; File S4) were digitised as polylines by manually tracing over the lines on the georeferenced map. Mertz's differentiation between solid, dashed and dot-dashed lines (see p. 40 in Mertz 1924) was represented by the addition of a 'Line style' field to the layer attribute table, and displayed by means of symbology rules. Figures 1 and 2 and a new 1:1 000 000 scale GIS-produced map are provided in .pdf format in Jackson *et al*. (2024; File S4).

Generation of new isolines

In addition to the original Mertz (1924) data points and isolines, we present a new set of isolines for the Litorina data set (Fig. 2A, .gpkg files provided in Jackson *et al*. 2024). These are based on the original data points and values but, unlike the manually drawn originals, were automatically generated using GIS processing tools. They are intended to provide a comparison between GIS methods and the interpreted isolines created for the original study. The new isolines were generated using the thin plate spline (TPS) method from the SAGA (System for Automated Geoscientific Analyses) toolset. An advantage of using a spline interpolation is that it produces reasonable results for areas in which divergent elevation values appear within tight clusters (as occurs in this data set), since the spline is not required to pass through individual data points. However, the spline is consequently an approximation at all points, including at data points. A range of interpolation methods are available, and we have not attempted to assess their respective merits. We limit ourselves to showing that it is indeed feasible to produce isolines that are remarkably congruent with the original using standard GIS tools and relatively light parameter tuning. The spline was assigned with a cell size of 1000 m and regularisation value of 1, with all other parameters at default values (processing steps and parameters for replicating the method are provided in the accompanying .txt file in Jackson *et al*. 2024, File S8). The output of the spline tool is a monochrome raster map of elevation values. This was contoured using the Contour tool from the Geospatial Data Abstraction Library (GDAL). The contouring interval is 0.5 m, and the range is 0–13 m, as in Mertz (1924), for easy comparison. As in the original, the Litorina isolines are based on a subset of points whose elevation is corrected by subtracting strandline elevation values. In Mertz (1924, p. 17–18) this is based on field measurements from at least 43 localities. The new Litorina isolines are based on 69 values calculated by subtracting the strandline from elevation values in the newly digitised data table. Also contributing to the interpolation are nine negative elevation values for submerged Stone Age settlements in the south and west of the map area, which helped to constrain the position of the 0 m elevation isoline. An alternative set of Litorina isolines was interpolated using all 280 mapped Litorina elevation values, at the expense of correcting for strandline elevation (Fig. 2B).

Data description and main features

The data set consists of a list of observations pertaining to late- and postglacial marine limits and transgressed ancient settlements. The key parameter in the database is elevation. Most entries record raised beach deposits, which are taken to indicate vertical displacement of a locality since the time of deposition. Maximum elevation values in such cases record the highest observed beach deposit at a given locality for a particular marine phase but should be considered asynchronous within each phase. The database (Files S1, S2) contains 658 entries, of which 392 are shown on the map produced by Mertz (1924). The selection of points represented on the map follows Mertz's own and the placement of points by Mertz is presumed to have been interpreted from the text of the sources. The coordinates listed in the new database do not originate from these sources, as they do not provide numerical coordinates, but are extracted from the digitisation of the georeferenced paper map. We have not attempted to interpret the location of further points from the text. The mapped points are symbolised in both the original (File S3) and new map (File S4), according to their source table in Mertz (1924). The unmapped points in the tables have no associated coordinates, though their approximate position can generally be inferred from the textual descriptions. Here, we provide a brief account of the distribution of each set of mapped points and isolines as shown on both the original and new maps (Files S3 and S4).

Yoldia Sea

Late glacial. Shown as red dots. Mapped points (63 in total) of Yoldia Sea deposits occur exclusively in northern Jylland – mostly in Vendsyssel and around Limfjorden, with one point on Anholt – as well as on Bornholm. Their elevation values range from 6.0 m to 57.0 m and generally increase towards the north and east.

Zirphæa Sea

After Yoldia Sea maximum. Shown as green dots. All mapped Zirphæa deposits (9 in total) are located in a small part of northern Vendsyssel, mostly near the northern coast and all within 40 km of each other. Elevation values range from 6.0 m to 24.0 m and are highest in the south.

