



Continuous record of Holocene sea-level changes and coastal development of the Kattegat island Laeso (4900 years BP to present)

Hansen, Jens Morten; Aagaard, Troels; Stockmarr, Jens; Moller, Ingelise; Nielsen, Lars; Binderup, Merete; Larsen, Jan Hammer; Larsen, Birger

Published in:
Geological Society of Denmark. Bulletin

Publication date:
2016

Document version
Publisher's PDF, also known as Version of record

Document license:
[CC BY](#)

Citation for published version (APA):
Hansen, J. M., Aagaard, T., Stockmarr, J., Moller, I., Nielsen, L., Binderup, M., ... Larsen, B. (2016). Continuous record of Holocene sea-level changes and coastal development of the Kattegat island Laeso (4900 years BP to present). *Geological Society of Denmark. Bulletin*, 64, 1-55.

Continuous record of Holocene sea-level changes and coastal development of the Kattegat island Læsø (4900 years BP to present)

JENS MORTEN HANSEN, TROELS AAGAARD, JENS STOCKMARR, INGELISE MØLLER, LARS NIELSEN, MERETE BINDERUP, JAN HAMMER LARSEN & BIRGER LARSEN



Hansen, J.M., Aagaard, T., Stockmarr, J., Møller, I., Nielsen, L., Binderup, M., Larsen, J.H. & Larsen, B., 2016. Continuous record of Holocene sea-level changes and coastal development of the Kattegat island Læsø (4900 years BP to present). © 2016 by Bulletin of the Geological Society of Denmark, Vol. 64, pp. 1–55. ISSN 2245-7070. (www.2dgf.dk/publikationer/bulletin).

Received 30 June 2014
Accepted in revised form
9 May 2015
Published online
28 January 2016

Læsø is the largest island of the Kattegat–Skagerrak region and exposes a vast array of relative sea-level (RSL) indicators, mainly raised beach ridges, swales, lagoons and saltmarshes. The physical environment of continuous glacial rebound, excessive supply of sediment, shallow surrounding waters, low amplitudes of near-shore waves, and micro-tidal conditions produced numerous sea-level proxies of both barrier coasts and saltmarshes. About 1200 RSL/age index points reflect not only short-term sea-level highstands as in most other parts of Europe, but also short-term sea-level lowstands, which in less regressive environments have normally been removed by coastal erosion or obscured by berms from subsequent highstands. Based on a high-precision lidar digital terrain model, the beach ridges have been mapped, typified, levelled and correlated relative to their order of appearance. Transformation of this relative chronology to a robust absolute age model of the RSL changes has been made on the basis of 119 optically stimulated luminescence (OSL) datings, ^{14}C datings, and tree-ring datings. By ground penetrating radar (GPR) and terrain analyses, the height of the swash zone (run-up) has been determined in order to transform the ridge elevations to a detailed curve of the RSL/age relation. The curve reveals eight centennial sea-level oscillations of 0.5–1.1 m superimposed on the general trend of the RSL curve, including a Little Ice Age lowstand of 0.6 m at 1300 AD. The island grew from now eroded landscapes of Weichselian glacio-marine deposits, including the oldest known post-Weichselian forested area in Scandinavia. During the last 4900 years new coastal landscapes have formed continuously, resulting in around 4000 km of still visible, raised palaeo-shorelines in mostly uncultivated landscapes. After formation of the oldest preserved beach-ridge complex, numerous sea-level proxies formed in a strongly regressive environment caused by glacial rebound supplemented with local uplift due to extensive erosion during Boreal and Atlantic time of the 1700 km² glacio-marine platform upon which the island is still being built. The combined uplift produced a relative sea-level fall of 10.3 m, corresponding to a mean vertical regression rate of 2.1 mm/year and a mean horizontal regression rate of 2 m/year, and formed eight distinct types of raised coastal landscapes where well separated beach ridges and saltmarshes developed continuously.

The oldest preserved part of Læsø appeared 4900 years BP as the eastern tip of a 10 km long barrier-spit system growing from a raised glacio-marine landscape, now represented only by boulder reefs west and north-west of the present island. Around 4000 years BP another barrier-spit system appeared to the south, growing northwards from another raised glacio-marine landscape at the raised boulder reefs in the town of Byrum and the abrasion landscapes of Rønnerne. Around 3000 years BP these two initial barrier-spit systems united and formed one major barrier between the present towns Vesterø and Byrum. To the north-east, a third glacio-marine landscape provided materials for the development of the eastern end of the island. Thus, around 2500 BP the island had become one triangular, completely detached island ('the old triangle') between Vesterø, Byrum and Bansten Bakke. From this detached stage, nine subsequent barrier-spit systems grew to the east and formed the present Østerby peninsula, while a series of nine barrier-island complexes developed south-west of 'the old triangle'. To the south and south-east, low-energy coasts developed and formed low beach ridges and saltmarsh landscapes.

Keywords: Læsø, Holocene, beach ridge, relative sea-level curve, isostatic rebound, Lidar DTM, optically stimulated luminescence (OSL) dating.

Jens Morten Hansen [jmh@geus.dk], Jens Stockmarr [sto@geus.dk], Ingelise Møller, Merete Binderup, Birger Larsen, Geological Survey of Denmark and Greenland (GEUS), Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. Troels Aagaard [taa@ign.ku.dk], Lars Nielsen [ln@ign.ku.dk], Department of Geosciences and Natural Resource Management, Copenhagen University, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. Jan Hammer Larsen [jhl@kystmuseet.dk], Coastal Museum of Northern Jutland, Bangsbo Division, Dronning Margrethesvej 6, 9900 Frederikshavn, Denmark.

The island of Læsø covers an area of 118 km² and is situated in northern Kattegat in the transition zone between the Baltic Sea and the North Sea. The main island and about 50 islets in its vicinity are situated on a platform with water depths less than 10 m, covering around 1700 km². The area inside the 3 m isobath covers around 400 km². An area of about 208 km² is covered by less than 0.3 m of water and comprises the present islands and a 90 km² temporarily dry sand platform south of the main island (Fig. 1, Fig. 2).

In contrast to all other major marine forelands of the Skagerrak, Kattegat, Danish Straits and the south-

ern Baltic Sea, Læsø has no central or marginal core of an older and more elevated landscape of different origin than the marine foreland itself (cf. the general hypothesis on the formation of marine forelands by Schou 1945, 1969a–g). Except for several residual boulder reefs, no such *xenomorphic landscapes* of different origin and sediment composition have been preserved within the present coastline of the island.

The present vegetation and animal wildlife on Læsø possess many characteristics of remote islands (cf. EU's *Natura 2000* plan for Læsø at www.laesoe.dk and the proposal by Olesen (2005) of Læsø as Marine

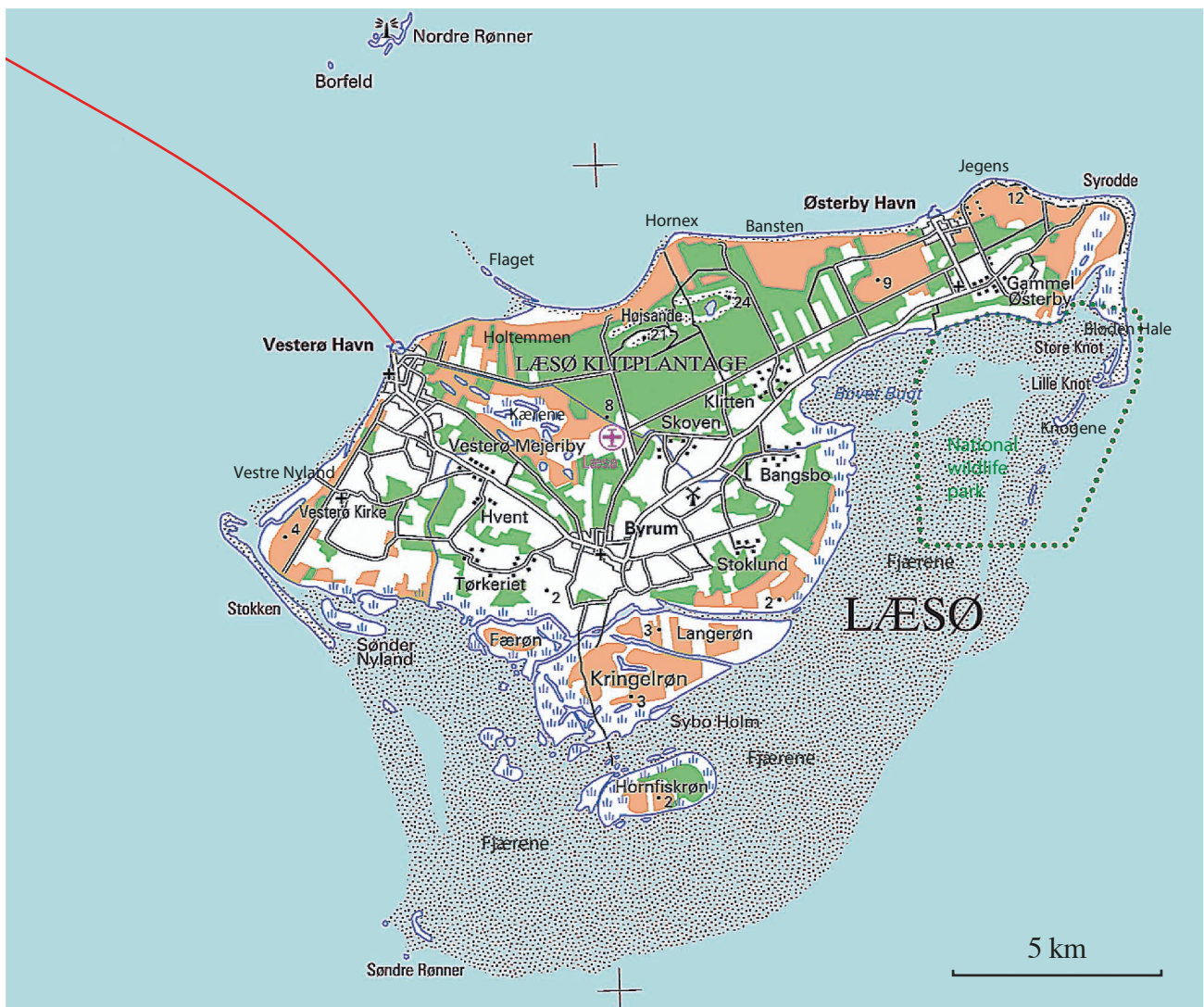


Fig. 1. Topographic map of Læsø. Map copyright Geodatastyrelsen 2006, with some place names added. Size of figure is 30×30 km. Geographical position: 11°00' E, 57°10' N (lower cross); 11°00' E, 57°20' N (upper cross).

National Park). However, some geological, archaeological and biological studies indicate that the island was once attached to older, now completely eroded landscapes and has a considerably longer history than indicated from its present wildlife, outline, position and shoreline ages (Hansen 1995, 2015; Bradshaw *et al.* 1999).

Thus, a robust description of the coastal history of Læsø should provide explanations for how detachment of the island from older and more elevated (xenomorphic) landscapes eventually took place, how initial stages of the outline and position of the island have been altered by erosion and redeposition, and how younger, detached stages of the island developed.

Based on such reconstructions it is our intention to present a relative sea-level curve for the past 4900 years, which greatly extends the findings of Hansen *et al.* (2012) for the past *c.* 900 years.

Pre-history of Læsø until the development of late Holocene coastal landscapes

This chapter gives a brief review of the late Quaternary history of the central northern Kattegat region. It touches on some issues which have been clarified by the present study and are presented later in the text, but which are needed in the context here.

The early, middle and late Weichselian glaciomarine environment of the Kattegat region

Compared to other major parts of Danish waters the Quaternary geology of southern Skagerrak and northern Kattegat has been considerably less studied. Consequently, specific knowledge about the Quaternary structure is sparse around Læsø and to some

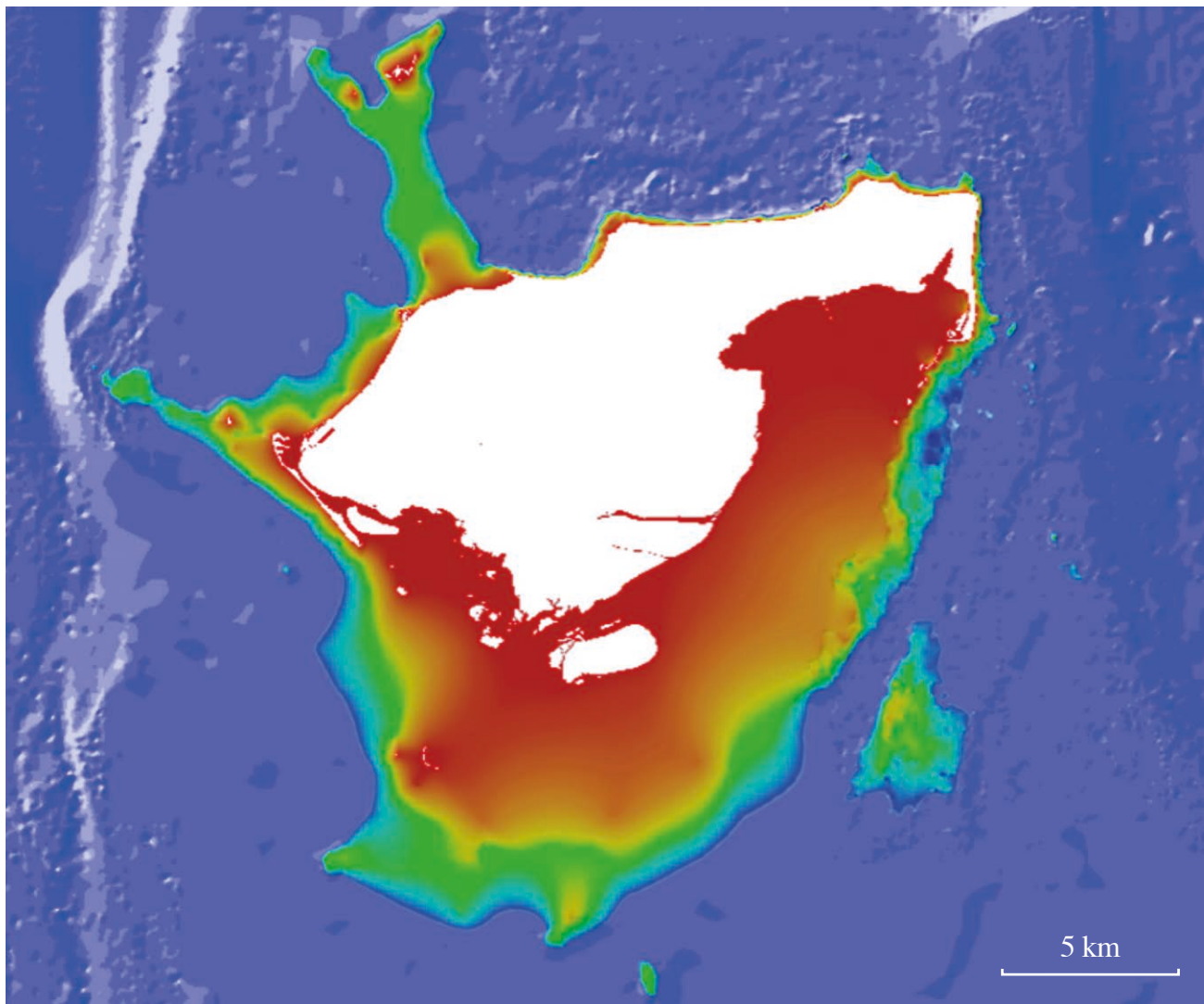


Fig. 2. Topography of the seabed around Læsø. Blue: water depths of 10 to 3 m. Other colours: water depths of 3 to 0 m. White: land. Size of figure is 35×35 km. Compiled by the Geological Survey of Denmark and Greenland.

extent rests with general conceptions derived from neighbouring regions. Until the Litorina transgression peaked in the Læsø region *c.* 6300 years BP (Christensen 1995), the landscape of northern Kattegat was probably characterized by landforms that had mainly been formed by glacial load and some glacio-tectonic deformation (Larsen *et al.* 1986; Bahnson *et al.* 1986; Vangkilde-Pedersen *et al.* 1993) of the >180 m thick deposits of early to middle Weichselian glacio-marine clays and silts (Bahnson 1986) which in this work are OSL (optically stimulated luminescence) dated to the period 37000–19000 years BP. As seen from correlations of five scientific boreholes (Bahnson *et al.* 1986) and from beach exposures along northern Læsø, these partly fossiliferous glacio-marine clays and silts have been glacio-tectonically deformed by the Scandinavian ice cap when it covered the Kattegat area during the early to middle Weichselian.

On top of the compacted glacio-marine formation, much less compacted late Weichselian glacio-marine clays and silts form a 0–15 m blanket of partly eroded deposits (on Læsø dated to the period 13800–12900 years BP, Table 1) which is mainly preserved in depressions in the glacially compacted and deformed landscape of early to middle Weichselian glacio-marine deposits. This second series of glacio-marine clays and silts was deposited when the Scandinavian ice cap had melted back to a line east of Læsø near the Swedish west coast.

As in most other parts of the central northern Kattegat area, no strictly glacial deposits in the form of diamictic tills and moraines have been found on Læsø, neither in the five scientific boreholes of Bahnson *et al.* (1986) nor in the approximately 200 geotechnical wells (for water supply and after natural gas) that have been made on Læsø (Fredericia 1985; for updates see the well database Jupiter at www.geus.dk). A similar situation exists in large parts of the northern Kattegat sea where Weichselian tills and moraines are extremely sparse (Lykke-Andersen 1992a, b; Lykke-Andersen *et al.* 1993a, b).

Thus, the common conception of a Weichselian ice cover of Kattegat including the Læsø region is mostly founded in necessity from robust models of the Weichselian glaciation of more south-western parts of Denmark (e.g. Houmark-Nielsen 2003, 2004; Houmark-Nielsen & Kjær 2003). The most robust empirical indications of a Weichselian ice cover of the Læsø area are ‘extradomainal’ glacial deformations (Bahnson *et al.* 1986) and, as seen from several geotechnical reports from constructional works on Læsø, an evident glacial load compaction of the early to middle Weichselian glacio-marine deposits. Such extradomainal glacial deformations, without preserved tills and moraines from the glaciers which have caused the deformations, are frequent in most parts of Denmark, and the

concept of extradomainal deformation constitutes an important basis for the glacial kineto-stratigraphy (Berthelsen 1978) and the general glacial stratigraphy of Denmark (Houmark-Nielsen 2004).

The early, middle and late Weichselian glacio-marine substrate of Læsø has been cut by a near-surface fault with up to 4 m vertical throw that passes through the southern part of the island (Hansen 1986); cf. Japsen & Britze (1991), Vejbæk & Britze (1994) and discussion in Gregersen & Voss (2014). The fault is related to the Fennoscandian Border Zone (or Sorgenfrei–Tornquist Zone) and probably developed during the relatively fast glacial isostatic adjustment (GIA) in the early Holocene, similar to major faulting effects of the GIA in south-western Sweden (see discussions on GIA-related neotectonics and seismicity in Mörner 1978, 1995, 2014 and Bungum *et al.* 2010).

The Boreal regression

During Boreal time the Læsø region formed the northern part of a large emerged landscape stretching from Sjælland to 10 km north of Læsø, surrounded to the west and east by rivers streaming northwards from the Baltic Sea through Lillebælt, Storebælt, Øresund and from fjords in eastern Jutland. Evidence for the existence of this landscape is also mainly built on necessity from robust models of the Boreal period in Denmark and Sweden (Iversen 1967; Noe-Nygaard *et al.* 2006). On Læsø, additional evidence comes from two ¹⁴C datings: One is of a Pinus trunk found in situ in 2010 by one of us (JHL) about 1 km south-west of Læsø at a water depth of 2 m, and in this work ¹⁴C-dated to 10274 years BP (calibrated). Another ¹⁴C dating is of a reworked lump of fresh-water gyttja in the sea cliff north of Vesterø Havn, dated by Mörner (1969) to 7750 years BP. Applying Mörner’s (1969, 1980) and Pässe & Anderson’s (2005) isostatic baselines for the south-westwards tilting of south-western Scandinavia after late glacial time, the –2 m level of the Læsø pine trunk fits well with Krog’s (1965, 1968) finding of slightly younger pine trunks below –23 m in Storebælt.

The Atlantic Litorina transgression and erosion

The Boreal landscape that formed on top of the >180 m thick deposits of glacio-marine clays, silts and coarser ice-rafted materials was drowned during the so-called Litorina transgression. As the Litorina sea successively inundated the landscapes of the Kattegat region, substantial erosion took place and the upper parts of the clayey and silty pre-existing formations were eroded to leave a widespread residual conglomerate composed of coarse materials that were originally contained in the clays and silts of the glacio-marine formations (Hansen 1995, 2015; Hansen *et al.* 2012).

While the erosion by the Litorina transgression

mostly formed prominent sea cliffs in the glacial landscapes along the margins of Kattegat (Schou 1945, 1969d), the Litorina sea erosion of the Læsø region is represented by a large number of boulder reefs (Fig. 3) at distances of up to 12 km from the present island. In other parts of central Kattegat only one small 'knoll' was not completely transgressed and eroded to the levels of the Litorina transgression (Jessen 1897, 1936; Lykke-Andersen 1990); this knoll constitutes the western side of the island of Anholt 70 km SSE of Læsø, where a 5 km² glacial landscape is surrounded, mainly to the east, by 17 km² of Holocene beach deposits to a maximum level of 13 m above present mean sea level (MSL) (Bjørnsen *et al.* 2008; Clemmensen *et al.* 2012b).

The many boulder reefs of the northern Kattegat area – as well as a 0.5–2 m thick continuous abrasion conglomerate on top of the glacio-marine deposits and below the Holocene marine deposits on Læsø – have been derived by erosion of the two glacio-marine deposits in which boulders and other types of coarse material were dropped from melting icebergs during both the early and late Weichselian marine periods (Jessen 1897, 1922; Hansen 1977, 1995, 2015; Bahnson *et al.* 1986). Four nearly identical ¹⁴C datings of *Balanus* and *Mytilus* adhering to large boulders that were dug out of the residual conglomerate at both the north and the south coast of Læsø indicate that the erosion of the glacio-marine and Boreal landscape had ceased around 3200 years BP (Table 1), and the landscape had become covered by younger marine sand within the outline of the present island.

During this work, we obtained OSL age determinations of marine sand deposits at the highest possible position in

the oldest part of present Læsø. The results indicate that the area became sea-covered no later than 6300 years BP and remained so until the present island emerged c. 4900 years BP (Table 1, plot in Fig. 15). Thus, the Holocene archipelago of Læsø has been deposited on top of a diachronous abrasion platform formed from the onset of the Litorina transgression of the region prior to 6300 years BP until c. 3200 years BP. Beneath and around Læsø this abrasion platform is found in an area of about 400 km² with a top level of –4 to +2 m above MSL (Hansen 1977, 1995, 2015; Hansen *et al.* 2012; cf. Larsen *et al.* 1986).

Glacial isostatic adjustment (GIA) and local relaxation uplift

Compared to analogies in northern Jutland (Denmark) and Halland (Sweden), the raised beach deposits of Læsø are found at 1–3 m higher levels than should be expected (Hansen 1977, 1980, 1995; Bahnson *et al.* 1986). Hansen *et al.* (2012) described how this level difference may be caused by a supplementary, isostatic relaxation uplift that occurs in northern Kattegat in response to the above described Holocene erosion of pre-existing landscapes. By granulometric comparison of the eroded glacio-marine deposits with the re-deposited coarser material which has formed the Holocene beach, dune and marine deposits at Læsø, it was calculated that c. 10 m of glacio-marine clay and silt had been removed from the platform, and that this unloading would have accelerated the GIA, provided that the eroded material was transported a sufficient distance away from Læsø. Moreover, during the late Weichselian glacio-marine transgression, relative sea level rose to c. 70 m above MSL (Jessen 1922, Mertz 1924).



Fig. 3. Nordre Rønner (viewed from north-east), a raised boulder reef with a lighthouse, 8 km north of Vesterø Havn (Fig. 1). (Photo: Eigil Holm).

Thereafter, unloading of a substantially larger water column in northern Kattegat than in the higher terrains of northern Jutland and western Sweden may have further accelerated the isostatic uplift of the central part of the region. By comparison of uplift rates of the youngest saltmarsh shorelines at Læsø with uplift rates of the tide gauges at the same GIA isolines in Jutland and western Sweden, Hansen *et al.* (2012) found that the supplementary relaxation uplift would presently be 0.82 mm/yr added to the regional glacial rebound of the tide gauges (GIA presently 1.50 mm/year) yielding a total present isostatic uplift of Læsø by 2.32 mm/year.