Ancylus Lake

Timing is the subject of discussion but ending *c.* 8000 BP (before present). Shown as brown dots. The points from the Ancylus Lake time (24 in total) represent peat deposits and have negative values. They occur in a broad band trending WSW–ENE across southern Denmark and Sjælland, as well as a cluster around Limfjorden and one locality on Bornholm. They range from –0.3 m (Samsø) to –20.0 m (northern Germany).

Litorina Sea

Postglacial, after *c.* 9500 BP. Shown as blue dots. The Litorina Sea points are by far the most numerous (280 in total). They are also the most geographically widespread, excluding the west and far south of the map area, from which they are absent. Their values range from 1.5 m to 14.9 m, generally increasing towards the north and east. Some areas are particularly densely sampled, such as around Limfjorden and Roskilde Fjord, and especially the island of Samsø. Among those points that have strandline values in the database (i.e. those which form the basis of the isolines in Fig. 2), Limfjorden and Roskilde fjord are conversely underrepresented, while Samsø remains overrepresented.

Submerged Stone Age settlements

Shown as blue crosses. Former settlements, at present submerged, are mapped across the southern part of the map area. Of these, nine are ascribed (negative) values, ranging from –1.1 m to –9.0 m, generally becoming more negative towards the south and east. These sites served as limiting points in the automated isoline interpolation. Seven localities are mapped that lack an elevation value, though implicitly they have an upper limit of 0 m.

Isolines

Yoldia Sea isolines (Fig. 1) interpreted by Mertz (1924) trend WNW–ESE across the eastern coast of Vendsyssel. They are generally evenly spaced at about 5–7 km, except for the 5.0 m (lowest elevation) isoline, which is over 20 km south of the 10 m isoline. Isolines on Bornholm have the same trend but are roughly twice as closely spaced.

Litorina Sea isolines (Fig. 2) interpreted by Mertz (1924) trend broadly NW–SE, with a gently sinuous course that inflects over the southern Kattegat. The 0 m isoline descends from the west coast of Jylland to bisect Fyn and exits Denmark at the island of Falster. Isolines from 0 m to 5.0 m are roughly evenly spaced at about 10–12 km. Isolines above 5.0 m undergo an apparent step change and are spaced more closely, at about 4–6 km, slightly tightening progressively NE. Isolines above 5.0 m converge markedly over the northernmost part of Sjælland. Litorina isolines on Bornholm trend WNW–ESE and have similarly close spacing to those on northern Sjælland. The trend of the Litorina isolines in Vendsyssel is rotated slightly clockwise relative to that of the Yoldia isolines, while the inverse is the case on the island of Bornholm. Note that isolines are not traced continuously from the Danish mainland to Bornholm in Mertz (1924) or this article.

Remarks on the new GIS-produced isolines

Computationally interpolating new isolines from the original data can help to assess how well the original manual isolines represent the underlying values. For example, over the island of Samsø, in the centre of the map area, there is a pronounced deviation in both the original 1924 (Fig. 1) and newly rendered Litorina isolines (Fig. 2). The appearance of this pattern in the computed isolines can be taken as corroboration that the shape of the manual isolines is indeed reflective of the elevations in this area. Conversely, the isolines crossing north Sjælland are drawn on the original map as converging strongly eastwards. This convergence appears weaker in the automatically generated isolines based on 69 strandline-corrected elevations (Fig. 2A), suggesting that the underlying values do not support such strong convergence. However, when interpolating elevation using all 280 data points, without considering strandline correction, this convergence reappears quite strongly, while also inaccurately offsetting all isolines towards the SW (Fig. 2B). This suggests that both corrected and uncorrected values were in fact considered in the construction of the original isolines, despite their being explicitly based only on corrected values. In general, point density appears to influence the shape of isolines, in effect attracting them to converge over densely sampled areas (as on the eastern coast of Sjælland, Fig. 2). We infer that the accuracy of the isolines is affected by an uneven geographic distribution of points, highlighting the potential value of incorporating additional data to achieve more even data distribution. Mertz did not connect her isolines across to Bornholm from the Danish mainland, and nor have we. We note that any automatic isoline generation clearly lacks Mertz's awareness of the overarching geological context, and this might be expected to account for some divergence in the outcome. We speculate that Mertz's Litorina isolines are, for sound geological reasons, a non-uniform treatment of the data, and may not be perfectly replicable from the numerical values. However, overall, if not in detail, the results of the automatic interpolation agree remarkably well with Mertz's interpretation.

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Additional information

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Authors' contributions

KSV and KKK: conceptualisation, supervision, editing.
SPJ: analysis, original draft.

Competing interests

The authors declare no competing interests.

Additional files

Thirteen additional files are available at: https://doi.org/10.22008/FK2/PI4GXI

These comprise:

Files S1 and S2: the main database table in two formats: **File S1** (Mertz 1924 Data Table 2024.csv) and **File S2** (Mertz 1924 Data Table 2024.xlsx).

File S3: a scanned copy of the original 1924 Mertz map (Mertz 1924 Map Original.png).

File S4: the newly digitised 1:1 000 000 scale map with GIS-generated isolines (Mertz 1924 Map 2024.pdf).

File S5: Fig. 1 from this study using original Mertz isolines.

File S6: Fig. 2 from this study using newly produced isolines.

File collection S7: geopackage files containing GIS point and line data (six files: S7a-f).

File S8: instructions on isoline processing steps (Mertz 1924 Isoline Processing Steps.txt)

References

Christensen, C. & Nielsen, A.B. 2008: Dating Littorina sea shore levels in Denmark on the basis of data from a Mesolithic coastal settlement on Skagens Odde, Northern Jutland. Polish Geological Institute Special Papers **23**, 27–38.

Gregersen, S. & Voss, P. 2010: Irregularities in Scandinavian postglacial uplift/subsidence in time scales tens, hundreds, thousands of years. Journal of Geodynamics **50**(1), 27–31. *https://doi.org/10.1016/j.jog.2009.11.004*

Hansen, J.M., Aagaard, T. & Binderup, M. 2012: Absolute sea levels and isostatic changes of the eastern North Sea to central Baltic region during the last 900 years. Boreas **41**(2), 180–208. *https://doi.org/10.1111/j.1502-3885.2011.00229.x*

Jackson, S.P., Svennevig, K. & Kjeldsen, K.K. 2024: Ellen Louise Mertz's 1924 'Overview of late- and postglacial elevation changes in Denmark' (V.1). GEUS Dataverse. *https://doi.org/10.22008/FK2/PI4GXI*

Mertz, E.L. 1924: Oversigt over de sen- og postglaciale niveauforandringer i Danmark. Danmarks Geologiske Undersøgelse, II. Række **41**, 49 pp. *https://doi.org/10.34194/raekke2.v41.6827*

QGIS Development Team 2021: QGIS Geographic Information System, (Version release date: October 2021) Open Source Geospatial Foundation Project. *https://www.osgeo.org/projects/qgis/*

Sander, L., Hede, M.U., Fruergaard, M., Nielsen, L., Clemmensen, L.B., Kroon, A., Johannessen, P.N., Nielsen, L.H. & Pejrup, M. 2016: Coastal lagoons and beach ridges as complementary sedimentary archives for the reconstruction of Holocene relative sea-level changes. Terra Nova **28**(1), 43–49. *https://doi.org/10.1111/ter.12187*

SDFI (Danish Agency for Data Supply and Infrastructure) 2022a: Danmarks Topografiske Kortværk 1:25 000. *https://dataforsyningen.dk/data/956* (accessed December 2022).

SDFI (Danish Agency for Data Supply and Infrastructure) 2022b: Ortofoto forår - GeoDanmark. *https://dataforsyningen.dk/data/981* (accessed December 2022).

SDFI (Danish Agency for Data Supply and Infrastructure) 2022c: Lave Målebordsblade. *https://dataforsyningen.dk/data/4519* (accessed December 2022).