Methods and data

The reconstruction of the coastal development and relative sea levels of Læsø is mainly based on three new sets of data. These are, firstly, a detailed digital terrain model (part of governmental 'Denmark's Elevation Model', see description below); secondly, 119 absolute age determinations, mainly OSL datings (see age model below and Table 1); and thirdly, 15 km of ground penetrating radar (GPR) profiles measured in 2009, supplementing Andreasen's 50 km of GPR measured in 1986 (report from Læsø Kommune 1989), some

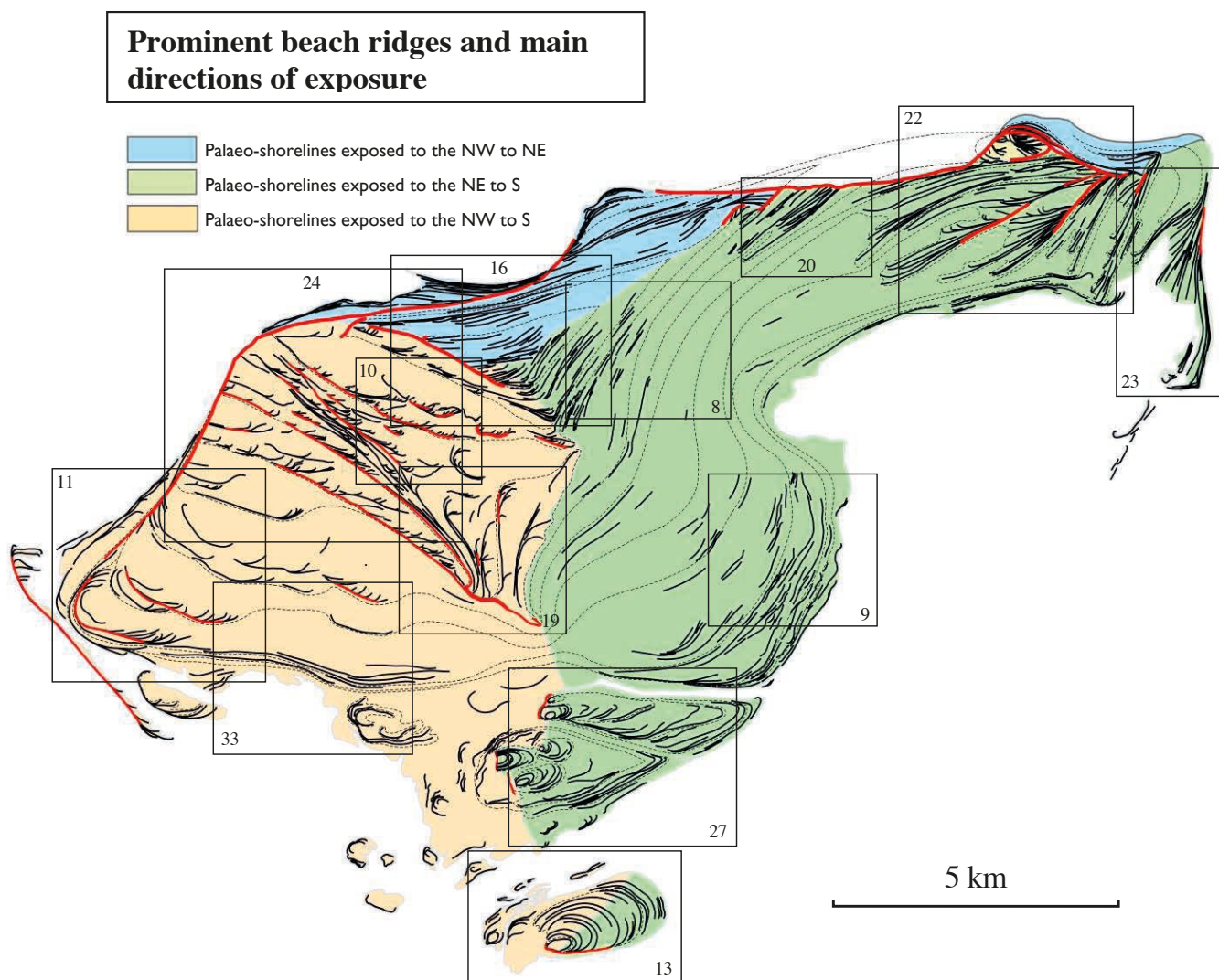


Fig. 4. Overview map of the most prominent beach ridges of Læsø, where around 4000 line-kilometres of such palaeo-shorelines are still visible. Three regions show where beach ridges have been exposed to the north (blue), to the south-east (green), and to the south-west (brown). Red lines indicate erosional structures such as brinks and cliffs. Dotted curves: Timelines (isochrons of the age model in Fig. 36). Black frames indicate locations of text figures of maps of the digital terrain model. Frame numbers refer to figure numbers.

of which have previously been published (Hansen 1995). The applied methods are described below.

Beach-ridge mapping, chronology and levelling

Mapping, chronological order and present levels of beach ridges have been determined from a digital terrain model (DTM) produced in 2006 from an advanced airborne laser-scanning survey. The real grid cell size of this DTM is c. 3 m² and the global, vertical precision is generally claimed by the lidar company to be better than 6 cm. Our independent Differential GPS level control on Læsø shows that the global (absolute), vertical precision is better than 4 cm in two separate test areas (Stoklund and Bansten Bakke). Moreover, we found that the local (relative) vertical precision of the present shoreface of the large sand flat south of Læsø, which was partly dry the day the DTM was measured, is c. 1 cm within distances of 1 km or more.

Determination of beach-ridge levels

From the DTM, levels of 1200 transects with a length of 100–500 m have been measured in three main areas (Fig. 4) where the ridges have been exposed to the north, south-west and south-east, respectively, and where the relative chronology of ridges is easily established (see below). The transects were oriented along the beach-ridge crests in order to determine the mean *base level of ridge crests* (BLRC) of each transect. By applying the base level of the crest transects, small aeolian dunes on top of the ridge crests as well as obvious erosional structures and ditches can be excluded. For each of the beach-ridge transects, the mean z coordinate (elevation) of the BLRC was calculated both manually and by a general mathematical algorithm, excluding outliers such as minor peaks (mainly small dunes) and narrow lows (mainly deflation carvings and ditches). The method is illustrated in Hansen *et al.* (2012, figs 2, 3).

The significance of applying base levels of beach-ridge crests (reduced for height of swash) for RSL reconstruction – instead of swale levels and other types of RSL proxies – is discussed later.

Absolute age determinations

All absolute age determinations known to us (November 2014) of materials from Læsø are listed in Table 1. Of these, 20 ¹⁴C, tree-ring and thermo-luminescence datings have previously been published in various contexts. For this work, we have acquired 99 new absolute age determinations. ¹⁴C datings have been performed at the AMS-laboratory at Aarhus University. OSL datings have been performed at the Nordic Laboratory for Luminescence Dating, Risø,

Denmark, and the Labor OSL laboratory, Waterville, USA. Tree-ring datings of a large, buried medieval vessel were performed at Moesgaard Museum, Aarhus.

Age modelling of coastal progradation

After identification of the oldest preserved beach ridge (see later section “4900–4000 years BP”), the age model presented here of the coastal progradation builds on four independent sets of chronology data:

- 1) observed, relative chronology of, and distances between, the numerous beach ridges.
- 2) absolute age determination of a number of selected beach ridges (Table 1), supplemented with
- 3) absolute age determinations of marine and terrestrial deposits that respectively pre-date and post-date beach deposits (Table 1, plot in Fig. 15).
- 4) cultural evidence such as ages and positions of archaeological finds, ages and positions of medieval churches, the settlements and agricultural phases of the island, ages and positions of ancient harbour and vessel finds, the positions of c. 1700 known ruins after medieval and renaissance salt production huts built on the contemporaneous shores on southern Læsø, and the position of shorelines on old reliable maps.

Of these four datasets, 1) and 2) are most important for building the age model, while 3) and 4) must not contradict the age model.

By applying the classical Stenonian principles of superposition and intersection, the exact chronological order of all observable beach ridges can be established within each of the three main areas.

Until recently, correlation of beach ridges between the three main areas of Læsø has been a major problem because the beach ridges of the three areas (Fig. 4) are only sporadically interconnected and traceable between the areas. Thus, until development of the detailed DTM, a complete history of the entire island has been dependent on relatively imprecise level correlations and a few absolute ¹⁴C age determinations (carbonate shell material is generally not preserved in the uppermost sediments, i.e. in the beach deposits). However, after refinement of the OSL dating technique, the greatly increased number of reliable absolute age determinations since 2006 (Table 1) has provided the basis for a robust, coherent, absolute age model of the coastal history of the island (result in Fig. 36).

The procedure for the construction of the age model for the island is outlined in Table 2.

Table 1. Compilation of absolute age determinations of materials from Læsø known to us (November 2014)

No.	Coordinates Degr. E	Coordinates Degr. N	Terrain m	Depth m	Level m	Type	Ag years BP	Cal. year AD	+/- years BP	Collec- ted AD	Collector (sample ID)	Environment (interpretation)	Published (reference)
1	10.8754	57.2546	1.99	0.3	1.69	OSL	740	1267	60	2007	A. Nielsen	Beach ridge	this work
2	10.8756	57.2537	2.39	0.3	2.09	OSL	113	1896	15	2009	T.Aagaard (0B)	Aeolian	this work
3	10.8855	57.2684	2.03	0.3	1.73	OSL	189	1820	14	2009	T.Aagaard (0A)	Aeolian	this work
4	10.8861	57.2535	3.08	0.45	2.63	OSL	850	1159	90	2009	T.Aagaard (1)	Beach ridge	this work
5	10.8903	57.2626	3.39	0.35	3.04	OSL	1400	609	90	2009	T.Aagaard (2)	Beach ridge	this work
6	10.8999	57.271	4.24	1.5	2.74	OSL	1590	418	90	2008	A. Murray	Beach ridge	this work
7	10.9128	57.2824	5.42	1	4.42	OSL	2230	-222	140	2008	A. Murray	Beach ridge	this work
8	10.9298	57.2886	6.84	0.45	6.39	OSL	3000	-991	180	2009	T.Aagaard (9)	Beach ridge	this work
9	10.9351	57.2912	7.39	0.4	6.99	OSL	3200	-1191	220	2009	T.Aagaard (10)	Beach ridge	this work
10	10.939	57.2927	8.05	0.5	7.55	OSL	3240	-1231	240	2009	T.Aagaard (11)	Beach ridge	this work
11	10.9401	57.277	6.07	0.55	5.52	OSL	2910	-901	180	2009	T.Aagaard (6)	Beach ridge	this work
12	10.9574	57.2945	7.4	0.54	6.86	¹⁴ C	2680	-730	100	1970	J.Stockmarr	Terr. (charcoal)	this work
13	10.9622	57.2975	9.1	0.2	8.9	¹⁴ C	1610	340	100	1970	J.Stockmarr	Terr. (Quercus)	this work
14	10.9622	57.2975	9.1	0.85	8.25	¹⁴ C	3355	-1405	80	1970	J.Stockmarr	Terrestrial (peat)	this work
15	10.9655	57.2711	5.58	0.45	5.13	OSL	2430	-421	150	2009	T.Aagaard (7)	Beach ridge	this work
16	10.9675	57.2737	7.94	0.3	7.64	OSL	1190	819	130	2009	T.Aagaard (5)	Aeolian	this work
17	10.9725	57.2868	8.94	0.6	8.34	OSL	3750	-1741	230	2009	T.Aagaard (12)	Beach ridge	this work
18	10.9919	57.2911	11.05	0.5	10.55	OSL	4900	-2890	300	2010	J.M.Hansen (03)	Litoral	this work
19	10.9989	57.3018	8.52	0.4	8.12	OSL	3340	-1330	180	2010	J.M.Hansen (01)	Beach ridge	this work
20	10.9989	57.3018	8.52	6.5	2.02	OSL	6300	-4292	500	2008	B.Larsen (B2)	Marine	this work
21	10.9989	57.3018	8.52	7.5	1.02	OSL	5700	-3692	400	2008	B.Larsen (B2)	Marine	this work
22	10.9989	57.3018	8.52	8.5	0.02	OSL	19700	-17692	1700	2008	B.Larsen (B2)	Glaciomarine ?	this work
23	11.0007	57.2934	10.77	0.5	10.27	OSL	4000	-1990	200	2010	J.M.Hansen (02)	Litoral	this work
24	11.0007	57.2934	10.77	2.5	8.27	OSL	4300	-2292	200	2008	B.Larsen (B1)	Marine	this work
25	11.0007	57.2934	10.77	3.5	7.27	OSL	4800	-2792	300	2008	B.Larsen (B1)	Marine	this work
26	11.0007	57.2934	10.77	4.5	6.27	OSL	4300	-2292	200	2008	B.Larsen (B1)	Marine	this work
27	11.0007	57.2934	10.77	5.5	5.27	OSL	4600	-2592	300	2008	B.Larsen (B1)	Marine	this work
28	11.0007	57.2934	10.77	6.5	4.27	OSL	4400	-2392	200	2008	B.Larsen (B1)	Marine	this work
29	11.0096	57.2833	9.16	0.15	9.01	OSL	3500	-1490	200	2010	J.M.Hansen (04)	Beach-litoral	this work
30	11.0096	57.2833	9.16	0.5	8.66	OSL	4800	-2790	300	2010	J.M.Hansen (05)	Marine	this work
31	11.0096	57.2833	9.16	8.5	0.66	OSL	4800	-2792	400	2008	B. Larsen (B3)	Marine	this work
32	11.0096	57.2833	9.16	10.5	-1.34	OSL	37000	-34992	4000	2008	B. Larsen (B3)	Glaciomarine	this work
33	11.0127	57.2923	10.75	13.5	-2.75	¹⁴ C	12987	-11037	180	1967	O.Michelsen	Glaciomarine (shell)	Michelsen 1967
34	11.0052	57.2882	10.05	0.8	9.25	¹⁴ C	3375	-1425	100	1970	J.Stockmarr	Terrestrial (peat)	this work
35	10.9334	57.2484	1.26	0.52	0.74	OSL	1369	642	112	2011	J.M.Hansen (M)	Marine	this work
36	10.9334	57.2484	1.26	0.36	0.9	OSL	241	1770	23	2011	J.M.Hansen (M)	Marsh ridge	this work
37	10.9337	57.2498	1.69	0.7	0.99	OSL	1951	60	154	2011	J.M.Hansen (N)	Marine	this work
38	10.9337	57.2498	1.69	0.38	1.31	OSL	1471	540	144	2011	J.M.Hansen (N)	Marine	this work
39	10.9337	57.2498	1.69	0.17	1.52	OSL	611	1400	64	2011	J.M.Hansen (N)	Marsh ridge	this work
40	10.9345	57.2522	2.01	0.38	1.63	OSL	1950	61	166	2011	J.M.Hansen (L)	Marine	this work
41	10.9346	57.253	2.31	0.43	1.88	OSL	1569	442	137	2011	J.M.Hansen (K)	Marine	this work
42	10.9354	57.2558	2.26	0.46	1.8	OSL	2015	-4	162	2011	J.M.Hansen (J)	Marine	this work
43	10.947	57.2446	0.99	0.49	0.5	OSL	1680	331	210	2011	J.M.Hansen (A)	Marine	this work
44	10.9465	57.2453	1.19	0.48	0.71	OSL	233	1778	50	2011	J.M.Hansen (B)	Marsh ridge	this work

Table 1 continued. Compilation of absolute age determinations of materials from Læsø known to us (November 2014)

No.	Coordinates Degr. E	Coordinates Degr. N	Terrain m	Depth m	Level m	Type	Ag years BP	Cal. year AD	+/- years BP	Collec- ted AD	Collector (sample ID)	Environment (interpretation)	Published (reference)
45	10.9465	57.2453	1.19	0.27	0.92	OSL	190	1821	43	2011	J.M.Hansen (B)	Marsh ridge	this work
46	10.9499	57.2595	3.71	0.84	2.87	OSL	1872	139	153	2011	J.M.Hansen (H)	Marine	this work
47	10.9499	57.2595	3.71	0.48	3.23	OSL	1688	323	138	2011	J.M.Hansen (H)	Litoral	this work
48	10.9501	57.2602	3.64	0.43	3.21	OSL	1716	295	140	2011	J.M.Hansen (G)	Litoral	this work
49	10.9509	57.2617	3.6	0.39	3.21	OSL	2011	0	170	2011	J.M.Hansen (F)	Marine	this work
50	10.9509	57.2617	3.6	0.19	3.41	OSL	1759	252	133	2011	J.M.Hansen (F)	Litoral	this work
51	10.9589	57.2442	1.25	0.5	0.75	OSL	1253	758	109	2011	J.M.Hansen (O)	Marine	this work
52	10.9589	57.2442	1.25	0.39	0.86	OSL	300	1711	36	2011	J.M.Hansen (O)	Litoral	this work
53	10.9589	57.2442	1.25	0.18	1.07	OSL	274	1737	28	2011	J.M.Hansen (O)	Marsh ridge	this work
54	10.9600	57.2453	1.98	0.71	1.27	OSL	667	1344	97	2011	J.M.Hansen (E)	Litoral	this work
55	10.9600	57.2453	1.98	0.29	1.69	OSL	594	1417	47	2011	J.M.Hansen (E)	Marsh ridge	this work
56	10.9631	57.2468	2.66	0.62	2.04	OSL	1728	283	141	2011	J.M.Hansen (I)	Marine	this work
56a	10.9623	57.2555	1.83	0.32	1.51	OSL	1794	217	310	2011	J.M.Hansen (D)	Marine	this work
57	10.9667	57.2500	1.99	1.5	0.49	¹⁴ C	12933	-10983	210	1973	Tauber & Krogh	Glaciom. (Saxicava)	Krog 1968
57a	10.9646	57.2483	2.12	0.38	1.74	OSL	1819	192	285	2011	J.M.Hansen (C)	Marine	this work
58	10.9667	57.2500	2.06	1.5	0.56	¹⁴ C	13793	-11843	180	1973	Tauber & Krogh	Glaciom. (Saxicava)	Krog 1968
59	10.9965	57.2669	7.75	0.8	6.95	OSL	4100	-2090	200	2010	J.M.Hansen (08)	Marine	this work
60	11.0041	57.266	7.0	0.6	6.4	OSL	3990	-1980	200	2010	J.M.Hansen (07)	Marine	this work
61	11.0041	57.266	7.0	0.35	6.65	OSL	580	1430	40	2010	J.M.Hansen (06)	Aeolian	this work
62	11.0052	57.2616	5.11	1	4.11	¹⁴ C	3182	-1232	200	1977	Jensen (1872)	Marine (whale)	Hansen 1977
63	11.0434	57.2394	1.66	0.2	1.46	Dendro	543	1466	0	2009	J.Vellev	Marsh ridge (pole/Pinus)	this work
64	10.8627	57.2319	-2	0	-2	¹⁴ C	10274	-8324	41	2009	J.H.Larsen (A.Fischer)	Terr. (trunk/Pinus)	this work
65	11.0102	57.2029	2.34	0.65	1.69	OSL	420	1589	30	2009	J.M.Hansen (1)	Marsh ridge	Hansen et al. 2012
66	11.0102	57.2029	2.34	0.4	1.94	OSL	340	1669	30	2009	J.M.Hansen (2)	Aeolian	Hansen et al. 2012
67	11.0131	57.2035	2.08	0.75	1.33	OSL	380	1629	30	2009	J.M.Hansen (3)	Litoral	Hansen et al. 2012
68	11.0131	57.2035	2.08	0.35	1.73	OSL	280	1729	30	2009	J.M.Hansen (5)	Aeolian	Hansen et al. 2012
69	11.0123	57.2069	1.91	0.55	1.36	OSL	330	1679	20	2009	J.M.Hansen (7)	Marsh ridge	Hansen et al. 2012
70	11.012	57.2079	1.78	0.3	1.48	OSL	320	1689	20	2009	J.M.Hansen (9)	Marsh ridge	Hansen et al. 2012
71	11.0078	57.2083	1.57	0	1.57	Map	220	1786	0	2006	R. Sci. Acad.	Shoreline	Hansen et al. 2012
72	11.0394	57.2108	0.22	1.8	-1.58	¹⁴ C	3297	-1347	23	2010	J.M.Hansen	Marine (Balanus)	this work
73	11.0375	57.212	0.2	1.8	-1.6	¹⁴ C	3347	-1397	29	2010	J.M.Hansen	Marine (Balanus)	this work
74	11.0535	57.2658	2.6	0.33	2.27	OSL	1800	209	140	2009	J.M.Hansen (07)	Marine	Hansen et al. 2012
75	11.0578	57.2614	2.05	0.15	1.9	OSL	700	1309	70	2009	J.M.Hansen (05)	Marsh ridge	Hansen et al. 2012
76	11.0578	57.2614	2.05	0.35	1.7	OSL	1660	349	110	2009	J.M.Hansen (06)	Marine	Hansen et al. 2012
77	11.0623	57.2599	2.16	0.35	1.81	OSL	870	1139	60	2009	J.M.Hansen (08)	Marsh ridge	Hansen et al. 2012
78	11.0647	57.2597	1.98	0.45	1.53	OSL	780	1229	50	2009	J.M.Hansen (12)	Marsh ridge	Hansen et al. 2012
79	11.0698	57.2605	1.82	0.35	1.47	OSL	820	1189	80	2009	J.M.Hansen (15)	Marsh ridge	Hansen et al. 2012
80	11.0719	57.2601	1.77	0.35	1.42	OSL	660	1349	40	2009	J.M.Hansen (16)	Marsh ridge	Hansen et al. 2012
81	11.0759	57.259	1.43	0.3	1.13	OSL	530	1479	40	2009	J.M.Hansen (17)	Marsh ridge	Hansen et al. 2012
82	11.0776	57.2585	1.61	0.25	1.36	OSL	420	1589	30	2009	J.M.Hansen (03)	Marsh ridge	Hansen et al. 2012
83	11.0817	57.2572	0.97	0.2	0.77	OSL	260	1749	40	2009	J.M.Hansen (01)	Marsh ridge	Hansen et al. 2012
84	11.0797	57.2693	1.48	0.2	1.28	Dendro	530	1463	1	1993	J.Vellev	Marsh ridge (pole)	Vellev 1993
85	11.0787	57.2709	1.45	0	1.45	TL	523	1470	50	1993	J.Vellev (Mejdahl)	Marsh ridge	Vellev 1993
86	11.0441	57.2884	5.12	1	4.12	¹⁴ C	3245	-1295	100	1993	J.M.Hansen	Marine (whale)	Hansen 1995

Table 1 continued. Compilation of absolute age determinations of materials from Læsø known to us (November 2014)

No.	Coordinates Degr. E	Coordinates Degr. N	Terrain m	Depth m	Level m	Type	Ag years BP	Cal. year AD	+/- years BP	Collec- ted AD	Collector (sample ID)	Environment (interpretation)	Published (reference)
87	11.0757	57.294	0.59	2	-1.41	Dendro	628	1381	0	2009	J.M.Hansen	Mar. (ship/Quercus)	this work
88	11.025	57.3154	4.05	0.3	3.75	OSL	290	1717	20	2007	A.Nielsen	Aeolian	this work
89	11.0305	57.3113	8.55	0.3	8.25	OSL	2900	-893	160	2007	A.Nielsen	Aeolian	this work
90	11.0636	57.3073	9.01	0.3	8.71	OSL	1460	549	130	2009	M.Binderup (07)	Aeolian	this work
91	11.0636	57.3073	9.01	0.6	8.41	OSL	2000	9	140	2009	M.Binderup (07A)	Aeolian	this work
92	11.1183	57.3069	4.83	0.5	4.33	OSL	310	1699	30	2009	M.Binderup (01)	Aeolian	this work
93	11.0871	57.3179	2.68	2	0.68	OSL	2610	-602	140	2008	A.Murray	Marine	this work
94	11.0893	57.318	3.95	3.9	0.05	¹⁴ C	3380	-1430	50	1976	J.M.Hansen	Marine (Mytilus)	Hansen 1977
95	11.0893	57.318	3.95	3.9	0.05	¹⁴ C	3340	-1390	50	1976	J.M.Hansen	Marine (Balanus)	Hansen 1977
96	11.0925	57.3179	7.94	3.5	4.44	OSL	2580	-572	150	2008	A.Murray	Marine	this work
97	11.0951	57.3179	6.09	5	1.09	OSL	2380	-372	140	2008	A.Murray	Marine	this work
98	11.1212	57.3152	5.41	0.3	5.11	OSL	830	1178	60	2008	M.Binderup (09)	Aeolian	this work
99	11.1212	57.3152	5.41	0.6	4.81	OSL	1570	438	220	2008	M.Binderup (08)	Beach ridge	this work
100	11.1314	57.3097	2.88	0	2.88	Dendro	1365	640	0	2005	P.Lysdahl	Litoral (pole/Taxus)	Hansen 1995
101	11.1402	57.3043	2.52	0.3	2.22	OSL	400	1608	50	2008	M.Binderup (10)	Aeolian	this work
102	11.1477	57.3152	4.98	0.3	4.68	OSL	2280	-272	160	2008	M.Binderup (03)	Beach ridge	this work
103	11.1439	57.3236	6.33	0.3	6.03	OSL	1860	148	180	2008	M.Binderup (04)	Aeolian	this work
104	11.1519	57.3257	3.28	0.3	2.98	OSL	1650	358	140	2008	M.Binderup (5A)	Beach ridge	this work
105	11.1783	57.3146	2.28	0.3	1.98	OSL	1050	958	110	2008	M.Binderup (06)	Beach ridge	this work
106	11.192	57.3146	1.28	0.3	0.98	OSL	260	1747	10	2007	A.Nielsen	Beach ridge	this work
107	10.9315	57.298	1	0	1	¹⁴ C	7750	-5800	120	1969	N.A.Möner	Terr. (reworked gytja)	Möner 1969
108	10.9971	57.2716	8.11	0.63	7.48	OSL	3740	-1727	270	2013	J.M.Hansen (5)	Beach ridge	this work
109	10.9864	57.293	10.84	0.46	10.38	OSL	5550	-3537	440	2013	J.M.Hansen (7)	Marine?	this work
110	10.9864	57.293	10.84	0.62	10.22	OSL	5210	-3197	430	2013	J.M.Hansen (8)	Marine?	this work
111	10.9901	57.2919	10.67	0.56	10.11	OSL	4840	-2827	350	2013	J.M.Hansen (10)	Beach ridge	this work
112	10.9911	57.2915	10.87	0.35	10.52	OSL	3890	-1877	350	2013	J.M.Hansen (11)	Beach ridge	this work
113	10.9911	57.2915	10.87	0.6	10.27	OSL	6100	-4087	380	2013	J.M.Hansen (12)	Marine	this work
114	10.9959	57.2869	9.63	0.37	9.26	OSL	5550	-3537	400	2013	J.M.Hansen (13)	Marine	this work
115	10.9851	57.2962	10.52	0.53	9.99	OSL	4470	-2457	280	2013	J.M.Hansen (14)	Beach ridge	this work
116	10.9777	57.2999	9.33	0.45	8.88	OSL	4890	-2877	330	2013	J.M.Hansen (17)	Marine?	this work
117	10.9774	57.3011	7.84	0.35	7.49	OSL	5200	-3187	310	2013	J.M.Hansen (18)	Marine	this work

This compilation comprises all age determinations known to us by November 2014. Coordinates are in decimal degrees.

Ages: BP (before present) relates to the year of collection (¹⁴C-samples to 1950 according to international convention). Dating methods: OSL: Optically Stimulated Luminescence.

¹⁴C: Radiometric dating. Dendro: Tree-ring counting. TL: Thermo-luminescence. Coring technique: due to water saturation of fine-grained sand deposits some boreholes may have caved during coring (only samples collected by B. Larsen).

Compensation for vertical displacement of sea-level proxies (RSL displacement)

Terrain levels of beach-ridge landscapes combine several types of active and previously active agents. Thus, in the case of Læsø (Hansen *et al.* 2012) the levels of the 1200 measured mean base levels of ridge crests (BLRC) can be described as:

$$BLRC = RSL + S + D - E$$

where

$$RSL = ASL + (U_L + U_R + U_I) - C$$

and RSL is the relative shore-level displacement, S is the height of swash (run-up), D is the thickness of possible aeolian dunes on top of the crests, E is the depth of possible, local erosion (deflation, ditches, streams), ASL is the absolute ('eustatic') sea level of the region,

Table 2. Procedure for construction of the age model of the island

1: Identification and chronological numbering of continuous series of subsequent beach-ridges within each of the three main areas, supplemented with a similar chronological numbering of continuous beach-ridges of the originally separate saltmarsh islets of Langerøn, Kringelrøn and Hornfiskrøn south of the main island.

2: Measurement of mean base levels of ridge crests (BLRC) of identified beach-ridges (calculation method, see Hansen *et al.* (2012) and next section) and relation of these levels to the chronological order of the ridges.

3: Level correlation of the chronologically ordered beach-ridges of the three main areas and saltmarsh islets.

4: Transformation of the exact chronology of beach-ridges to an absolute age model of the coastal progradation by application of the collated absolute age determinations. By linear interpolation, based on the distances

between the beach-ridges, an absolute interpolate age is assigned to each of the beach-ridges.

5: By comparison of the age/level curves of each of the three main areas, prominent peaks and lows are adjusted by at most 100 years to the age of that part of the curves with most absolute age determinations.

6: Correlation of all curves of step 5 such that interpolated age differences of more than 10 years will not occur. Then every single one of the 1200 measured beach-ridge levels from the three main areas is assigned with a measured (when existing) or interpolated absolute age.

7: Construction of one single, integrated RSL curve of the island is done on the basis of step 6 by calculating age and level means of every 10 year interval of the 1200 measured beach-ridges.

U_L is local tectonic uplift, U_R is regional relaxation uplift, U_I is glacio-isostatic adjustment (GIA), and C is (negligible) compaction of underlying, unconsolidated sediments. Because RSL constitutes the sum of absolute sea level (ASL) and vertical terrain changes (U and C), the present RSL reconstruction is only dependent on how base levels of beach-ridge crests (BLRC) were measured in order to avoid effects of small dunes (D) and erosional features (E) and how BLRC measurements were compensated for height of swash (S).

On Læsø, the geological parameters of U and C were thoroughly examined by Hansen *et al.* (2012) in two test areas where these geological agents could be parameterized for the last *c.* 900 years. However, in other areas and regions the problem of geological background noise is still a global, often unrecognized and mostly unsolved problem in sea-level reconstructions and tide-gauge measurements (see discussion below on 'Identification of geological background noise in a low seismicity region'). Therefore, in the present context of RSL reconstruction we abstain from absolute sea-level (ASL) calculations.

Estimation of swash heights (run-up) by ground penetrating radar (GPR)

In GPR cross-sections of beach ridges (examples in Fig. 18 and Fig. 25), the relative sea level (RSL) of the actual beach ridge can be identified as the points where relatively steep reflectors of beach faces downlap on less steep reflectors of the upper shore face (Tamura *et al.* 2008; Nielsen & Clemmensen 2009; Clemmensen & Nielsen 2010; Clemmensen *et al.* 2012a; Hede *et al.* 2013). On the basis of cross-shore GPR and levelling profiles on Feddet (Sjælland), Hede *et al.* (2013) showed that the inclinations of beach-face reflectors (mean around 5°) and upper shoreface reflectors (mean around 1°) are clearly separated into two distinct populations. Moreover, Hede *et al.* (2013) showed that the inclina-

tions found by cross-shore levelling clearly correspond to inclinations found by cross-shore GPR profiling of beach ridges at the same locations, when levels of the shorelines of the actual beach ridges are identified by downlap of steep reflectors on less steep reflectors.

At Læsø we used the method of GPR identification of downlaps in the depth interval of 0.3–2.5 m below the surface levels of the beach-ridge terrains. About 15 km of reflection GPR profiles were measured in 2009 in the south-western and northern parts of Læsø. The GPR data was acquired using a pulseEKKO PRO system manufactured by Sensors & Software™, equipped with 250 MHz shielded transmitter and receiver antennae providing the required resolution for the purpose (Nielsen & Clemmensen 2009). The antenna separation was 0.38 m and the spatial and temporal sampling was 0.05 m and 0.4 ns, respectively. Topography along the GPR sections was measured with a Trimble GPS system with an accuracy of *c.* 0.02 m in open areas while the topographical information in forests was depicted from the DTM. A standard processing sequence was applied to the data (e.g. Nielsen & Clemmensen 2009; Hede *et al.* 2015), including dewowing to suppress the low-frequency inductive part of the GPR signal, low-pass filtering to reduce high-frequency noise and increase signal-to-noise ratio, migration to move dipping reflections into their proper subsurface position and collapse diffraction hyperbolas, and a robust automatic gain control function with an operator length of either four or eight pulses to account for loss of amplitude due to geometrical spreading and attenuation. GPR velocity information was obtained from sparsely observed diffraction hyperbolas revealing velocities about 0.1–0.12 m/ns in the most shallow and dry sediment, decreasing to about 0.06 m/ns in the deeper and completely water saturated sediments. The migration, the time-to-depth conversion and the topographical correction

were performed using a constant velocity field with an average of 0.08 m/ns as the velocity information from the diffraction hyperbolas was too sparse to set up 1D or 2D velocity fields. The uncertainty on the determination of the velocities was transferred to the time-to-depth conversion, resulting in an underestimation of the depth of up to 0.5–1.0 m within the upper 3 m of the subsurface where the velocities can be higher than 0.08 m/ns.

This data set has allowed determination of swash heights for the two main areas faced to the north and to the south-west (Fig. 4). Thus, by subtracting depths of the downlap points from the actual BLRC level the swash heights can be determined.

About 50 km of GPR profiles measured with an early version of the GPR technique (Andreassen 1986) from other parts of Læsø have also been available, but due to the use of an antenna with a lower frequency the data resolution mostly does not allow identification of the downlap levels.

Estimation of swash heights (run-up) by terrain level analyses

In the main area faced to the east and south-east (Fig. 4), determination of swash heights is mainly based

on the lidar digital terrain model terrain level. This can be done in two ways that supplement each other:

1) By comparison of the BLRC of the individual beach ridges with the levels of neighbouring swales, when both mean levels of ridges and swales are measured parallel to the beach-ridge direction.

2) By profiling perpendicular to the length direction of the beach ridges and applying a mathematical transform (corresponding to the BLRC-transform) in order to find the actual base level of the swales.

We found that method 1 is applicable in terrains where beach ridges are well separated, whereas it is not applicable in terrains of condensed high- and low-ridge plains. Method 2 is generally applicable when repeated in several parallel profiles. In areas where modern GPR data are available, there is good agreement between the GPR downlap method and both lidar model methods, although thus determined swash heights are about 0.1–0.2 m lower than when determined by GPR profiling. This small, but general difference probably shows that the downlap point may be situated up to 0.2 m below mean water level, depending on the coastal exposure. Alternatively, small errors in the GPR velocity estimate may lead to a small bias in depth estimation of the downlap points.

Table 3. Contents of the RSL series database for Læsø. See Fig. 4 and Fig. 5 for the various areas and Fig. 1 for place names. The coastal types are described in the Results chapter

Læsø south-west: Beach-ridges from the oldest parts of present Læsø (the ‘top’ of the island) to Stokken at the south-western corner.

Coastal types and ages of ridges:

- Condensed high-ridge plain of the ‘top’ of the island (4900–4000 years BP)
- Barrier spit and lagoon systems of Kærene and more south-westwards (4000–2500 years BP)
- Barrier island and lagoon systems of south-western Læsø (2500 years BP to present)

Læsø north: Beach-ridges from the oldest parts of present Læsø (the ‘top’ of the island) to the north coast at Hornex and Holtemmen.

Coastal types and ages of ridges:

- Condensed high-ridge plain from the top of the island to Hornex (4900 years BP to present)
- Condensed high-ridge plain from the top of the island to the high cliff at Holtemmen (4900–3000 years BP)
- Condensed high-ridge plain from the high cliff to present shoreline at Holtemmen (c. 1000 years BP to present)

Læsø east: Beach-ridges from Bansten along the northern and central part of the Østerby peninsula to Bløden Hale.

Coastal types and ages of ridges:

- A series of nine attached barrier spit and lagoon systems (3500 years BP to present)

Læsø south-east: Beach-ridges and saltmarsh ridges formed from the ‘top’ of the island to the present coastline at Stoklund and Bangsbo.

Coastal types and ages of ridges:

- Condensed high-ridge plain from the ‘top’ to south-east of Højsande (4900–3500 years BP)
- Condensed low-ridge plain (raised saltmarsh) from south-east of Højsande to the present coast of Stoklund and Bangsbo (3500 years BP to present)

Læsø south: Raised saltmarsh ridges of Tørkeriet. Coastal type and ages of ridges:

- Attached, condensed low-ridge plain and present saltmarsh (1700 years BP to present)

Læsø, Rønnerne: Saltmarsh ridges originally formed around raised boulder reefs on the shallow abrasion platform of southern Læsø.

Coastal types and ages of ridges:

- Detached, concentric low-ridge plain of Langerøn (c. 1000 years BP to present)
 - Detached, concentric low-ridge plain of Kringelrøn (c. 1000 years BP to present)
 - Detached, concentric low-ridge plain of Hornfiskrøn (900 years BP to present)
-

Database for measured and modelled RSL/age index points

By combination of the procedures described above, a database presently containing more than 1200 entries has been created for the RSL/age relation, including also distances between subsequent ridges, data on age and level uncertainties, and modelled isostatic uplift. The database also comprises already published results by Hansen *et al.* (2012) from the saltmarshes and low heathers of Hornfiskrøn, Stoklund and Bangsbo.

The following periods are covered by RSL/age index points from a number of geographically separated areas:

4900–4000 years BP: Three areas exposed to the north, south-west, and south-east.

4000–3500 years BP: Three (four) areas exposed the north (two), south-west, and south-east.

3500 years BP to present: Four areas exposed to the south-west, north, east, and south-east.

1700–900 years BP to present: Nine areas exposed to the north (two), south-west (one), south (four), south-east (one), and east (one).

Thus, the entire period 4900 years BP to present is represented by index points from at least three geographically separate areas which are exposed towards different main directions (N, SW, and SE to E), while young sections also include exposures towards the south. The contents of the database are detailed in Table 3.

Pollen analyses

Pollen analyses of peat samples from swales in the oldest preserved part of the island have been performed in order to illustrate the vegetation of this small beach-ridge landscape, and if the maturity of this coastal vegetation would suggest connection to larger, more fertile and now completely eroded glacio-marine landscapes.

In the pollen diagrams (Figs 29–31) tree pollen counts have been reduced by 4 (*Betula*, *Pinus*, *Alnus*, *Corylus* and *Quercus*) or by 2 (*Ulmus*) or multiplied by 2 (*Tilia* and *Fraxinus*) in order to compensate for differences in pollen productivity between species (Andersen 1970), before calculating their percentages of the total number of tree pollen.

Results

Types of raised coastal landscapes

The typification of raised coastal landforms used here is based on detailed beach-ridge mapping of all parts

of Læsø as they can be traced from the DTM, supplemented by field studies of the coastal development, vegetation history (Hansen 1994, 1995), medieval settlement and salt industry (Hansen 2010). Thus, the land- and seascapes of the present island can be classified into a number of distinct morphological types based on the origin of the landscapes and the original coastal setting and processes (Fig. 5). Each type of coastal landscape is here given a short morphological definition, a general explanation and examples of locations.

Raised boulder reefs

Piles of boulders jutting out of the sea bottom, sea surface or landscape (Fig. 3, Fig. 6).

The boulder reefs comprise the coarse residual after erosion of the glacio-marine substrate of the region upon which the boulders rest (Fig. 7). The boulders may subsequently have been pushed together and piled up in boulder reefs by ice packing in periods when they were situated close to the sea level of the time. Ice packing processes are still active on the shallow platform south of Læsø when the shallow water freezes to the bottom, forming a widespread ice sheet. During strong winds and high water levels the ice sheet is lifted free of the bottom, and the wind is able to drag frozen-in boulders around, often leaving more than 100 m long plough marks behind them. In areas with high concentrations of large boulders the ice packing process may be able to pile boulders, thus forming new boulder reefs.

The islands of Nordre Rønner and Borfeld 8 km north of Vesterø Havn, as well as Søndre Rønner 5 km south-west of Hornfiskrøn (Fig. 1), are emerged boulder reefs. The large submerged boulder reef of Læsø Trindel 12 km north of Østerby Havn has been nearly removed by stone fishing, but since 2009 it has been reconstructed by dumping of large quantities of imported Norwegian granite blocks. Inside the present outline of Læsø, raised boulder reefs are found in the town Byrum (Bakken and Tingstedet), at the south-western side of Hornfiskrøn ('Engelskmandens Grav', Fig. 6), in the landscape of Tørkeriet (most boulders are removed), and in the 'umbos', i.e. the incipient nuclei of Langerøn, Kringelrøn and Færøn.

Raised abrasion plains ('sand-paper plains')

Plains characterized by widespread, often monolithic boulders resting directly upon the eroded glacio-marine platform, which here and there may also exhibit a residual cover of gravel and stones (Fig. 7).

In most places the abrasion residual of gravel and stones is covered by a thin layer of sand, whereas

Coastal progradation types of Læsø

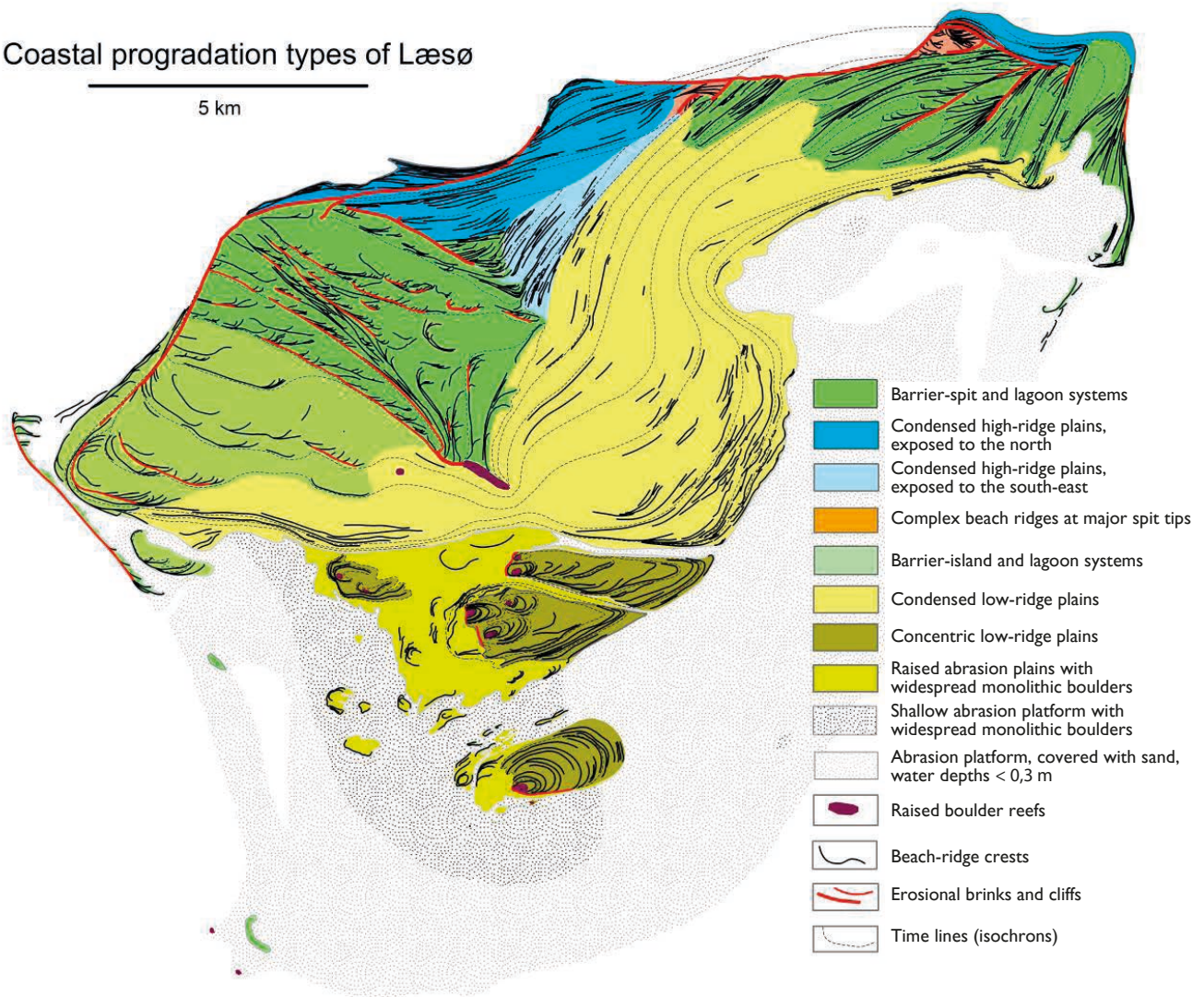


Fig. 5. Coastal progradation types of Læsø, each representing a specific type of coastal origin, morphology and landscape.



Fig. 6. Raised boulder reef around which the saltmarsh island of Hornfiskrøn has been formed, in this case 'Engelskmandens Grav' viewed from south-east.
(Photo: Lasse Gudmundsson).

boulders jut out of the sand. This kind of landscape is one of the most characteristic Læsø landscapes, e.g. in low saltmarshes forming the western parts of Rønnerne and the western part of Hornfiskrøn. The thin cover of sand on the abrasion plain forms a surface where the elevation above MSL controls the extent of frequent surges. Thereby the saltmarsh vegetation from 0 to 100 cm above MSL becomes clearly divided into a series of level-defined vegetation zones (see Hansen 1995 for classification, levels and vegetation map of Rønnerne).

Condensed high-ridge plains (‘high-rippled washboard plains’)

Laterally stacked beach ridges forming plains of basically parallel ridges and swales where the widths of swales are of the same order as the widths of ridges (Fig. 8).

Swash heights have been relatively large, enabling formation of gravelly and stony sand berms, mostly up to 0.2–0.9 m above swale level but not exceeding 1.5 m above mean sea level of the time. As deduced from occurrences at e.g. the high part of Holtemmen and the area south of Højsande, such plains developed at quasi-linear beaches where the shoreface was relatively steep. At present, formation of stacked high-ridge plains can be observed at the northern coast of the low part of Holtemmen.

Condensed low-ridge plains (‘low-rippled washboard plains’)

Vertically accreted sand ridges forming wide plains of basically parallel ridges and swales at coasts protected by shallow water to large distances from the shore (Fig. 9).

Relative to the swales, the height of such beach ridges is generally less than 0.25 m and mostly 0.10–0.15

m. Swash heights were low, typically less than 0.2 m, even during storms, and the beach ridges were mainly formed during storm surges when fine-grained sand was caught in the halophile vegetation growing close to the shoreline (Hansen *et al.* 2012). At present, such beach ridges are generally formed behind a 3–5 km broad sandy coastal plain with water depths less than 0.3 m, where beach ridges accrete to a height of mostly 0.35 m and at maximum 0.6 m before isostatic uplift and invasion of halophile vegetation creates a new low beach ridge on the extremely shallow sand flat some 50–200 m seaward of the preceding beach ridge. Most parts of the agricultural landscapes of southern and south-eastern Læsø, as well as present-time saltmarshes of Bangsbo, Stoklund and Tørkeriet, have formed as such low-ridge plains.

Barrier-spit and lagoon plains (‘tail-fan plains’)

Spits growing alongshore from a nucleus of pre-existing land from where eroded material has been re-deposited in classic spit complexes (Fig. 10).

The spits are generally straight or slightly convex towards the sea and recurve distally towards the hindlying lagoon. Proximally, most spits are eroded and truncate older recurved spits of the same barrier system. This erosion and truncation may continue to where the youngest part of the barrier recurves towards the lagoon. Overwash fans may occur inside the eroded parts of the spits. Landscapes formed by such spit-and-lagoon systems characterize the raised wetland of Kærene, most of the area immediately south-west of Kærene, and most parts of the Østerby peninsula. At present, the formation of a spit complex can be studied by the growth of Bløden Hale at the easternmost part of Læsø.



Fig. 7. Raised abrasion plain (‘sandpaper plain’) with numerous boulders resting on top of the eroded glacio-marine clayey platform. Western part of Kringelrøn. (Photo: Lasse Gudmundsson).

Barrier-island and lagoon plains ('staircase plains')

In contrast to barrier-spit complexes which are dominated by alongshore transport of sediment, barrier islands appearing seaward of the coastline of the main island were formed by cross-shore sediment transport at a time when sediment sources for alongshore transport disappeared (Fig. 11, Fig. 12).

Originally, such barrier islands have been convex and growing laterally to both sides, forming series of recurved spits at both ends, while the central parts of the islands were gradually straightened during storms by beach erosion and redeposition as overwash fans on the leeward side of the barrier. Through such processes, the hindlying lagoon narrowed and in some

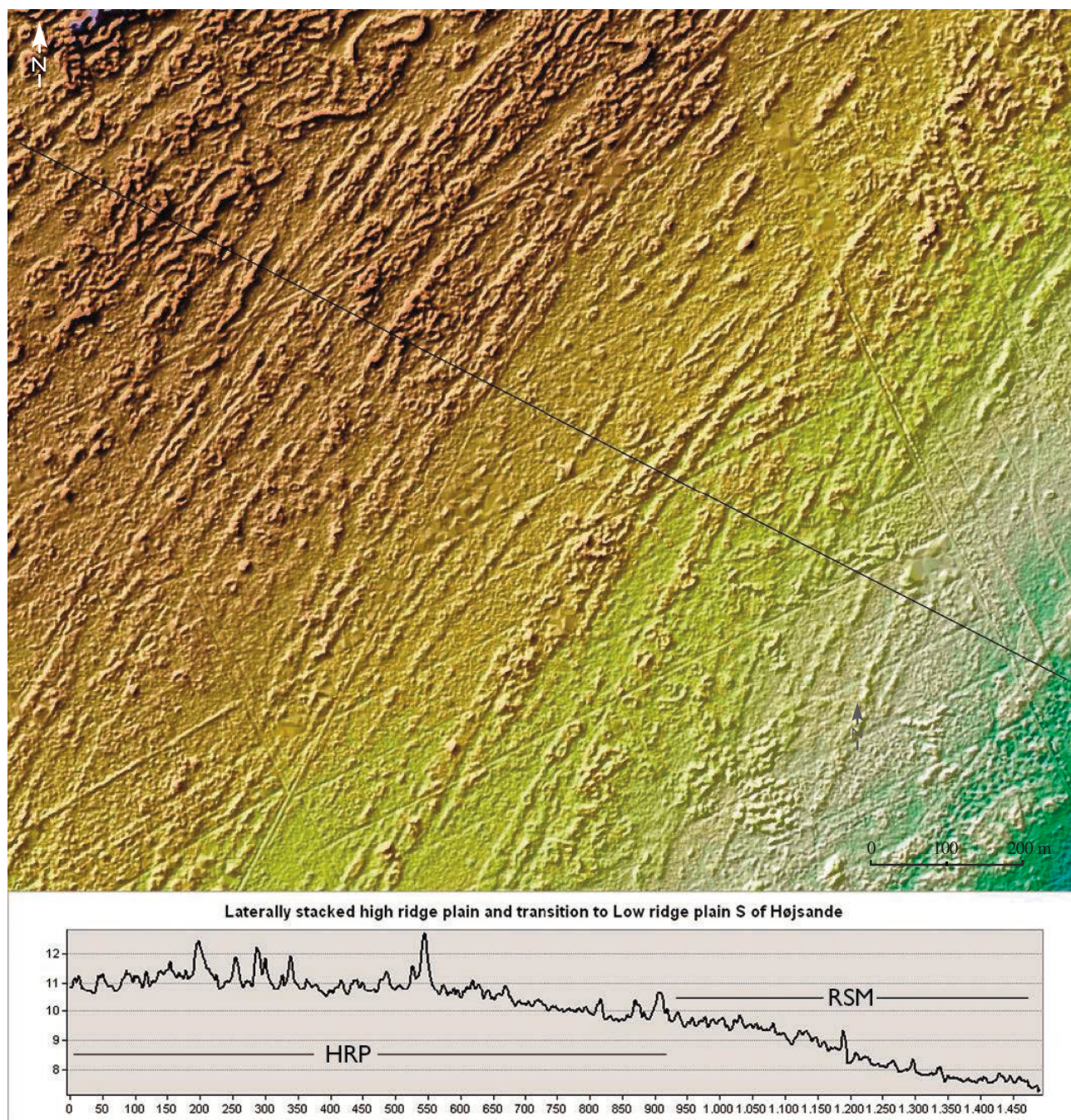


Fig. 8. Digital terrain model (DTM) of an area south of Højsande exposing a condensed high-ridge plain (HRP, 'high-rippled wash-board plain') that originally was formed as laterally stacked, linear beach ridges, and a condensed low-ridge plain ('low-rippled wash-board plain') that originally was mostly formed as raised saltmarshes (RSM). In the north-western part of the area there is an incoherent cover of aeolian sand, often in the form of 'dune-ruin' rings consisting of the vegetated foot of larger dunes of which the barren higher (central) parts have been completely eroded by the wind. The profile shows levels (m above MSL) and distance (m) along the black line.

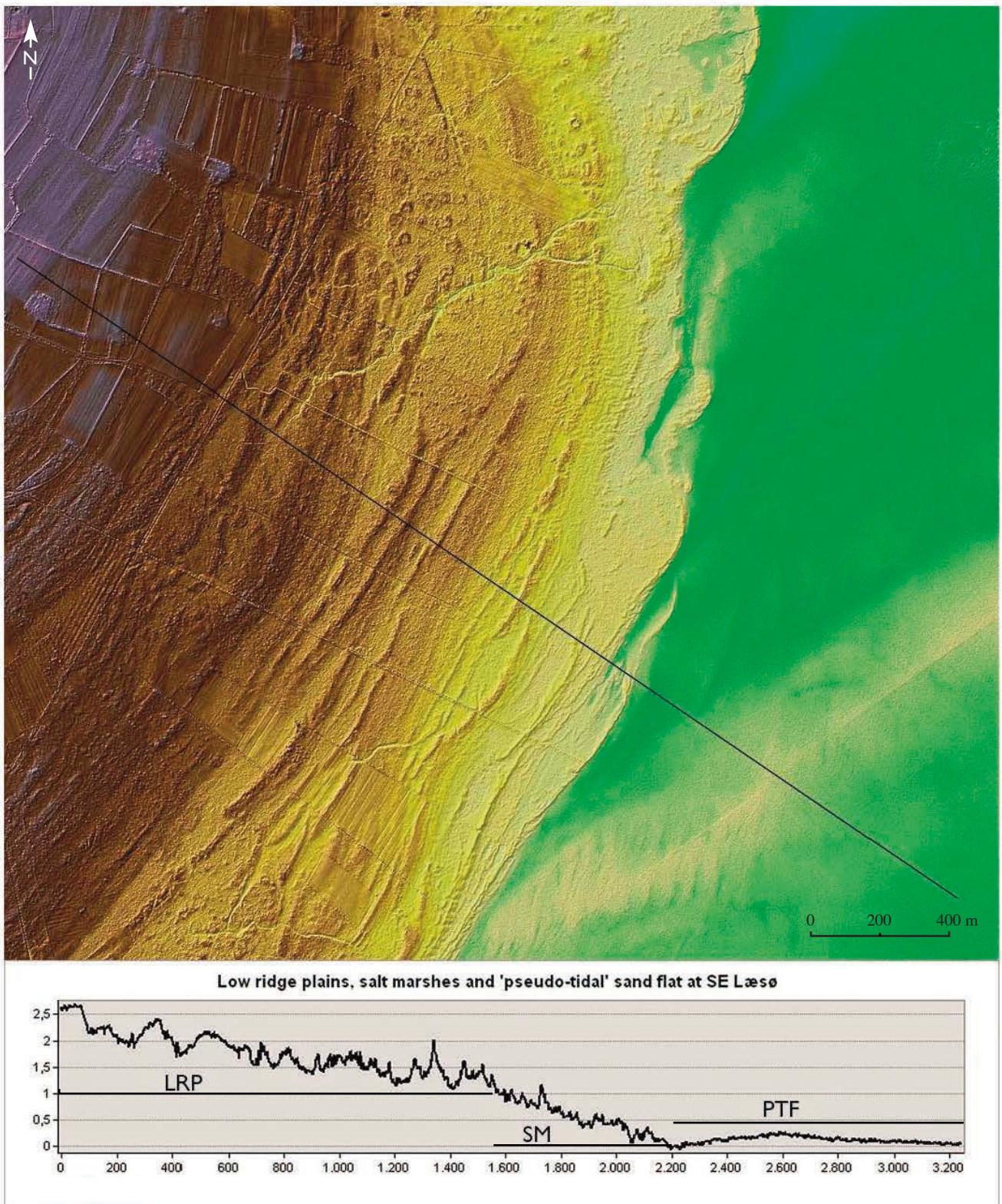


Fig. 9. Digital terrain model (DTM) of the Bangsbo and Stoklund areas of south-eastern Læsø showing a condensed low-ridge plain (LRP, 'low-rippled wash-board plain') that originally was formed as saltmarsh, the present saltmarsh (SM), and the partly dry pseudo-tidal sand flat (PTF). The many circular structures in the upper part of the figure are 20–50 cm high ruins of salt-production huts. The profile shows levels (m above MSL) and distance (m) along the black line.

cases completely disappeared when the central part of the barrier connected with pre-existing land. Mostly one, and more rarely both, of the distal ends of the barriers have been preserved. Agricultural landscapes originally formed as barrier islands and lagoons can be found over most of south-western Læsø. Consecutive series of barrier islands may form a 'stair-case landscape' due to a combination of land uplift and

shoreline straightening of the barrier islands. Such terraced landscapes dominate south-western Læsø, where the surface of each terrace is situated within a narrow elevation range and separated from the subsequent terrace by a relatively steep slope or an erosional cliff. At present, the 5 km long barrier island Stokken at the south-western corner of Læsø represents this kind of depositional process, while smaller barrier islands

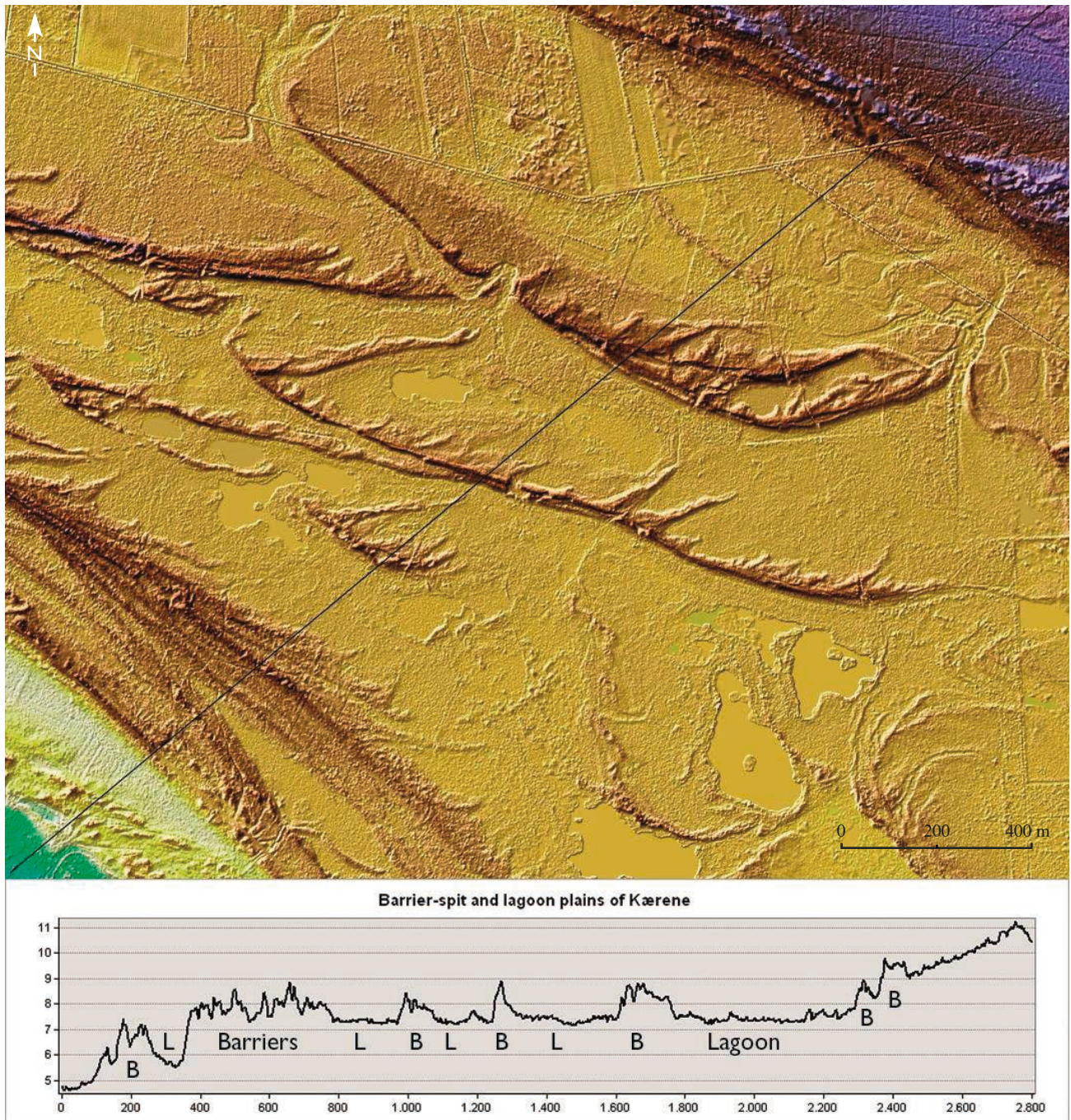


Fig. 10. Digital terrain model (DTM) of the raised barrier-spit and lagoon plain (raised 'tail-fan plain') of Kærene between the towns of Vesterø Havn and Byrum. The profile shows levels (m above MSL) and distance (m) along the black line. B: raised barriers. L: raised lagoons.

(Knogene) are emerging south of the Østerby peninsula. At a distance of 5 km south-west of Hornfiskrøn, another 1 km long barrier island began emerging c. 1990 about 700 m inside the boulder reefs of Søndre Rønner.

Concentric low-ridge plains ('mussel-shell plains')
Vertically accreted sand ridges, originally forming isolated islets around raised boulder reefs, surrounded

by extensive shallow water areas (Fig. 13).

Basically, this kind of landscape is comparable with low-ridge plains that are attached to a pre-existing landscape. The main difference is that unattached low-ridge islets and plains comprise successive, concentric, low beach ridges formed around the raised boulder reef. Seen from the air, such islets are usually shaped like mussel-shells with clearly visible

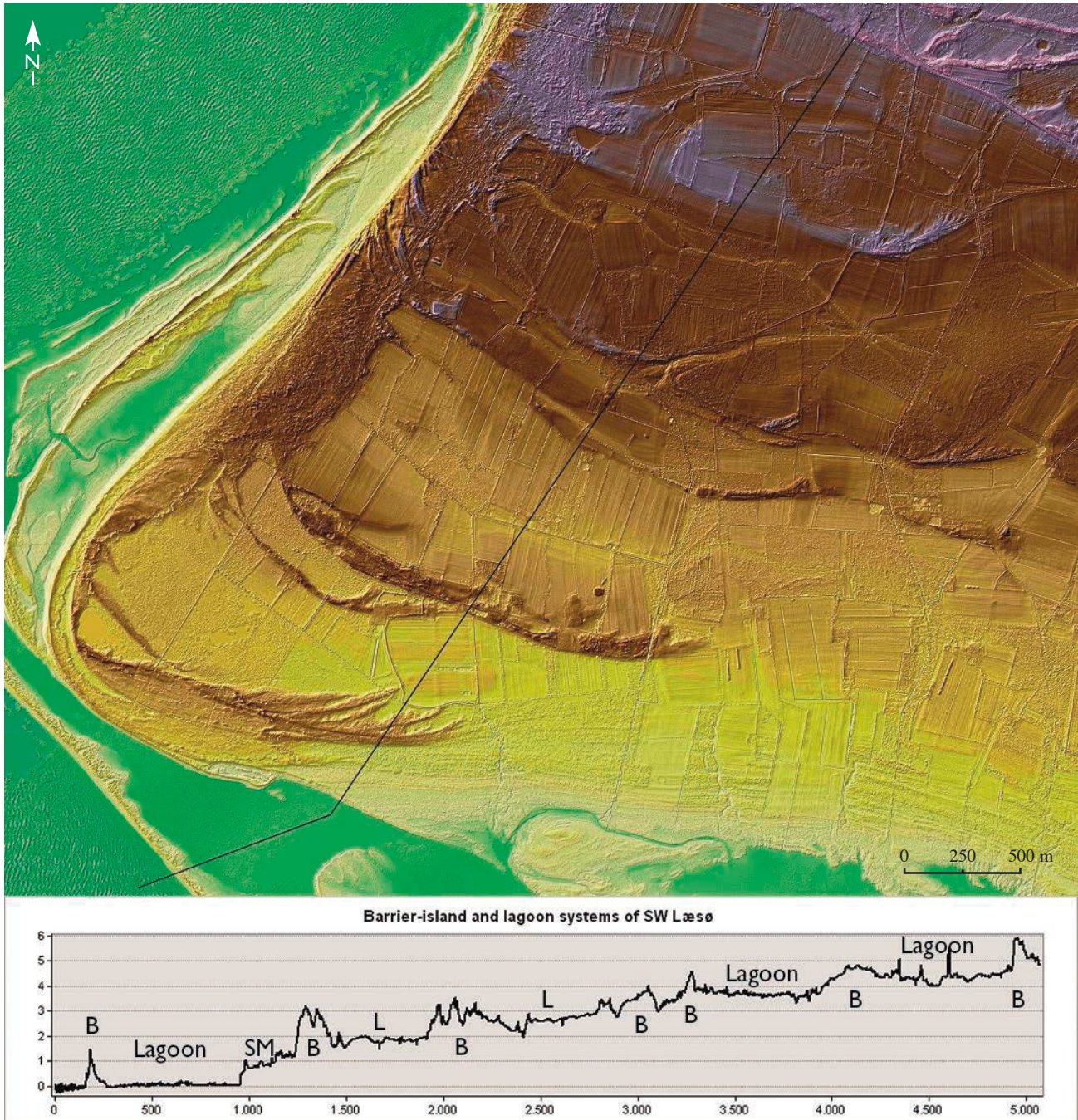


Fig. 11. Digital terrain model (DTM) of barrier-island and lagoon plains (raised 'stair-case plains') of south-western Læsø. To the lower left is seen a part of the present barrier island, Stokken. The profile shows levels (m above MSL) and distance (m) along the black line. B: raised barriers. L: raised lagoons.

concentric growth lines. The growth and position of the islets may be governed by local updoming of the substrate as documented in the case of Hornfiskrøn by Hansen *et al.* (2012). Beach ridges exposed to the main wind direction may be eroded, and coastal progradation is largest in the opposite direction. This kind of landscape is represented by the saltmarshes and low heathers of Rønnerne (Langerøn, Kringelrøn, Færøn and Hornfiskrøn) and by a number of islets still emerging south-west of Læsø.

Shallow, temporarily dry sand plains ('pseudo-tidal flats')

Widespread (about 90 km²), coherent flats or plains with water depths less than 0.3 m that have formed south of Læsø by deposition of a thin (mostly 1–2 m) layer of fine-grained sand on top of the eroded glaciomarine platform (Fig. 14, Fig. 28).

In several places the sand cover is less than 1 m thick or absent, and in such areas the residual conglomerate on top of the clayey platform may be directly exposed, while single, or groups of, large monolithic boulders jut out of the sand. This is seen in large parts of the sand plain, particularly in the areas south, north and west of Hornfiskrøn, west of Kringelrøn, south-west of Færøn and south of Tørkeriet (Fig. 14). The cover of fine-grained sand has most likely been transported and deposited by storms at the margins of the sand flat where also low barrier islands may occur, e.g. the low barrier 0.5 km north-east of Søndre Rønner, the islet SSE of Søndre Nyland, and the low barrier islands of Knotterne and Knogene south-east of Læsø. From such marginal positions exposed to weak wave action,

fine-grained sand may be transported onshore during rising water and storm surges.

In periods of up to one month, mainly during the spring and summer months, large parts of the sand flat are dry. During such periods a millimetre-thin crust of temporarily salt-cemented sand normally develops on top of the plains. Such events usually take place 1–4 times every year, and during such periods some aeolian transport occurs, for example when a rain shower has dissolved the salt crust, followed by formation of thin windblown sandsheets and dunes before the next inundation. (photos in Hansen 1977, 1994).

In contrast to normal tidal flats, e.g. the Wadden Sea, this land- and seascape is 'pseudo-tidal' and biologically extremely barren due to the strongly changing environmental conditions over a year (Hansen 1995). The slow alternation between submerged and emerged, and between salt and fresh conditions ensures that the sand flats are nearly barren of macroscopic stationary inhabitants except for the millimetre-long crustacean *Corophium volutator* and a few other species with a very short reproductive cycle. Moreover, due to evaporation during dry periods the salt concentrations in the pore water are mostly between 4 and 16 % (the salt concentration in Kattegat is about 2.4 %). Therefore, also deeply burrowing species like lugworms (*Arenicola maritima*) occur only in places where the pore water salt concentrations are low enough (< 4 %). Some environmentally robust blue-green algae may here and there form thin, loosely coherent algal mats during longer periods of sea coverage. At the innermost part of the sand flat, where it is mainly dry, halophytes like *Statice (Limonium)* and *Salicornia* often form incoherent vegetation.



Fig. 12. View from the west of the northern end of the barrier island Stokken with series of recurved spits pointing to the east. Overwash fans are seen to fill in the lagoon by erosion of the west coast of the barrier island. Active as well as abandoned channels of the lagoon are visible. Length of the shown part of Stokken is 800 m. (Photo: Eigil Holm).

Carbonate cementation of beach, saltmarsh and seabed deposits

Besides these widespread land- and seascapes it should be mentioned that seepage of methane from the glacio-marine clays and silts may locally and occasionally lead to formation of strongly cemented parts of present seabeds, beach faces and saltmarshes, or internally in the marine deposits. Gas occurrences in the glacio-marine deposits are well known from northern Jutland, Kattegat and Læsø (Fredericia & Grambo-Rasmussen 1985; Laier 1992; Laier *et al.* 1992). Gas seepage from younger sediments is also known from sedimentary structures at Læsø (described from the cliff at Bansten by Hansen 1977) and most likely

also from the northern tip of Jutland (Skagen Odde) (Nielsen & Johannessen 2009). Bacterial activity at places where gas seeps to the surface may give rise to cementation by formation of calcite, aragonite or gypsum (Jørgensen 1980) in the matrix of the sediment (Pedersen *et al.* 1989; Jensen *et al.* 1992; Jørgensen 1992). Cemented parts of the seabed around Læsø, of beach faces along the north coast of Læsø, and of the residual conglomerate exposed on Rønnerne, may take form as decimetre-sized to more than 50 m long, hard plates looking much like concrete. In other places cementation is formed around vertical gas pipes deeper in the seabed. Such vertical pipe-like cementations may later be eroded free of the sea bottom to form up to 10

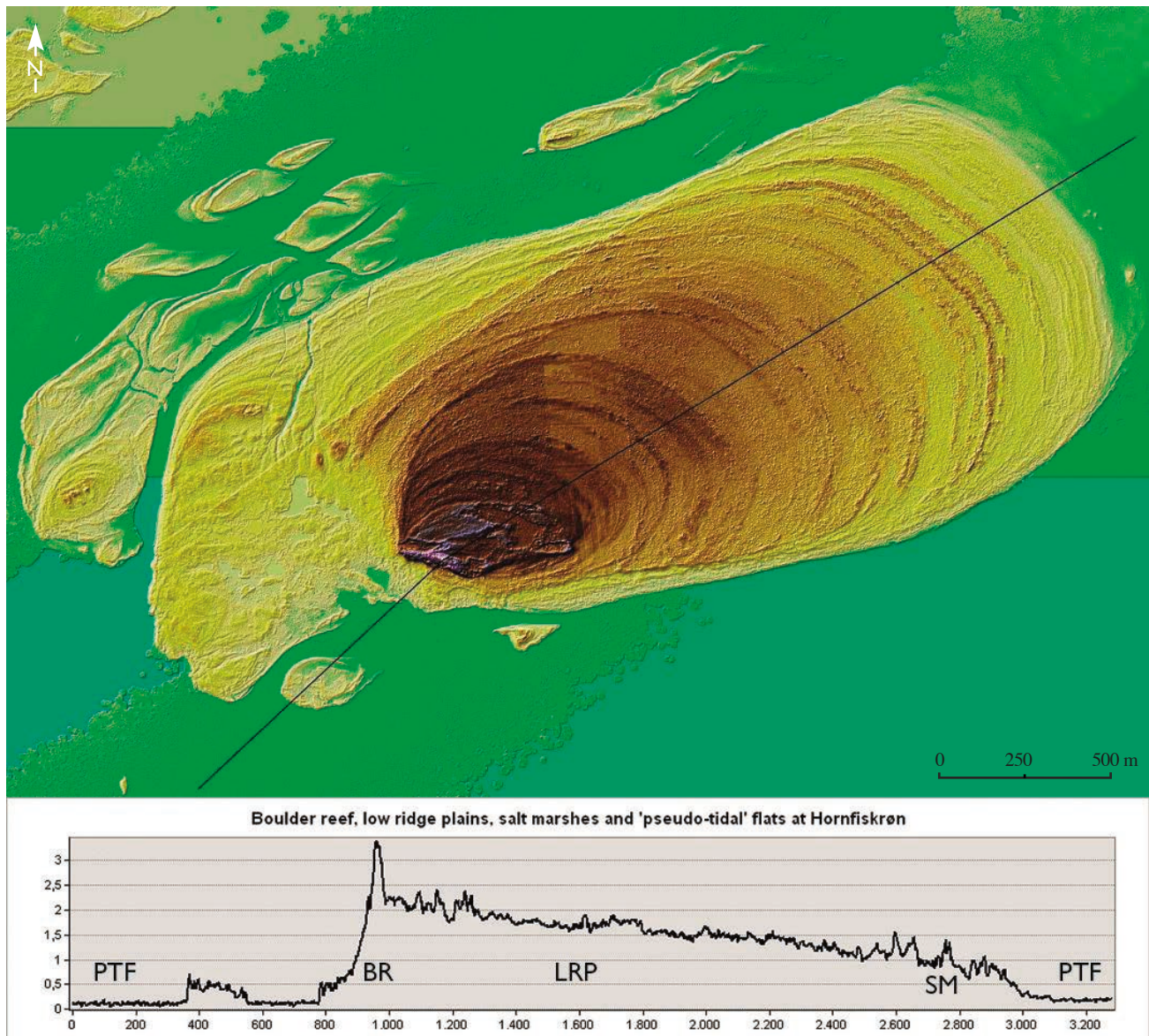


Fig. 13. Digital terrain model (DTM) of the concentric low-ridge plain (raised 'mussel-shell plain') of Hornfiskrøn. The profile shows levels (m above MSL) and distance (m) along the black line. BR: the raised boulder reef ('Engelskmandens Grav', photo in Fig. 6). LRP: raised low-ridge plain. SM: present saltmarsh. PTF: pseudo-tidal sand flat.

m high and 2 m wide vertical structures of cemented sand, gravel and fossils (locally named 'corals') that act as substrate for a highly specialized epifauna and algal vegetation. These hard structures are characteristic of the seabed around Læsø and were first described by Nordmann (1903), who already then revealed a precise understanding of this unusual phenomenon.

Reconstruction of the emergence, growth and coastal development of Læsø

The overall relation of ages, levels and depositional environments of the emerging island and its pre-history can be deduced by plotting the ages of dated samples versus the level of the individual samples. Then, by drawing shore level lines above marine samples and below terrestrial samples and by detailing such lines where the samples represent beach deposits, the level/age relation of relative sea levels (RSL) and terrain levels (RSL plus estimated heights of wave run-up) can be compared with more detailed analyses of beach-ridge levels and their relative chronology of appearance (Fig. 15).

Applying the DTM, a total of about 4000 km of beach ridges have been identified and mapped throughout Læsø. Thus, even low beach ridges are mostly traceable over 1–3 km and frequently up to 7 km in 110 km² of the surface of the island. Only in the inland dune fields of Højsande and in the coastal dune fields of eastern Læsø, i.e. in a total area of about 8 km², the beach ridges are mostly obscured. This provides a unique situation where the geometry and relative chronology of the numerous beach ridges can be unambiguously observed and numbered. The island comprises three main areas in which

the beach-ridge formation has progressed towards north, south-east and south-west, respectively (Fig. 4). In order to present basic results of how these sea-level proxies of the present island have been formed, the coastal types and stages are illustrated in Fig. 5, while the results of the emergence history (the age model) and relative sea-level (RSL) displacement are presented later in Fig. 36 and Fig. 38.

The numerous and well separated beach ridges make it possible to establish a formation chronology of the coastal progradation in each of the three main areas. To define a starting point for this chronological numbering of the seaward progradation of the beach-ridge systems it is necessary to know exactly which of the beach ridges is the oldest one in the most elevated candidate area. This problem has been solved by GPR profiling whereby it can be shown which of the ridges has been formed first, and which have been formed subsequently by lateral accretion to the oldest preserved spit. This position was already indicated by Hansen's (1977) studies of aerial photographs, and more robustly by Andreassen's (1986) pioneer GPR profiling. Andreassen's GPR profiling indicated the 'initial spot' to be situated within a 1 km² area where northern beach deposits are inclined to the north, while southern beach deposits are inclined to the south. This small area was classified by Hansen (1994, 1995) as the oldest preserved part of the island.

The growth history of Læsø presented below (and in Fig. 4, Fig. 5, Fig. 36) is mainly based on the high-resolution DTM of the island, which forms the basis for a more precise palaeo-shoreline mapping than previously published at scale 1:50,000, as well as a vegetation/level map at scale 1:15,000 of the saltmarshes



Fig. 14. Abrasion plain ('sand-paper plain') and sand flat (pseudo-tidal flat) with many boulders resting on the eroded glacio-marine clay platform and jutting out of a thin Holocene sand cover. The largest boulder in front of the photo juts 90 cm out of the sand. South coast of Tørkeriet. (Photo: Conny Andersen).

of Rønnerne (Hansen 1995). The growth history is a result of many years of field work on the past and present coastal development which has previously been published (Jessen 1897; Michelsen 1967; Mörner 1969; Hansen 1977, 1980, 1994, 1995, 2010, 2015; Bahnson *et al.* 1986; Olesen 2005; Hansen *et al.* 2012).

The absolute ages presented in the headings of each sub-section are derived from Table 1, the result of the age model presented in Fig. 36, and the above described 1200 RSL/age index points of the database.

Formation of a sandy shoal where the present island emerged

Trunks of a *Pinus* forest from the Boreal continental period found 1 km south-west of Stokken show that the Holocene transgression stood more than 2 m below MSL around 10274 years BP (calibrated), while ¹⁴C and OSL datings of the oldest late Holocene marine deposits on Læsø (Table 1, Fig. 15) show that the Litorina transgression at Læsø reached above the highest levels of the preserved beach ridges, i.e. at least 11–12 m above MSL around 6300–5700 years

BP, and that the present island emerged some 800 to 1400 years later (c. 4900 years BP) at a relative sea level of 10.3 m above MSL (Fig. 17).

The ages of the marine deposits between the abrasion platform and the older beach ridges show that the present island emerged after relatively fast deposition of 6–12 m of marine sand in a >30 km² area (Michelsen 1967; Hansen 1977, 1995). This amount of marine sand (> 0.3 km³) was deposited/redeposited during at least 2500 years (OSL ages of c. 6300 to 4000 years BP). Thus, the erosion of the pre-existing late glacial landscape and redeposition on its surface is clearly related to the transgression by the Litorina sea. The transgression probably began submerging and eroding the Læsø platform c. 8500 years BP and raised the RSL of the region with >13 m from below -2 m (Fig. 15).

Mainly due to the relatively rapid crustal uplift of the area, the RSL transgression soon turned into a RSL regression, which in this region began around 6300 years BP (Fig. 15 and Christensen 1995). As the regression continued, the erosion also continued at

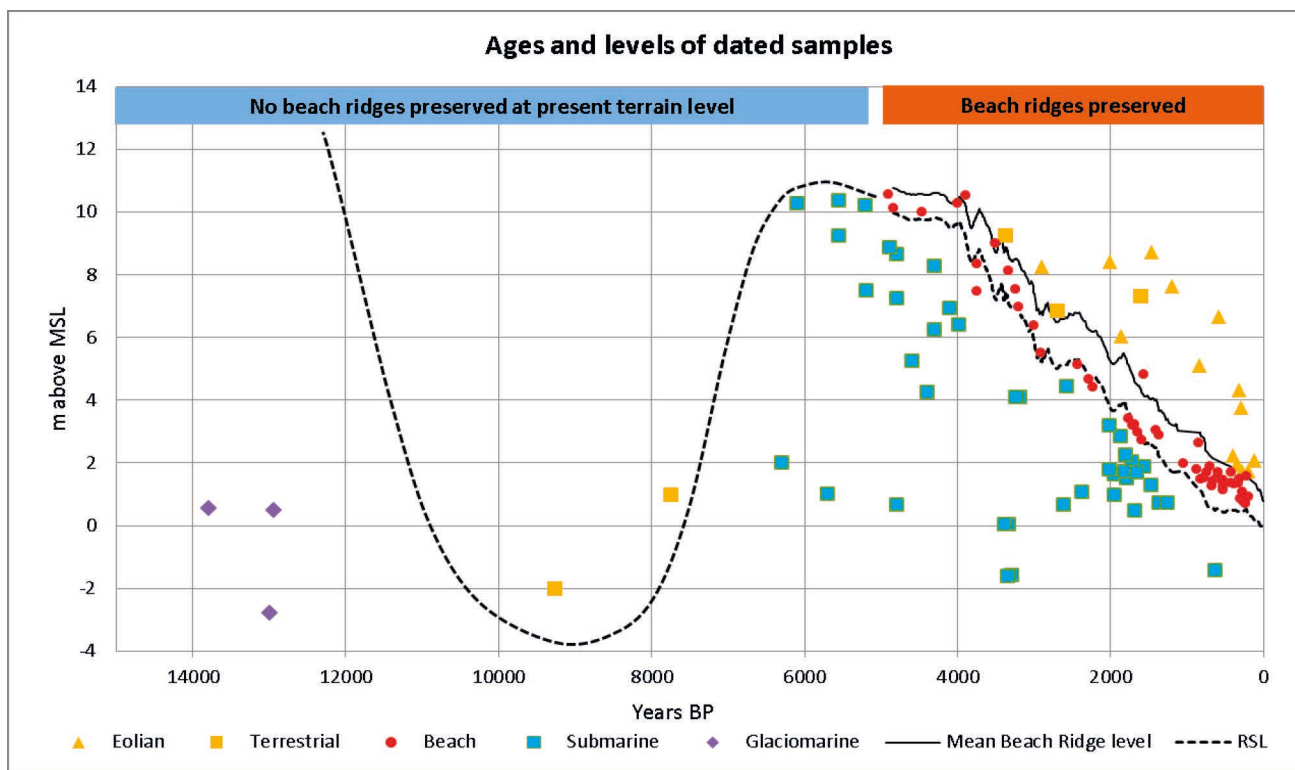


Fig. 15. Level vs age diagram of absolute age datings in Table 1 (except for two samples with older ages). Results are shown according to the interpretation of the sedimentary environment of the samples. Yellow triangles: Aeolian sand (i.e. fine-grained sand above beach deposits). Yellow squares: Peat, freshwater gyttja and tree trunks. Red circles: Beach deposits (i.e. mostly relatively medium- to coarse-grained sand with pebbles and stones). Blue squares: Marine deposits (i.e. fossil shells, teeth of two individuals of sperm whale, or fine-grained sand without pebbles). Purple diamonds: Glacio-marine deposits (i.e. fossil shells of *Saxicava arctica*). Solid black curve: Crest level of the island's beach ridges (see text for reconstruction method). Dashed curve below solid curve: Reconstructed RSL (see text for transformation of crest levels to RSLs). Dashed curve for ages older than 4900 years BP: Proposed RSL of the late glacial sea, the Boreal regression and the Litorina transgression until Læsø emerged at 4900 years BP.

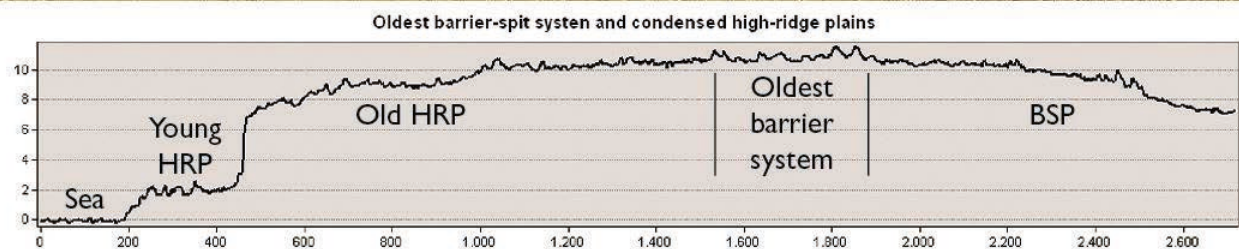
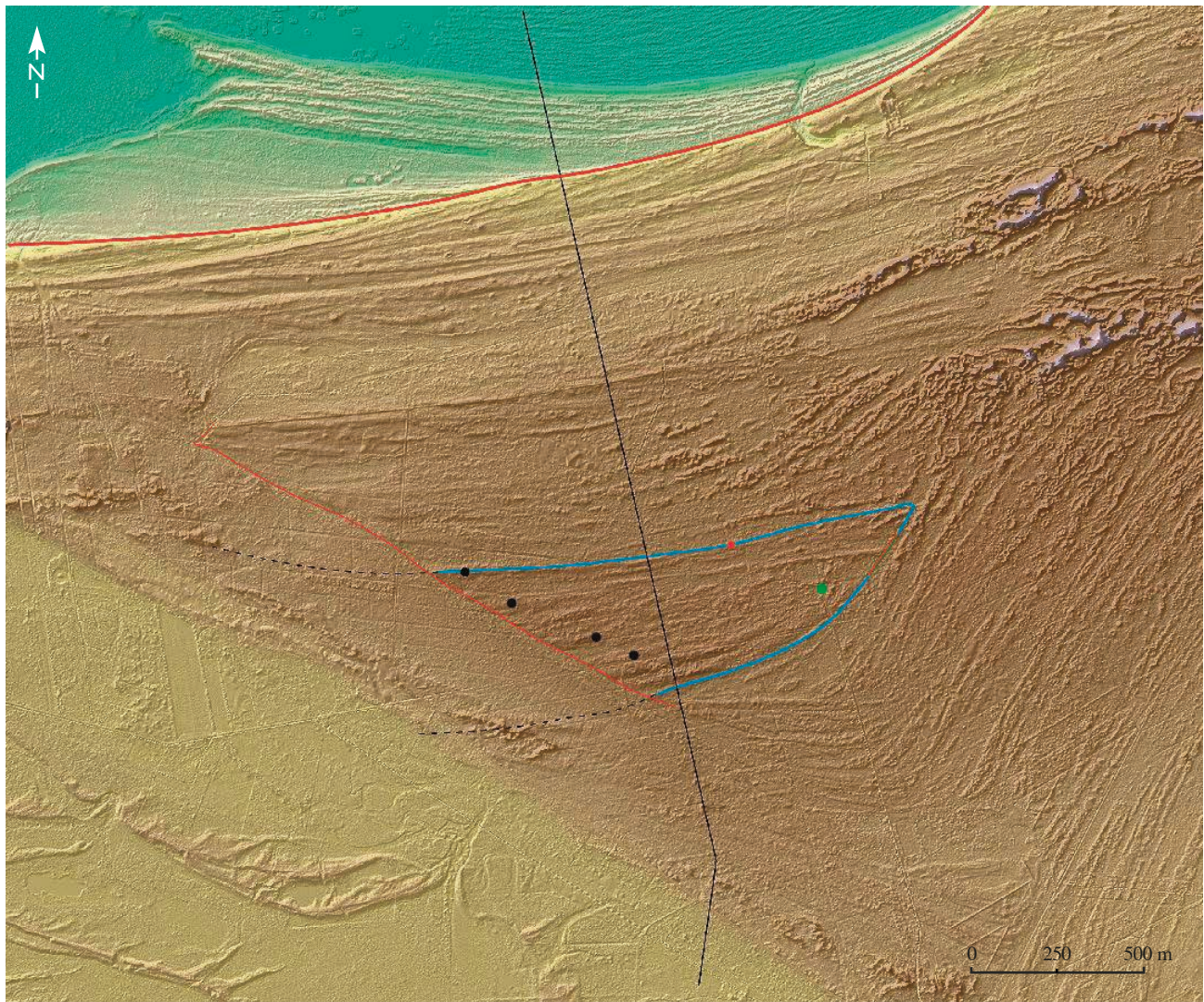


Fig. 16. Digital terrain model (DTM) of the oldest preserved part of Læsø, which formed as the easternmost part of a barrier-spit system that subsequently prograded to the north, south, south-east and north-east and was later eroded to the south-west (red line). Blue line indicates the position of Læsø's oldest preserved beach-ridge system, which both to the north and to the south is fringed by younger beach ridges. Black dots: Position of Læsø's oldest OSL dated samples of beach sand found at the present terrain surface (max. 4900 years BP, cf. Fig. 17). Red dot: Position of core boring with five OSL datings ranging from 4300 to 4800 years BP (2.5–6.5 m below terrain). The red dot also shows the position of Læsø's so-called 'birth-stone'. Green dot: Position of pollen samples (Fig. 30) from a thin peat layer (14C-dating: 3375 years BP) deposited in a swale of the initial barrier-spit system, showing that the oldest known forest of post-Boreal stages was dominated by *Taxus* (yew). North of the initial barrier-spit system are seen two generations of condensed high-ridge plains (Old HRP and Young HRP) at Holtemmen along Læsø's north-coast. The two plains are separated by an up to 6 m high cliff (long red line) that was formed after 3000 years BP until c. 1500 years BP. To the south-west are seen parts of the barrier-spit and lagoon plains of Kærene, where the shown double barrier was formed c. 3750 years BP. The profile shows levels (m above MSL) and distance (m) along the black line. BSP: Barrier spits.

more marginal parts of the platform until c. 3200 years BP, which is indicated by four ^{14}C datings of *Balanus* and *Mytilus* attached to boulders both north and south of Læsø, lying on top of the glacio-marine platform and covered with younger marine sand.

Emergence of the present island

On top of this sandy shoal the oldest preserved beach ridges of the emerging island were formed c. 4900 to 4000 years BP (see below), i.e. c. 1400–2300 years after the Holocene transgression had culminated in the region. In the berms of the oldest beach ridges, reworked flint tools and pottery are frequently found; these are from a fisher and seal-hunter culture (the Pit-Ceramic culture) that in the south-western Scandinavian coastal regions had adapted to the high sea level of the Litorina transgression and consequent loss of land. The culture existed only in the period c. 5200 to c. 4800 years BP and the Læsø finds probably originate from settlements along the coasts of western Sweden or northern Jutland. The artefacts (Lysdahl 1985, 1987) were probably brought to the emerging coasts of the shoal during seal hunting trips (Hansen 1995).

The period 4900 – 4000 years BP: The first barrier system attached to older landscapes

The oldest parts of the present island are represented by the eastern part of a 0.7 km broad and 1.5 km long recurved spit system in the highest part of Læsø's beach sediments (between blue lines in Fig. 16) at terrain levels of maximum 11.3 m (corresponding to a RSL of 10.3 m).

OSL datings of this oldest preserved spit system (Fig. 17) show that it was formed between c. 4900 and c. 4000 years BP. The oldest beach ridge has been identified in several GPR sections showing that the ridge at a terrain level of up to 10.8 m is bordered on both sides by slightly younger beach ridges facing to the north and to the south, respectively (Fig. 18). From this and neighbouring ridges, and from the substrate of the ridges, a total of 20 OSL datings have been obtained. Within an OSL age uncertainty range of mostly 200–350 years it is concluded that the oldest beach ridge appeared c. 4900 years BP.

The shape of the preserved part of the spit system shows that the spits migrated from a position north-west to west of Vesterø Havn and recurved towards

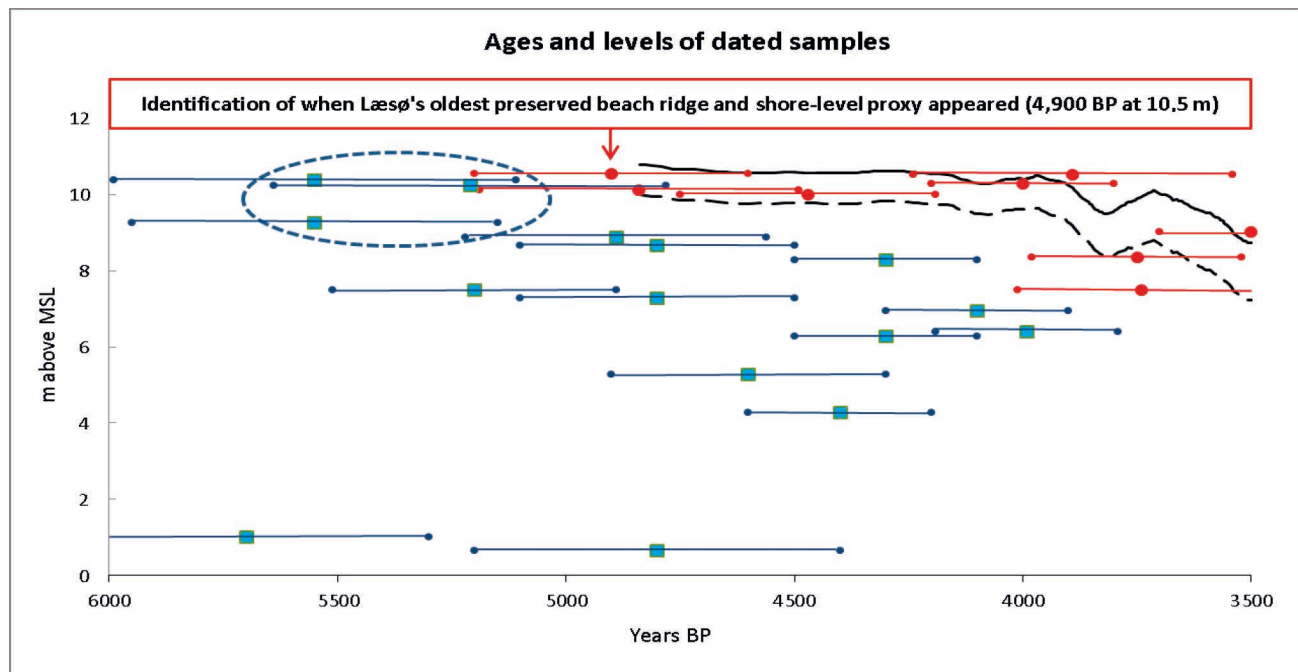


Fig. 17. Expanded right part of Fig. 15, addressing when exactly the oldest preserved parts of Læsø emerged. Because the raised shorelines at Læsø are situated up to 3 m higher than contemporaneous shorelines at comparable isostatic isolines in northern Jutland and western Sweden, it has often been discussed if the 'top' of Læsø could be older than suggested by Hansen (1977, 1980, 1994, 1995). The 22 OSL dated samples from the oldest beach-ridge complex, its substrate and nearby beach ridges show that the oldest preserved part of Læsø emerged c. 4900 years BP at a present terrain level of 11 m (sample level 10.5 m; RSL=10.3 m), i.e. 1000–2000 years 'too late' compared to the general isostatic position. It should be mentioned that the three encircled samples have been collected from layers below the OSL dated beach deposit samples at the same locations, thus ruling out that the 'top' of Læsø at a terrain level of 11 m is significantly older than c. 4900 years.

the north-east at its eastern tip. A GPR section crossing the spit system (Fig. 18) displays that while the spit grew eastward it also prograded both to the north and to the south. While the underlying 6–12 m of marine sand is almost devoid of coarse material, the stone and gravel of the superposed spit system most likely was supplied from an emerged land area composed of glacio-marine deposits with a significant content of coarse material. According to the palaeo-shoreline erosional geometry, e.g. the orthogonal relation between the present coastline and raised beach ridges at Vesterø Havn (Fig. 4, Fig. 5, Fig. 36), the source area must have been situated west and north-west of the preserved parts of the spits, i.e. most probably outside

the present north-western coastline, or 6 km or more west or north-west of the preserved part of the system. Judging from the occurrence of large boulders and boulder reefs in the sea north-west of Læsø, as well as the geometry of the spit systems that formed during the ensuing 1500 years, the most probable source area is situated up to 8 km west to north-west of the present island. This area is now completely eroded down to the emerged boulder reefs of Nordre Rønner and Borfeld, to the 8 km long, shallow, sand covered reef, Flaget, between Nordre Rønner and Læsø, and to the many small submerged boulder reefs west to north-west of Vesterø Havn at app. 2–4 m below MSL. Most of these small, submerged boulder reefs have now been

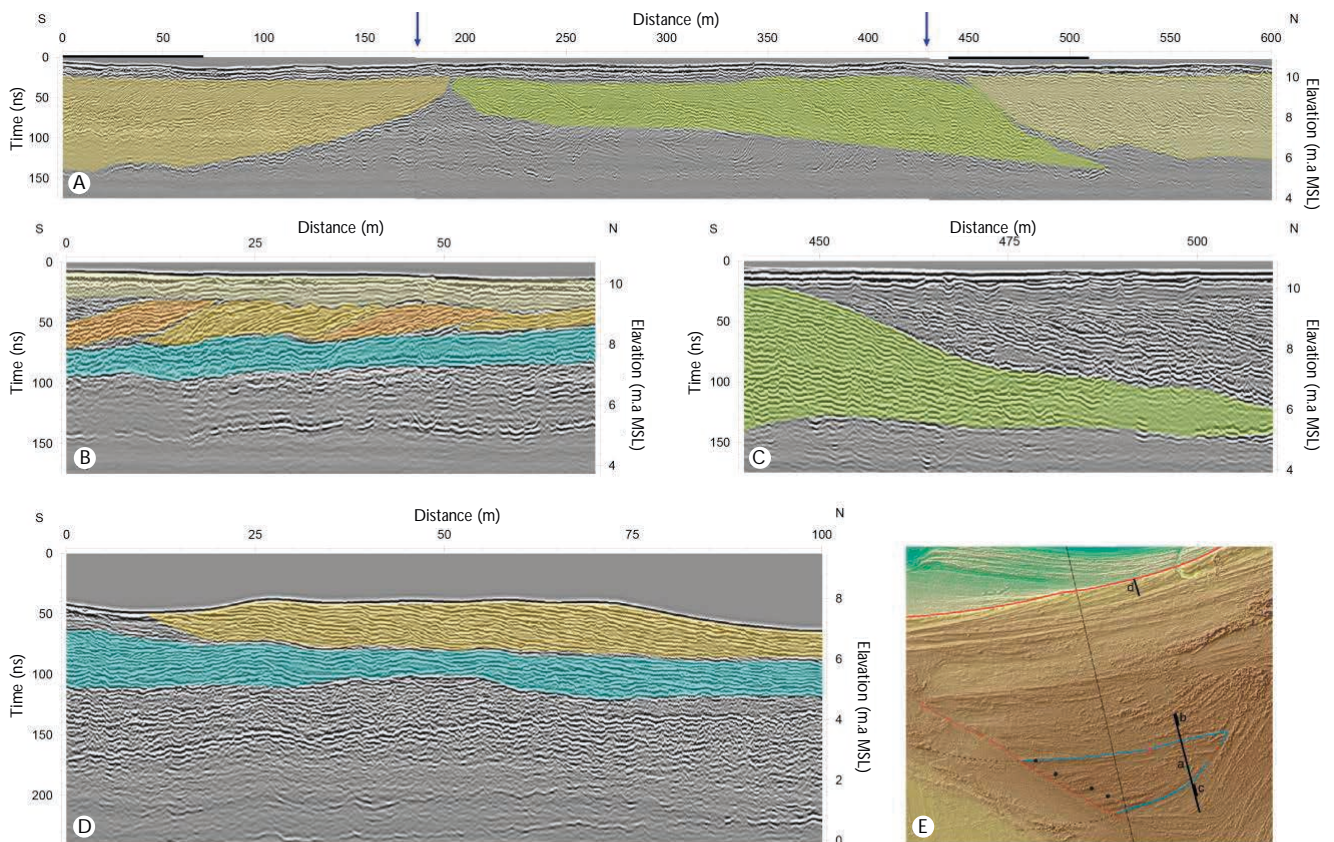


Fig. 18. GPR sections of the oldest preserved spit complex of Læsø (A) and subsequent beach ridges formed on the northern side (B) and southern side (C) of the oldest spit. A, a 600 m long GPR profile displays how the oldest part of the island prograded (between the blue arrows). Beach-ridge plains evolved both to the south (0–180 m) and to the north (430–600 m) of the oldest part. Enlargements of the profile sections at 0–70 m and 440–510 m are shown in (B) and (C), respectively. B, section showing that the more steeply dipping beach-ridge and beach deposits (orange) downlap on the more gently sloping shoreface deposits (light blue). The beach ridge is overlain by aeolian sand deposits (light yellow). C, section showing that the oldest northward-dipping spit deposits are overlain by steeply dipping beach and shoreface deposits, illustrating that the island at this stage was more exposed to the south-south-east than the to the north, i.e. probably protected by a pre-existing, later completely eroded land area between Nordre Rønner and Læsø. D, section displaying the northernmost and youngest part of the oldest generation of the condensed high-ridge plain. The ridge crests are slightly truncated upwards by wind deflation and cut east of the section by the 6 m high cliff between the old and the subsequent much younger condensed high-ridge plain. Below the coloured parts of the sections are seen major sedimentary structures of the sandy shoal upon which the island's beach deposits were formed. E, subarea of Fig. 16 showing the positions of the GPR sections in A to D.

removed and applied for harbour building at many places in Denmark. Only the most heavy boulders (> 20 tonnes) have not been removed.

The period 4000 – 2500 years BP: Linear beach-ridge plains, barrier-spit and lagoon systems, and formation of a twin island

Shortly after the formation of the oldest preserved system of recurved spits, linear beach-ridge plains began evolving on the south-western, south-eastern and northern side of the initial spit system (Fig. 16). OSL datings indicate that the development of linear beach-ridge plains continued on the south-western side of the initial spit system until c. 3900 years BP, and on the south-eastern and northern sides until c. 3000 years BP.

Around 3900 years BP a new barrier-spit and lagoon system began migrating south-eastwards from Vesterø Havn (Fig. 10, Fig. 24) sourced from the above mentioned area situated west and north-west of Læsø. Simultaneously, another source area began developing to the south near the present centre of Læsø (Fig. 19), where the town of Byrum was initially built on a 1.5 km long and 0.3 km broad boulder reef now protruding from the superimposed younger beach deposits. Here, the Byrum spit and lagoon system began developing around 4000 years BP from a raised, but gradually completely eroded glacio-marine landscape which is now only represented by the raised boulder reef in Byrum and by hundreds of widespread large boulders resting on top of the eroded glacio-marine platform south of Byrum. Due to erosion of this landscape, a large coarse-grained barrier spit (previously exploited in several gravel pits) began migrating to the north. Soon after appearance of the first barrier spit, several new barrier spits and lagoons developed from the Byrum source area at still more westerly positions, while a system of low beach ridges and saltmarsh plains began developing on the eastern leeward side of the initial Byrum barrier (Fig. 19).

Before the Byrum barrier-spit system connected with the Vesterø barrier-spit system, there was a 1 km broad strait between the two 'twin-islands' of the Byrum system and the oldest part of the island that emerged 6 km north of Byrum some 500–1000 years earlier (Fig. 5, Fig. 36). East of the strait a narrower gap developed between the Byrum system and an east-growing recurved spit system from the northern island. This recurved spit system protruded into the sea east of the two initial islands, forming an eastward bulge in the later shoreline pattern when the two islands had coalesced c. 3000 years BP.

Gradually, the Vesterø and Byrum systems inter-fingered with each other and ultimately (c. 3000 years BP) they formed one large 7 km long barrier from Vesterø Havn to Byrum (Fig. 19 and Fig. 24) (on top of

which the road 'På Remmerne' between Byrum and Vesterø Havn has been built in the 1980s). Moreover, the two systems formed the presently 7 km long and up to 3 km broad wetland of Kærene, where present moors and lakes represent former lagoons, while heather ridges between them represent former barriers (Fig. 10).

After c. 3000 years BP and during the following c. 500 years, the Vesterø barrier-spit and lagoon system continued developing and several long spits migrated 5–7 km from a position seaward of the present west coast to Byrum, while further development of the Byrum spit/lagoon system had ceased (as seen in Fig. 19 and Fig. 24).

The period 3200 – 2500 years BP: Initial development of the Østerby peninsula

Simultaneously with the development of barrier spits and lagoons on the south-western side of the island, the north-eastern tip of the island developed with a series of coarse-grained beach ridges. At Bansten (Fig. 20) the beach ridges of this north-eastern tip of the initial Østerby peninsula are cut by an up to 8 m high sea cliff, providing an excellent exposure across the internal structures of the tip (detailed description in Hansen 1977). In the eastern and middle part of the sea cliff, strata with abundant and well preserved trace fossils of the heart urchin *Echinocardium cordatum* are interbedded with strata burrowed by the lugworm *Arenicola marina* (Fig. 21). This interbedding of strata with species living at distinctly different water depths indicate that RSL oscillated significantly in the period 3200–2800 years BP according to absolute age datings of the exposed strata of the cliff. In the eastern part of the cliff, a 300 m long section exposes very coarse-grained beach deposits of the south-east coast of the triangular stage, while in the western part of the cliff more fine-grained beach deposits represent the north coast of the triangular stage.

In the period c. 3200 to 2500 years BP, the north-eastern tip of the island grew 5 km to the east and formed a long complex spit of which the easternmost tip is preserved at Jegens (Fig. 22), where the internal construction of the tip of the spit can be seen in the 7 m high sea cliff east of Østerby Havn. The geometry of the very coarse-grained beach ridges in the preserved parts of the spit indicates that this system was initially derived from glacial or glacio-marine raised landscapes or shoals north of the present island where now a number of boulder reefs represent eroded shoals or completely eroded landscapes that supplied coarse materials for the growth of the long spit.

Moreover, the geometry of the very coarse-grained beach ridges on the preserved part of the easternmost tip of the large spit at Jegens show that the tip was

initially formed as a separate island supplied with materials from the north, and with beach ridges exposed to the west (Fig. 22). However, soon after the formation of this small coarse-grained island it connected with the large spit system growing eastwards from Bansten. Today, the middle part of the 6 km long spit has been eroded, and it might be questioned if it ever existed in one piece. However, several GPR sections from the north coast and southwards

(Andreasen 1986) clearly show that all beach ridges along the north coast of Læsø between Bansten and Østerby Havn were exposed towards the south and south-east, as also seen from the southward inclination of the raised beach deposits in the sea cliffs east of Bansten. Thus, the northernmost beach ridges at the present north coast are parts of later stages of the long spit, and the south- and south-east-facing geometry of the beach ridges at the present north coast shows

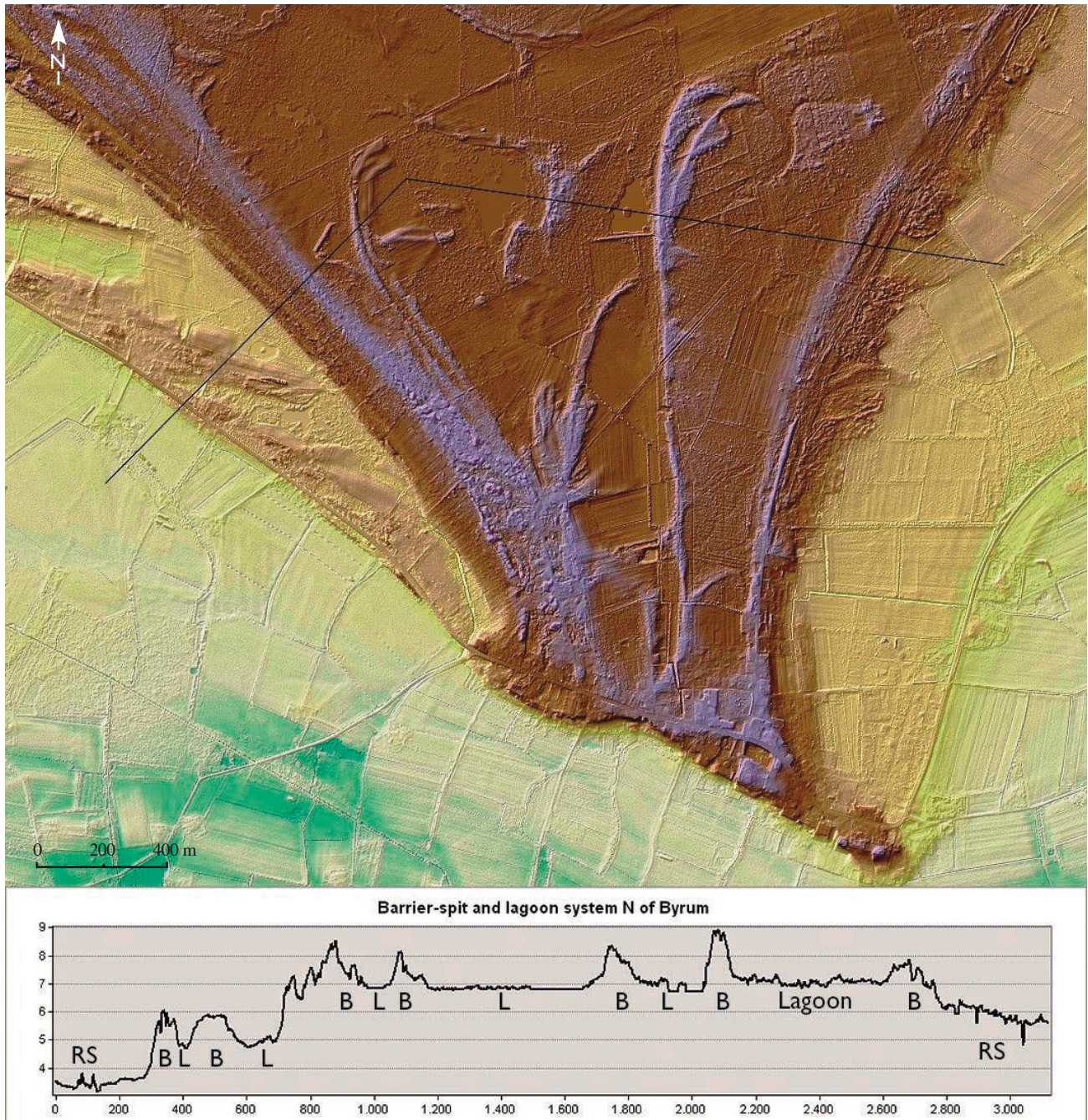


Fig. 19. Digital terrain model (DTM) of the barrier-spit and lagoon plains (raised 'tail-fan plains') north of the town Byrum, which is situated on a raised boulder reef forming the 4 m high cliff in the lower part of the figure. The profile shows levels (m above MSL) and distance (m) along the black line. B: raised barriers. L: raised lagoons. RS: raised saltmarshes (condensed low-ridge plains).

that substantial later erosion has taken place from the north, whereby 3 km of the middle part of the spit were removed so that only its root at Bansten and its easternmost tip at Jegens have been preserved.

The period 2500 years BP – present: Barrier-spit and lagoon systems of the Østerby peninsula
 After development of the 6 km long complex spit of the triangular stage, the development of the Østerby

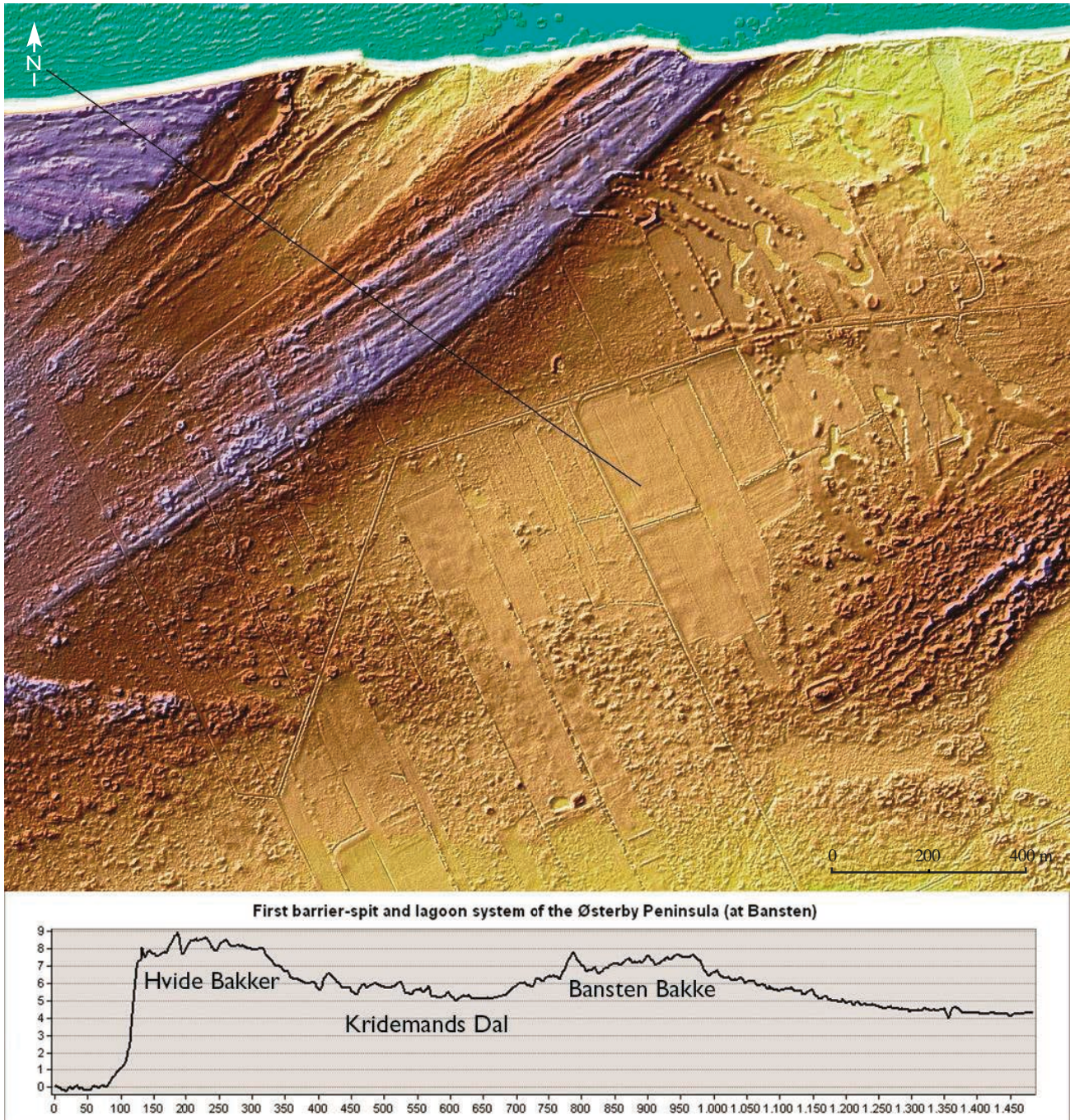


Fig. 20. Digital terrain model (DTM) of the raised barrier-spit and lagoon system at Bansten, i.e. the first of nine barrier-spit systems forming the Østerby peninsula at the south-eastern side of the older triangular island. The raised spit (Bansten Bakke) and raised lagoon (Kridemands Dal) are both cut by the 8 m high present sea cliff. The barrier-spit system in the upper left part of the figure (Hvide Bakker) was formed on the north coast of the older triangular island. The odd terrain morphology seen in the upper right part is caused by terrain regulations of a gulf club. The rectangular structure seen in the lower right part of the figure is the ruin and cemetery of the medieval Hals Church.

peninsula was continued with the formation of a 3.5 km long and very coarse-grained barrier complex (the Hals complex) that grew in west-south-westerly direction from the acute eastern tip of the peninsula. Barrier growth ceased around 1500 years BP and at that time it formed an attached, complex barrier with a shallow lagoon behind. On this barrier the medieval church of Hals (Fig. 20) was built c. 1250 AD, some 750 years after the barrier had been formed, while new settlers in the village of Hals cultivated the raised former lagoons on both sides of the barrier and probably also more westerly in more raised landscapes. Today, the position of westerly fields of the parish of Hals may be indicated by the straight northwards extension of a dune field (lower left of Fig. 20), probably showing that the settlers built a 2 km long shelter belt here. In the 18th century the village, its fields and church were destroyed by migrating dune fields most of which continued into the bay of Bovet during the late 18th and early 19th century. Presently, the barrier system is intensively exploited by gravel digging (Fig. 22).

After development of the initial Bansten and successive Hals barriers, a series of seven further barrier and lagoon complexes formed at the south and east coast of the gradually enlarged Østerby peninsula (Figs 20, 22, 23). The oldest of these is the Gammel Østerby complex which developed until c. 1000 years BP. On the northern side of its lagoon a small Iron Age harbour has been found. The poles were made of yew (*Taxus baccata*), a species that also dominated the forests of the island 3000 years earlier. Tree-ring

dating has shown that the trees were felled in 640 AD (Lysdahl 1985).

Gradually, the growth directions of the barrier complexes swung from west-south-west to south (Fig. 5, Fig. 36). On average the individual barrier and lagoon complexes were formed within periods of 200–250 years. The presently developing barrier complex (Bløden Hale, Fig. 23) grows rapidly towards the south. In 1950 the barrier began passing its lagoon (Bløden) and grew rapidly in front of two small barrier islands (Store Knot and Lille Knot) that had appeared in the first half of the 20th century on the eastern edge of the very shallow sand platform south of the Østerby peninsula. During the last 60 years the Bløden Hale barrier has grown 1.5 km towards the south.

The period 2500–2000 years BP: Detachment of the island from older eroded landscapes

Around 2500 years BP the barrier and beach-ridge systems formed a triangular area with a present size of app. 45 km² (Figs 4, 5, 36). As seen from the geometry of the palaeo-shorelines to the south, west and north-west, this triangular area appears to have become detached from previous source areas, i.e. glacio-marine landscapes or shoals that had finally been completely eroded to below sea level of the time.

Such pre-existing, xenomorphic landscapes most likely included parts of the large arc-shaped area between Læsø and Nordre Rønner, where the eastern side of the present sand-reef of Flaget now forms an 8 km long shallow arc. To the south-east the arc is being



Fig. 21. Trace fossils after the heart urchin *Echinocardium cordatum* (in layers behind and below the knife and in the uppermost part of the picture) and trace fossils after the lugworm *Arenicola marina* (funnel-shaped structures in upper part of the picture) exposed in the sea cliff at Bansten. The sea cliff exposes a cross section of the marine substrate (deposited c. 3200 to 2800 years BP) of a large, complex spit system ending 4 km east of the section at Jegens east of Østerby Havn. At present the two species live at distinctly different water depths. The sequence of trace fossils indicates a temporary sea-level fall by 1 m or more, corresponding to the >0.7 m lowstand at c. 2900 years BP found from beach-ridge levels elsewhere on Læsø (Table 4).

re-shaped by the presently north-west growing sand barrier, and to the north the arc is generally submerged under less than 1 m of water. However, as seen from the

east-west trending beach-ridge pattern of the older part of the Holtemmen area, such a probable xenomorphic arc landscape had been completely detached from Læsø

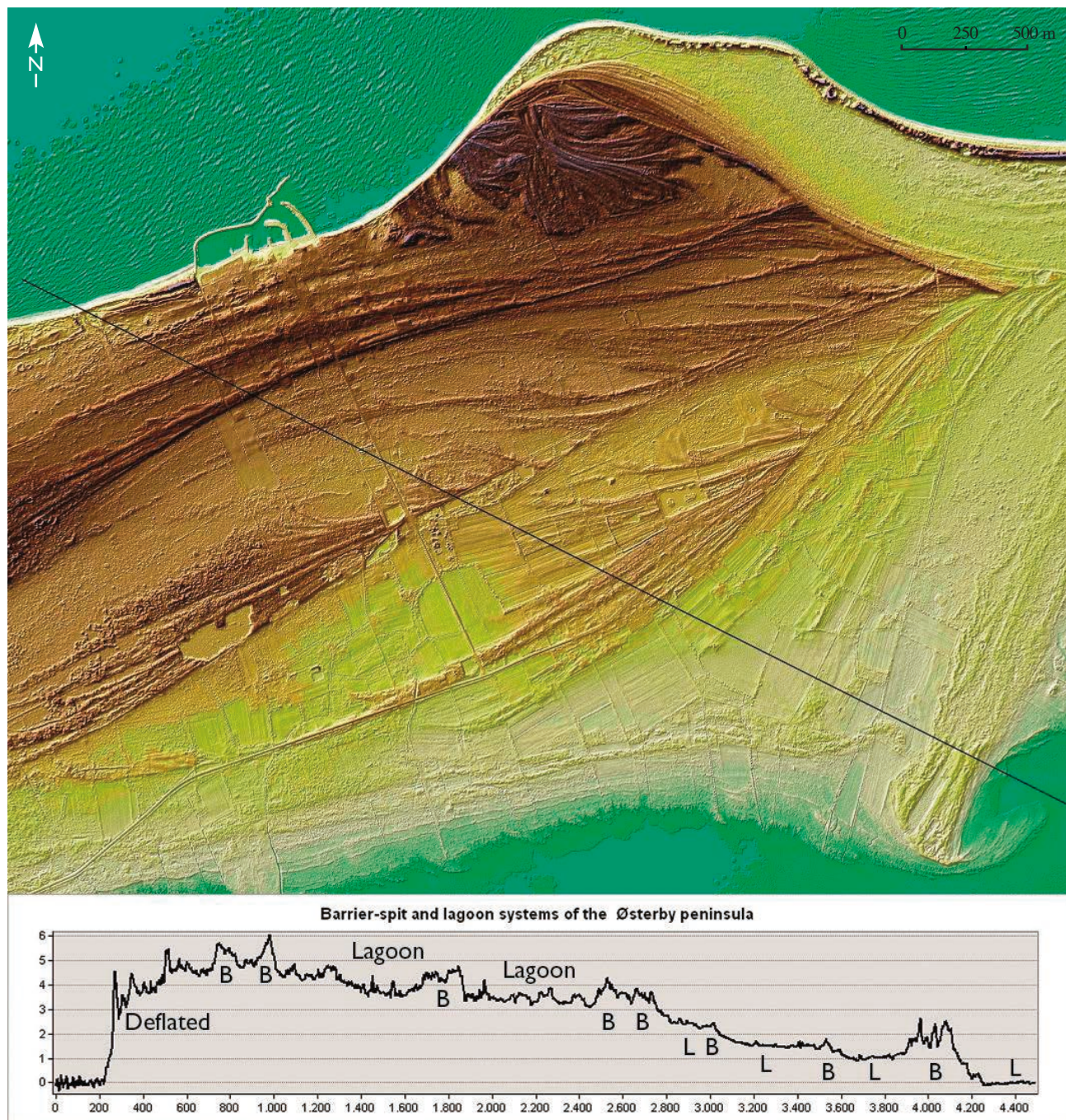


Fig. 22. Digital terrain model (DTM) of raised barrier-spit and lagoon plains of the Østerby peninsula. East of Østerby Havn (harbour) is seen the preserved acute tip of the (now partly eroded) complex spit system stretching from Bansten 4 km west of the harbour (Fig. 4, 5 and 36). The complex spit geometry of the oldest acute eastern tip of the island (800–1500 m east of the harbour) indicate that the tip was initially formed by sediment supply from a landscape north of the harbour before it united with the spit system growing from Bansten. The figure shows parts of five subsequent barrier-spit and lagoon systems (and some gravel pits). All barrier spits are faced to the south-east to east, and barriers close to the coast west of Østerby harbour (at 250–500 m on the profile) have been eroded (lowered) by wind deflation. To the south is seen a young saltmarsh landscape facing the bay of Bovet. The profile shows levels (m above MSL) and distance (m) along the black line. B: raised barrier spits. L: raised lagoons.



Barrier-spit and lagoon systems at Bløden Hale

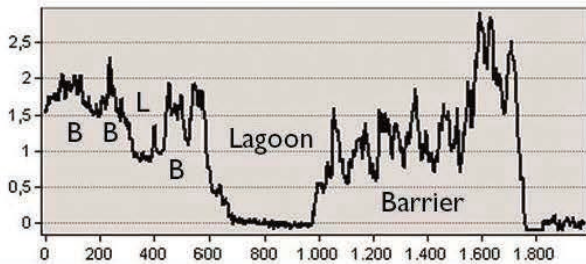


Fig. 23. Digital terrain model (DTM) of the barrier-spit and lagoon system of Bløden Hale (barrier) and Bløden (lagoon). Most of the 2 km long 'tail' in front of the two islets has been formed after 1950. The >2.5 m high tops at the east side of Bløden Hale are beach ridges topped with aeolian dunes. The profile shows levels (m above MSL) and distance (m) along the black line. B: raised barriers. L; raised lagoon.

at the latest around 3500 years BP. This interpretation does not exclude that a xenomorphic arc still extended from Nordre Rønner and some kilometres to the south and south-east, but the part nearest to the older high-ridge plain at Holtemmen had definitely disappeared when these ridges were formed. More westerly, i.e. immediately north of Vesterø Havn, where many boulders are found at the shore on the west side of Flaget, there may still have been a xenomorphic connection between Nordre Rønner and Læsø until the 6–8 m high erosional cliff between the older and the younger high-ridge plains of Holtemmen had been formed.

It is not possible exactly to date when the high cliff at Holtemmen began developing. The eroded parts have ages around 4000–3500 years BP, and the formation of a younger high-ridge landscape at the seaside of the cliff began around 1500 years BP or even later. Aeolian drapings on the low beach ridges in front of the cliff were formed during the 17–18th century (Table 1). The east–west trend of the older, long and nearly straight ridges shows that pre-existing land immediately north of them had disappeared no later than 3500 years BP and that the present easterly extension of the large arc of Flaget must be a younger feature, although initiated by a pre-existing, more westerly landscape. Consequently, the eastern side of the arc of Flaget is considered to have been built from sand derived by erosion of the western side of the arc, so that the arc by this process of erosion and re-deposition gradually shifted to a more easterly position. This interpretation may also explain the position of many boulders west of Flaget, in particular Læsø's probably largest monolithic boulder, Friises Sten, which is situated 1 km west of the middle part of Flaget, whereas boulders, stone and gravel are not observed on the eastern side of Flaget.

As seen from the palaeo-shoreline pattern at Vesterø Havn up to 2 km south of the harbour, raised beach ridges that developed in the time interval 3500–2500 years BP are perpendicular to the present coast (Fig. 24). These beach ridges were formed by alongshore transport as barrier spits attached to a landscape containing coarse materials, probably a xenomorphic, glacio-marine or glacial landscape west of Vesterø Havn, where now a number of submerged boulder reefs are found at water depths down to 4 m. In the town Byrum at the southern corner of the old triangular area, a steep palaeo-cliff with a height of up to 4 m separates the triangular area from the younger saltmarsh landscape that formed south, east and west of Byrum during the last 2000 years (Fig. 19).

After 2500–2000 years BP, the island had no emerged major contact with glacio-marine land masses to the south, west and north-west (Fig. 11, Fig. 19), and this probably led to a depletion of sources that caused the development of the erosional cliff along the north coast

of Læsø. Instead, the continued coastal progradation of the south-western, eastern, south-eastern and southern parts of the island appears to have been supplied by erosion of the detached western and northern sides of the island, and by erosion of the constantly rising sea-

bed. Likewise, the geometry of the palaeo-shorelines in the eastern part of the present island indicates that coastal progradation continued, mainly supplied by coarse materials derived from the seabed and from erosion of the north coast.

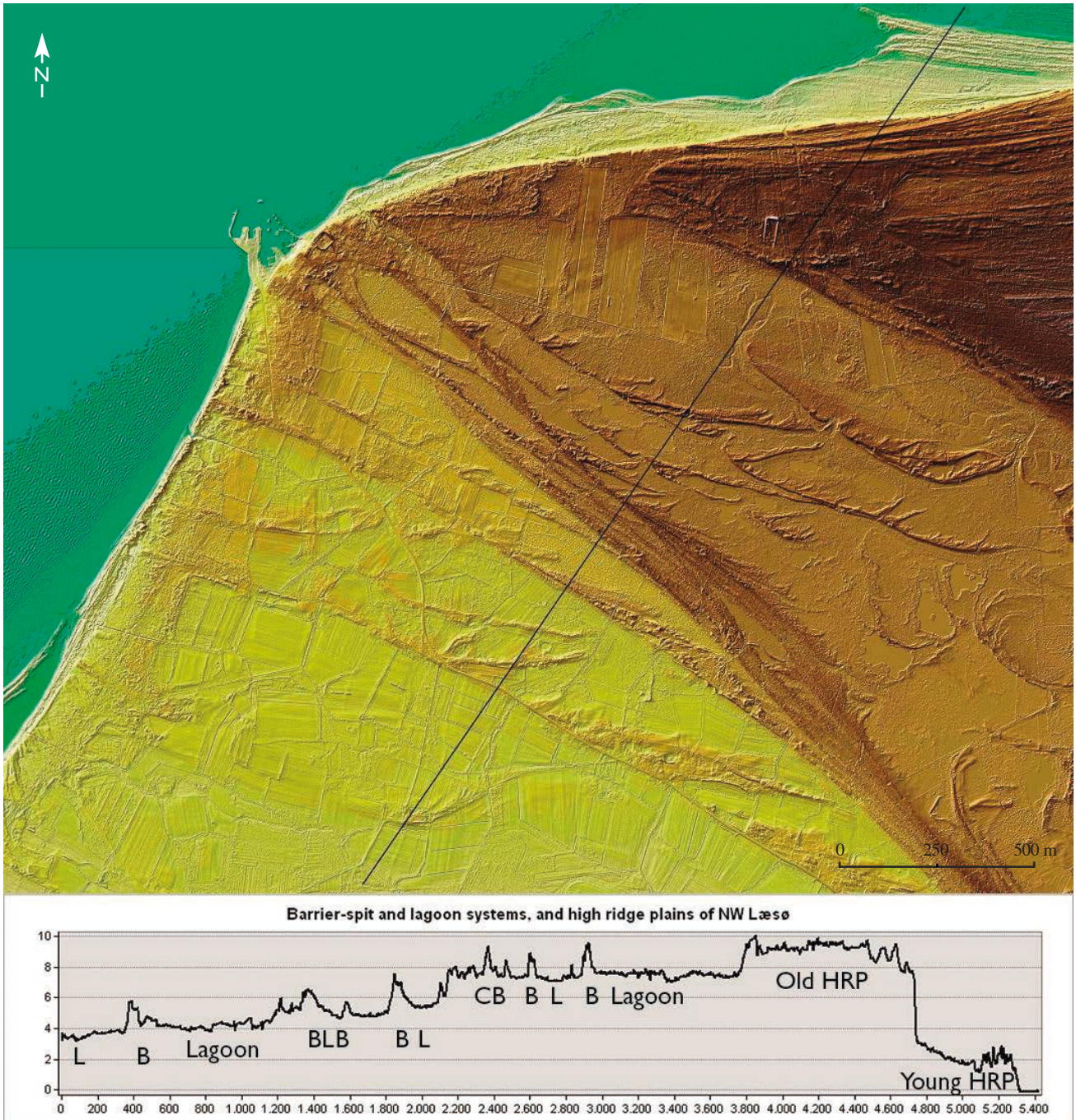


Fig. 24. Digital terrain model (DTM) of north-west Læsø showing raised high-ridge plains (Old HRP, 8–10 m above MSL), raised barrier-spit and lagoon plains (B and L, 5–9 m above MSL) and raised barrier-island and lagoon systems (B and L, 3–6 m above MSL). In the raised barrier-spit and lagoon systems, a 7 km long complex barrier is found (CB, 7–8 m above MSL), stretching from the harbour to the town Byrum (Fig. 19). The barriers are almost perpendicular to the present coastline, indicating strong erosion in the past. To the north is seen the raised cliff (8 m above MSL) between the old and young condensed high-ridge plains of Holtemmen. The profile shows levels (m above MSL) and distance (m) along the black line.

For obvious reasons, it is unknown how much material the erosion and formation of ancient sea cliffs supplied to the continued growth of the detached south-western, southern and south-eastern coasts. However, if it is assumed that the slopes and elevations of the removed parts of the island are comparable to the slopes and elevations of the preserved parts, it can be roughly estimated that the removed volume comprises about 30% of the volume that was deposited during the formation of younger parts of Læsø. Consequently, the main part of the sediment contributing to the formation of the younger parts of Læsø was supplied by erosion of the seabed. This is in good agreement with the fact that most of the top of the eroded glacio-marine platform after 2500 years BC was situated at water depths less than 4 m, and that the water depth continuously decreased due to isostatic uplift. At south-western and south-eastern Læsø, most beach ridges formed after 2500 years BP consist of sand, indicating material supply by erosion at some water depth, while many ridges of the older (attached) stages have a considerable content of gravel and stone that most likely were derived by erosion of emerged xenomorphic landscapes or seabed close to sea level.

The period 2500 years BP – present: Barrier-island and lagoon systems of the south-west coast

After detachment of the island from older and completely eroded xenomorphic landscapes, the coastal progradation of the south-western part of the island was supplied mainly by erosional products from the seabed and by erosional retreat of the north-western and northern coasts (Figs 4, 5). This supply of mainly sand and much less gravel together with isostatic uplift resulted in a series of nine unattached barrier islands, each separated by a time span of 200–300 years (Fig. 11). A GPR section of some of the youngest raised barrier-island and lagoon systems (Fig. 25) displays the internal structure of such systems, including seaward inclined shoreface deposits of barriers, sub-horizontal stratification of lagoon deposits, and erosional structures of draining channels of the lagoons.

The present barrier island of Stokken at the south-west corner of Læsø (Figs 4, 5, 11, 12, 26) developed during the last 100 years. Studies of air photograph (1945–2015) show that the barrier island formed initially at least some 500–700 m from the coast and subsequently migrated 300–500 m closer to the coast (Paradeisis-Stathis 2015). Over time, alongshore sediment transport extended the barrier in both directions. To the north-west, a series of presently five recurved spits developed successively. At the same time, many barrier breaches and washover fans (Fig. 26) transported beach and dune sand from the

seaward side to the lagoon. The position of concrete pylons (for navigation marks) erected in 1965 indicate that since then the barrier has grown to a length of 4 km and has migrated about 300 m landward.

Bird (2008, p. 237) applied Stokken (then named “Knotten”) as a school example of barrier islands in isostatically regressive environments.

In 1991 a new barrier island emerged rapidly 1.5 km west of the north tip of Stokken. During less than one year the island grew to a length of 300 m. The island formed on the inner part of a 10 km long reef stretching northwestwards from Stokken and was built mainly of gravel, stones and about 10% of large reworked, fossil (stone age) shells of *Ostrea* and *Cypripina*. After three years the island disappeared again.

The ongoing and future development of Stokken may be illustrated by the way the two barriers of Vestre Nyland and Sønder Nyland (Fig. 1, Fig. 11) developed from a single barrier island that formed off Læsø at the beginning of the 19th century (not on the 1786 map, but on the 1888 map). As now observed at Stokken, this barrier island extended alongshore and migrated landwards. By the end of the 19th century, the north-western end of the barrier reached land (Vestre Nyland) and the northern part of the lagoon turned into a brackish lagoon and presently a nearly fresh lake that is drained into the sea through a narrow channel. The south-eastern end of the barrier (Sønder Nyland) never reached land before it was protected from the sea by the emergence of the next barrier island (Stokken) and became a non-migrating island in the lagoon behind Stokken.

Some of the older barriers and lagoons that emerged in south-western Læsø during the last c. 2500 years follow a similar development, while other palaeo-barriers are separated from the preceding barrier with a much broader palaeo-lagoon than seen at Vestre Nyland (Fig. 11). Most of the former barriers are composed of mainly sand, but among them are also two prominent barrier systems of mainly gravel and coarser material, namely the large barrier behind Sønder Nyland (formed c. 800 years BP) and the barrier, formed c. 1500 years BP, on which the medieval church of Vesterø was built. Such occurrences of coarse-grained barriers interspersed among sand barriers may indicate that the isostatic uplift and erosion of the seabed have occasionally exposed glacial, glacio-marine or even younger formations at shallow water depths such that coarse material could be eroded and transported onshore by wave action.

The period 2500 years BP – present: Low-ridge plains and saltmarshes of south-eastern Læsø

After 2500 years BP, while the formation of the barrier and lagoon coasts of the Østerby peninsula took

place, a completely different kind of coastal landscape began developing on the eastern side of the oldest and easternmost barrier of the Byrum barrier and lagoon system (Figs 8, 9).

The eastward prograding coasts that formed here are characterized by much lower beach ridges than in other contemporaneous parts of Læsø. While the swash height of the barrier systems of northern Læsø are mostly between 0.8 and 1.5 m, the height differences of the ridges and swales in the south-eastern beach-ridge plain are generally less than 0.3 m, often less than 0.2 m (cf. Figs 8, 9), indicating a low-energy environment with small wave heights, resembling the present south and south-east coasts where the 3–5 km broad and very shallow sand platform limits the wave height at the coastline to no more than 0.2 m, even during strong winds (Hansen *et al.* 2012). Where elevated more than 2 m above MSL, most parts of this type of landscape have been cultivated since medieval times, and it is consequently difficult to determine from the lidar maps if all of the landscape emerged as a broad saltmarsh plain similar to the present southern and south-eastern coastal zone.

Separate finds of two large sperm whale skeletons

(*Phyceter catodon*) with ^{14}C ages of c. 3200 years BP (Hansen 1977, 1995) in the marine sand below the beach ridges in this landscape, app. 0.5 km and 1 km outside the south-eastern coast of the 'old triangle', suggest that the water depths before 2500 years BP were considerably larger than at the present south-eastern coasts. Consequently, the low height of the older beach ridges may be a leeward effect, indicating that south-east storms had no significant effects on the south-eastern coasts in the period 3500 to 2500 years BP.

However, there is a strong contrast between the prominent coarse-grained beach ridges that formed at the eastern end of the Østerby peninsula simultaneously with the constantly prograding, low-relief coasts of south-eastern Læsø (Fig. 9) and north of the bay of Bovet (Fig. 22). This may indicate that strong east to south-east storms during the period 2500 to 1000 years BP were more prominent, and that the bay of Bovet initially was considerably deeper and unprotected from the open sea to the east, while the shallow platform south-east of Læsø had already developed around 2500 years BP, but clearly separated from the deeper waters of the bay to the north. As indicated

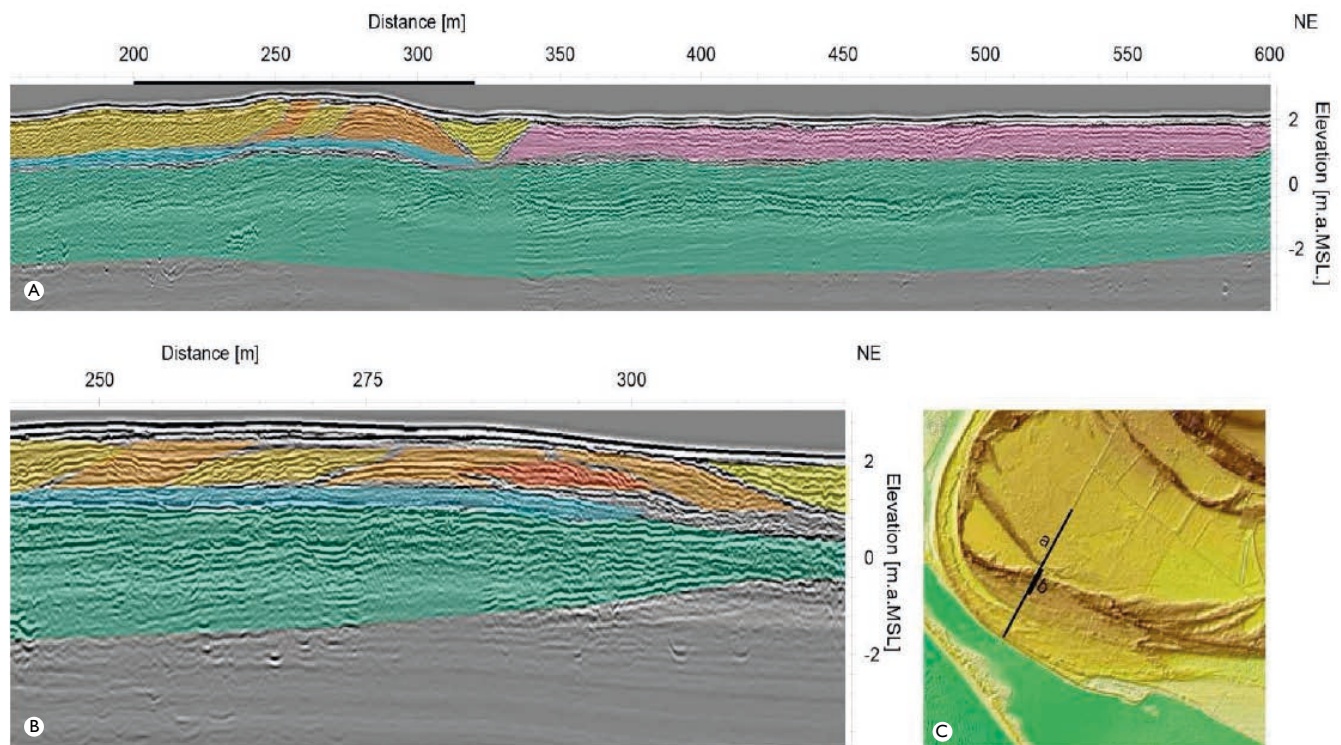


Fig. 25. A, GPR section from the south-west coast of Læsø traversing a raised barrier-island and lagoon system. About three sets of seaward (south-westwards) dipping reflections indicate that more than one generation of barriers have prograded seawards (light orange) separated by areas with doming or horizontal reflections (orange). A channel structure (yellow), probably a draining channel of the raised lagoon, separates the barrier from the flat lagoon deposits (pink) with subhorizontal reflections. Subhorizontal shoreface sediments (blue) and older marine deposits are overlain by the barrier. B, enlargement of the north-eastern and oldest part of the barrier. C, subarea of Fig. 11 showing the position of the GPR sections in A and B.

by the level of the top of the constantly rising glacio-marine platform south, south-west and east of Byrum (now around MSL), the water depths at c. 1000 years BP most probably had been reduced to less than 2 m to distances of several kilometres from the south and south-east coasts of that time.

The period 2500 years BP – present: Development of the bay of Bovet

It is well documented by archaeological finds and historical sources that the water depths in the bay of Bovet, south of the Østerby peninsula and north of the very shallow waters off south-eastern Læsø, were larger than today until the 17th and 18th century, when the bay was partly filled with aeolian sand from dune fields that migrated across the island from the west and north-west and covered the medieval church of Hals, its village and fields and migrated further to the east and south-east where much of the dune sand ended in the bay of Bovet (Hansen 1995). Before these events the bay was used as a natural harbour for even large vessels (e.g. Stoklund 1973).

In 2010 we found a large medieval vessel 700 m inside the present coastline of the bay, buried under 1.5 m of sand. Tree-ring studies of the planks show that the material is oak, felled in 1383–86 AD in the southern Baltic region. Also recently, a boulder reef including a very large boulder of about 260 tonnes was located 0.5 m below terrain close to the medieval vessel, indicating that the vessel may have been wrecked on this boulder reef and that also the innermost part of Bovet at that time was accessible to large ships.

Today the bay of Bovet is protected to the east by the young barrier of Bløden Hale and a row of young barrier islands (Knotterne and Knogene) that began developing at the mouth of the bay during the 19th and 20th century. Presently, large parts of the sandy

bottom are often dry and the water depth of the centre of the bay is at maximum 1 m, while the water depth of its draining channel between Bløden Hale and Knogene is 4–6 m.

The period 1000 years BP – present: Saltmarshes of southern Læsø (Rønnerne)

Shortly after the peak of the medieval sea-level highstand c. 1000 years BP, a number of small and one large boulder reef emerged south of the island (Figs 6, 7, 13, 27) as a result of the long ongoing regional glacial isostatic adjustment as well as the local relaxation uplift (Hansen *et al.* 2012). Thus, a part of the abrasion platform formed a 30–40 km² and steadily growing area with extremely shallow water depths, where numerous monolithic boulders on top of the eroded glacio-marine surface jut out of a thin layer of sand (Figs 7, 14). By ice packing, some of the boulders have been piled together to form boulder reefs of various sizes, while others are too large to be moved by such action.

Around such boulder reefs, sand accumulated near sea level and slightly above, forming areas where halophytes like *Salicornia* and *Statice* could invade the new land. Thus, the islands of Langerøn, Kringelrøn, Færøn and Hornfiskrøn began developing as saltmarshes at the shallowest parts of the abrasion platform. Continued accretion takes place in the outer vegetated zone, mostly during storm surges, when sand is caught in the halophile vegetation on top of low beach ridges fringing the raising islands. The islands grew and grow forming shoreline patterns resembling growth rings of mussel shells (Figs 13, 27, 33). As the growth of land continued, some of the initially five small islands of Kringelrøn and Langerøn joined and formed two larger islands, which subsequently merged with each other and Færøn and now form the southern part of the main island. The island of Hornfiskrøn is still separated from the main island by a 1 km broad and extremely shallow sound,



Fig. 26. The barrier island Stokken viewed from the north. The picture shows the straightening process of barriers and recurved spits by erosion and formation of overwash fans during storm surges, resulting in a steadily narrower lagoon. (Photo: Eigil Holm).

while new saltmarsh islands continuously emerge and grow at the platform south-west of Læsø.

The large sand flat south of Læsø and formation of hypersaline groundwater

As the upper part of the large sand flat south of Læsø (overview in Figs 1, 2, 5) came still closer to sea level it also remained dry for weeks and months, mainly during spring periods (April to May) dominated by southerly winds, when the sea level of Kattegat is generally around 25 cm lower than during autumn and winter periods of mainly westerly to northerly winds. This periodic drying and the ensuing evaporation of the salty pore water leads to crystallisation of salt on top of the sand. During the next incursion of the sea, this salt dissolves to form a nearly saturated brine (Fig. 28) which, due to its high density, percolates downwards into the sand and accumulates on top of the glacio-marine clay and silt platform, normally less than 2 m below the surface of the sand flat (Hansen 2010).

At the beginning of the 12th century, widespread accumulations of such nearly salt-saturated brines were discovered by monks from Jutland who founded a salt industry on the island c. 1150 AD. The salt brine was extracted from shallow wells at the south-eastern shores of Kringelrøn and Langerøn and on the south-eastern coast of the main island (Bangsbo and Stoklund). The brine was evaporated by heating in large iron pans in huts built over or close to the wells (Velle 1991, 1993, 2001). During the following four centuries the number of salt production huts steadily grew and culminated c. 1585 AD, when around 135 simultaneously active salt production huts were situated on a 7 km long row from Bangsbo to Kringelrøn along the south-eastern shores of the saltmarshes (Hansen 2010). The salt production was important for the salt supply of Denmark–Norway and culminated with a total annual export of around 2000 tonnes of salt. A total of 1700 ruins of salt production huts have been discovered on the ancient, raised beaches (Velle 1993, Hansen 2010) (Fig. 27); this large number reflects that the production wells, pans and huts had to be moved seawards as the shores moved due to the isostatic uplift as well as sedimentary progradation of the shores. On average the wells, pans and huts were moved every 19 years (Hansen 2010), corresponding to the Lunar nodal oscillation period, which in combination with the isostatic uplift caused sea-level drops of 7 cm at intervals of 18.6 years and, consequently, displacements by 100–200 m of the shoreline along the extremely flat shoreface of the south-eastern coasts (Hansen 2011).

Terrain level effects of forestation, deforestation, agriculture and salt industry

The preservation of relative terrain levels of sea-level proxies, and thereby sea-level reconstruction, is dependent on the subsequent vegetation development and land-use practices, because continuous existence of natural vegetation may preserve relative terrain levels, whereas long-time agricultural practices such as ploughing, draining, extraction of peat and digging of turf reduce terrain levels. Likewise, precise measurements of sea-level proxies to some extent are dependent on correct understanding of the local environmental and climatic changes. In the case of the decimetre-scale precision at which we attempt to reconstruct the RSL development of Læsø, the initial vegetation and forestation is important in order to understand how sea-level proxies have been preserved, while knowledge about subsequent practices of land-use are important in order to understand where and how levels of sea-level proxies may have been altered. This section intends to provide a summary of terrestrial developments of relevance for the RSL reconstruction at the attempted decimetre-scale precision.

Initial forestation of the island

As described below, there is circumstantial evidence that the region contained a forested Boreal landscape prior to the Litorina transgression c. 6300 years BP. However, after the flooding and until preserved parts of the island emerged c. 4900 years BP there is no direct evidence of the forestation of the region.

During the period 4900 to 2500 years BP, the oldest preserved parts of Læsø were still attached to a raised glacio-marine landscape north-west of the present island. Trunks of pine, stems of oak, and pollen analyses (see below) from peat on the small preserved part of Læsø's initial beach-ridge landscape indicate that the early coastal landscape, despite its small preserved size (2 km²), was vegetated by meadows and a relatively mature forest which would hardly develop in such environments unless it was attached to a more fertile and considerably larger land area. This would also explain how the island later, when it was much larger and completely detached, could become a refuge for the formerly widespread Boreal pine that still covers poor soils in southern Norway and western Sweden, but which is extinct in Denmark with the exception of Læsø where a few large trees and many seedlings have survived until present time and today may be considered endemic – the so-called 'Læsø pine'. A find of red deer (*Cervus elaphus*) in peat on the Østerby peninsula supports this theory, as does king Valdemar Sejr's *Liber Census Daniae* from 1231 which mentions royal hunting of red deer on Læsø, indicating that this large animal

maintained the initial light-open forest and meadow landscape and survived more than 1000 years on the completely detached, but by then much larger island.

Evidence from pollen analyses

Due to the widespread practice of 'concentration agriculture' during the 17th to early 20th centuries, Læsø's

original moors and bogs are now nearly devoid of peat because this has been intensively exploited for fuel and soil improvement (Stoklund 1980, 1986, 1990, 1999; Hansen 1995). Nevertheless, in the 1970s one of us (JS) found and analysed two small peat profiles for pollen, and the results illustrate the initial forestation and vegetation of the older parts of the island.

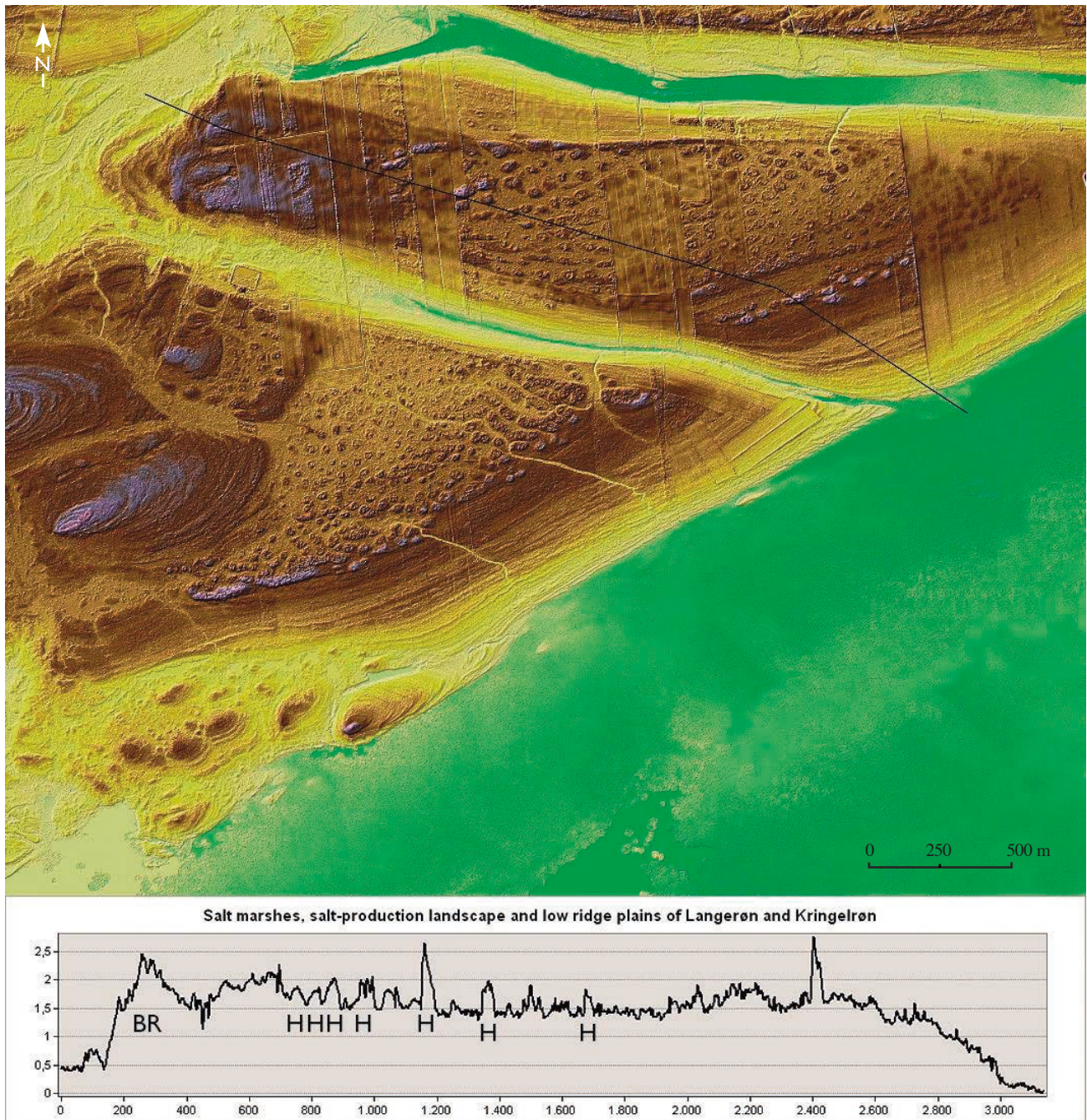


Fig. 27. Digital terrain model (DTM) of the raised concentric low-ridge plain of Langerøn (upper part) and Kringelrøn (lower part). The highest parts of the landscape in the centres of concentric beach ridges are small raised boulder reefs. The many 'dots' of the two former islets are ruins after salt production huts built at the shore of any time in the period 1150–1652 AD. In all 899 ruins have been identified on the two islets. The profile shows levels (m above MSL) and distance (m) along the black line. BR: raised boulder reef. H: ruins of salt production huts.

The initial forest on the higher and older part of the island consisted of a light-open forest of trees with light seeds like birch (*Betula*), pine (*Pinus*), willow (*Salix*) alder (*Alnus*) and to a minor degree poplar (*Populus*). Also climax forest trees with heavier seeds like oak (*Quercus*), hazel (*Corylus*), lime (*Tilia*), elm (*Ulmus*), ash (*Fraxinus*), and yew (*Taxus*) were present. It is clear from all pollen analyses that grasses (*Gramineae*) played a dominant role, corresponding well with the origin of the name of the island (in the old Anglo-Saxon language 'Læsø' (læsoy) means 'grass island').

Pollen analyses (Fig. 29) of peat from a swale of Læsø's oldest beach-ridge system that formed 4900–4000 years BP (¹⁴C dated to 3375 years BP) show that the forest of that period (at least at that very location) was dominated by yew (*Taxus baccata*) and grasses (*Gramineae*) with minor amounts of light-open forest trees as well as climax forest trees such as ash (*Fraxinus*). Also note the occurrence of *Plantago lanceolata*, *Plantago* cf. *media*, *Artemisia* and *Chenopodium*, indicating the nearby coast and maybe also some human influence.

The diagram from peat at Træbakke (Fig. 30, ¹⁴C dated to 3355 years BP), which according to our age model is slightly younger than the above-mentioned vegetation, represents the lower part of a thin peat profile very close to the western tip of the preserved part of Læsø at that time. The pollen diagram indicates a light-open forest dominated by birch (*Betula*), pine (*Pinus*), hazel (*Corylus*), ash (*Fraxinus*) and oak (*Quercus*) with alder (*Alnus*) and willow (*Salix*) indicating moist soils, and with only minor amounts of other climax forest trees. The amount of grasses is high and weeds like *Plantago lanceolata*, *Artemisia* and *Chenopodium* are again present. The high amount of coastal indicators

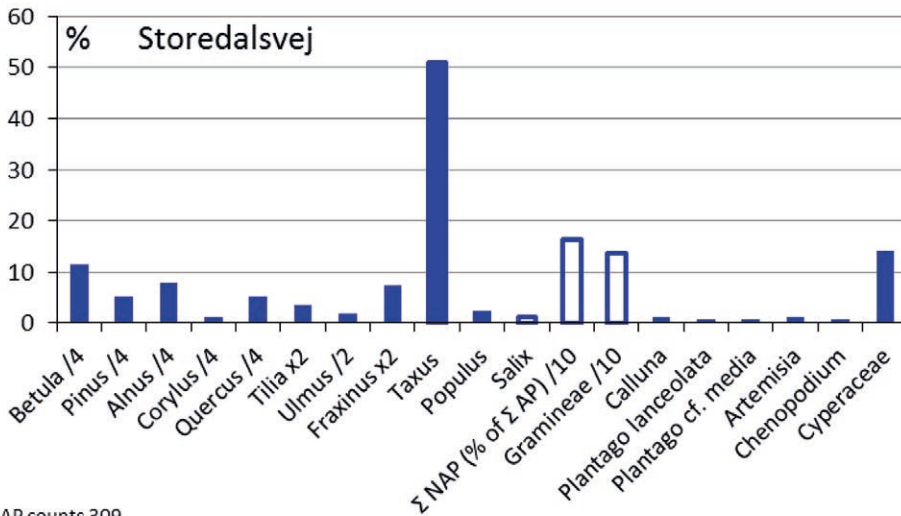
(*Plantago lanceolata*, *Plantago maritima*, *Artemisia* and *Chenopodium*) indicate that the site was close to the coast. However, the tree distribution also indicates a nearby rather mature forest cover. Yew is common in similar poor, light-open forests of southern Sweden.

Figure 31 shows pollen analyses of four samples from a peat found in a younger part of the 'old triangle'. Sample 71/984 is taken from a layer with charcoal that is ¹⁴C dated to 2680 years BP. After the charcoal formation (burning), an increase in yew (*Taxus*), willow (*Salix*), elm (*Ulmus*) and poplar (*Populus*) and a decrease in pine (*Pinus*), lime (*Tilia*), ash (*Fraxinus*), grass cover (*Gramineae*), heather (*Calluna*) and weeds (*Plantago lanceolata* and *Chenopodium*) is significant.

Yew (*Taxus*) is very rare in other parts of Denmark (only finds of single pollen grains), but it is obvious that it was abundant on Læsø until more recent time. However, until the early medieval age *Taxus* was a dominant pioneer tree of many southern Scandinavian coastal zones (Sarmaja-Koronen *et al.* 1991), but because all parts of *Taxus* are highly poisonous to humans, cattle and horses, the species has been sought extinguished from inhabited areas. South of Østerby Havn a harbour for small vessels was built of poles of *Taxus* felled in 640 AD, and from the medieval settlement of the island around 1100–1300 AD some location names may indicate which kind of forest the settlers met and cleared for agriculture (Stoklund 1980, 2007; Hansen 1995). Thus, the medieval Danish name of *Taxus* appears in two local names (Irumgård and Irum Have) on south-east Læsø, while Hornex and Jegens Odde on the north part of the island refer to *Quercus*. The name 'Lunden' of a forest on the central part of the island means a mixed, mainly deciduous forest.

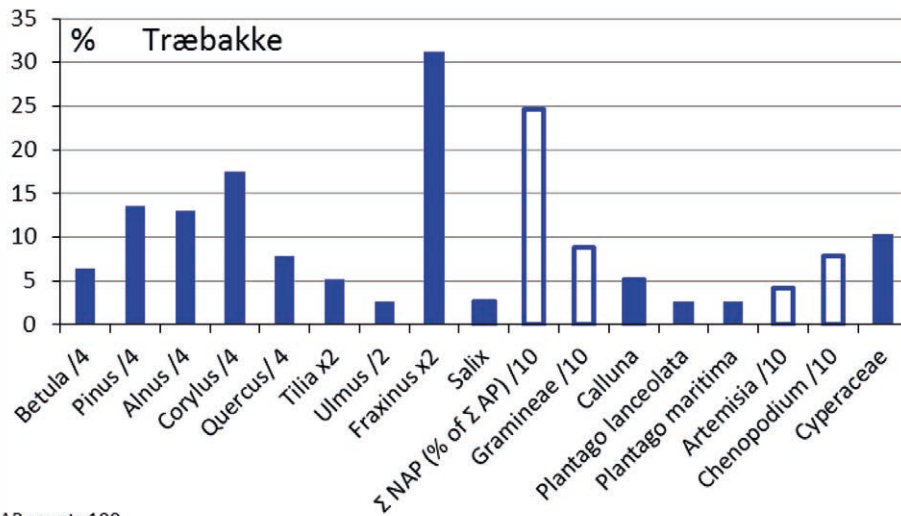


Fig. 28. After days or weeks of drying, evaporation and salinization of the sand surface, the sea returns to the sand flat south of Læsø as a widespread thin film of sea water with an initial salt content of 2–2.5%. By dissolving salt that crystallized during the preceding period and by mixing with hypersaline pore water, the film of incoming sea water becomes nearly salt saturated. Consequently, the water film becomes a heavy salt brine with a salt content of 10–16% that percolates downwards until it hits the low-permeable glacio-marine clay platform 1–3 m beneath the surface or already accumulated, equally heavy salt brine. (Photo: Lasse Gudmundsson).



AP counts 309

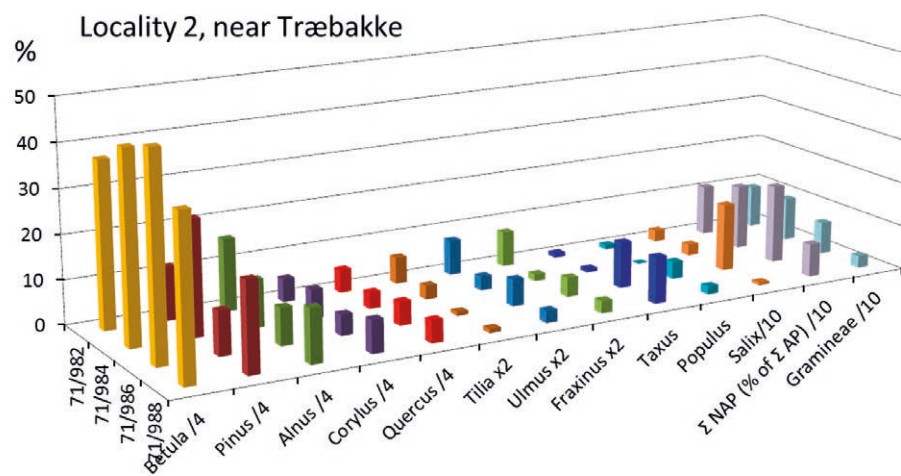
len (Σ AP) is given in the lower left corner of the diagram. The extremely high concentration of yew (*Taxus*) pollen could make it plausible that the yew pollen derive from a local stand of trees. Non-arbores pollen grains are almost entirely grasses (*Gramineae*).



AP counts 100

Fig. 29. Pollen counts from a thin peat profile (No. 34 in Table 1, green dot in Fig. 16) from the oldest preserved part of Læsø that formed in a spit system 4900–4000 years BP (peat 14 C dated to 3375 years BP). The y axis represents percentages relative to total Arboreal (tree) Pollen (Σ AP). The counts are reduced as indicated to give a more proper forest tree distribution compared to herbs (see Methods chapter). Some pollen counts of herbs, especially grasses, or bushes (Non-Arbores Pollen, NAP) are reduced by 10 for better overview only (white columns). The total counted tree pollen (Σ AP) is given in the lower left corner of the diagram. The extremely high concentration of yew (*Taxus*) pollen could make it plausible that the yew pollen derive from a local stand of trees. Non-arbores pollen grains are almost entirely grasses (*Gramineae*).

Fig. 30. Pollen counts from the bottom of an almost 1 m thick peat profile at Træbakke (No. 14 in Table 1). Explanation as in Fig. 29. This part of the island was formed as a condensed high-ridge plain 4000–3500 years BP. The peat is 14 C dated to 3355 years BP. The age may be underestimated as the peat contained many younger alder roots of which all visible parts were removed before dating. No yew (*Taxus*) were found (only 100 pollen grains were counted) and ash (*Fraxinus*) is dominating, together with grasses (*Gramineae*), *Artemisia* and *Chenopodium*.



AP counts 352,506,1087,771

Fig. 31. Pollen diagram from a ditch side peat profile, 16 cm thick. Explanation as in Fig. 29. This landscape was formed as a barrier-spit and lagoon plain 3500–3000 years BP. Sample 71/984 was 14 C dated to 2680 years BP (No. 12 in Table 1). There are 2 cm between the samples and sample 71/982 is the bottom. The counts are reduced by the indicated factors for pollen productivity in order to give a more realistic forest tree distribution. *Salix*, NAP (non-arbores pollen) and *Gramineae* are reduced by a factor 10 in order not to dominate the diagram.

Post-detachment period and development of endemic wildlife characteristics

The present fauna on Læsø has many endemic traits and is rich in migratory flying animals but poor in non-migratory wildlife, in particular mammals. There is an absence of many species that are widespread elsewhere in Denmark, such as small mammals, reptiles and amphibians. These traits are most probably caused by the complete detachment of Læsø c. 2500–2000 years BP from larger and more fertile landscapes, and reinforced by the nearly complete manmade deforestation of the island during the 17th to first part of the 20th century.

The vegetational diversity of Læsø is generally larger than in most other sandy parts of Denmark (cf. EU's Natura 2000 and habitat protection plans), and this situation is first and foremost caused by the highly intensive agricultural practices in other parts of Denmark. On Læsø around 75% of the land remained

undrained and unploughed until the 1920s when a forest plantation program was initiated (and partly obstructed by the locals). After 1950, increasing parts of the island came under nature conservation, thus preserving about 40 % of the area from agriculture, plantation and urbanization. Thus, Læsø's presently relatively diverse vegetation is mainly an effect of less deteriorated conditions than elsewhere in Denmark.

Settlement, salt industry, deforestation and crises of the Little Ice Age

The initial settlement of the island is mostly referred to the 12th century. The discovery at that time of hyper-saline groundwater under the beaches of south-east Læsø, and the resulting salt industry, was contemporaneous with a sea-level drop of 0.8 m that commenced c. 1200 AD and culminated c. 1300 AD (see section below and Hansen 2010, Hansen *et al.* 2012).). These saline groundwater deposits were continuously formed until

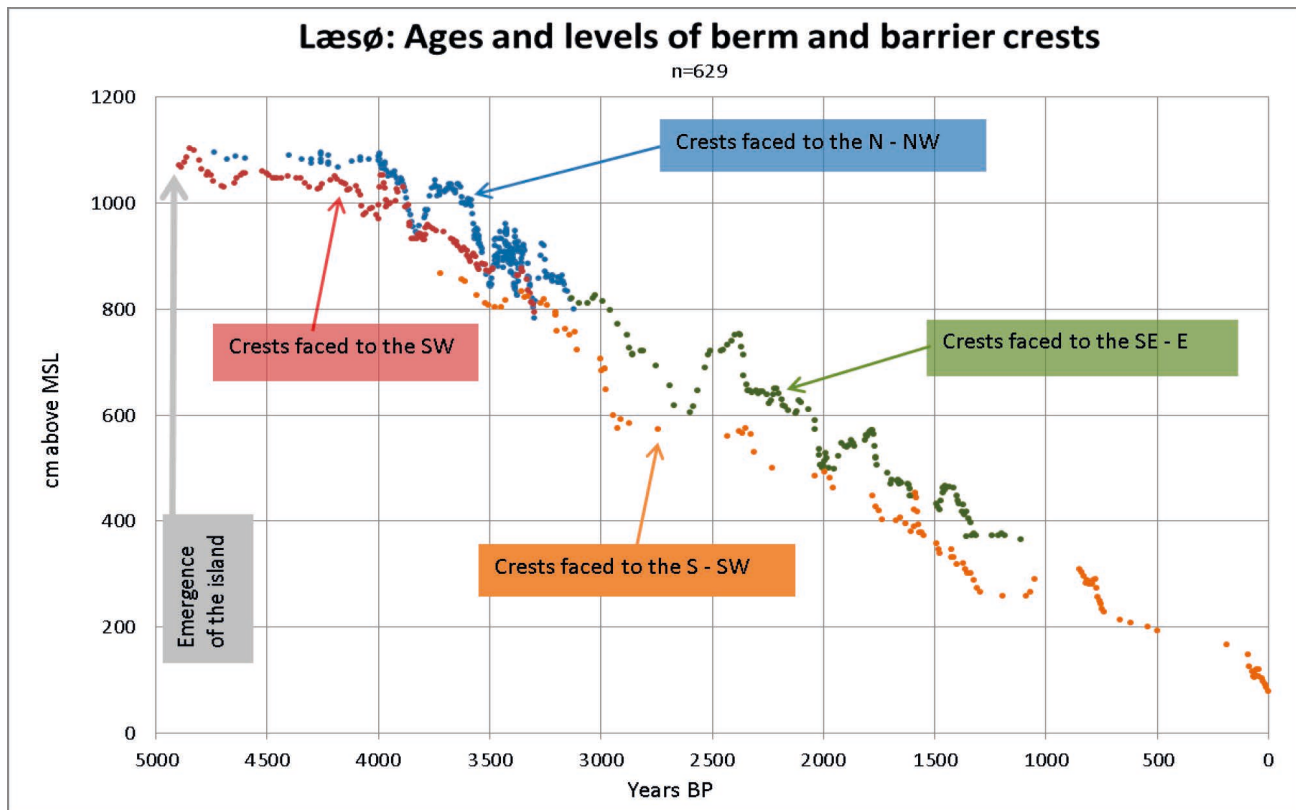


Fig. 32. Levels of raised berms, barrier-spit and barrier-island beach-ridge crests on Læsø measured by the BLRC method and plotted against ages of the ridges as inferred by the age model of the island. The diagram shows applied measurements from areas without inland or coastal dune fields (i.e. measurements from Højsande and Bløden Hale are excluded). Levels of raised, cultivated saltmarshes of south-eastern Læsø are also excluded due to lowering of the terrain by 600 years of agricultural practices (including widespread digging of turf). Colours indicate coastal exposure directions corresponding to the regions shown in Fig 4. Note differences in levels of ridges exposed to the north, east and south-east compared to ridges exposed to the south-west, west and south. To some extent these level difference are caused by the general isostatic SW-tilting of the region and differences in height of the swash (maximum 0.7 m). The remaining level differences are probably caused by local geological 'background noise' such as differences in local relaxation uplift and compaction (see Discussion).

the number of salt production huts peaked c. 1585 AD.

Soon after establishment of the initial salt industry many settlers arrived to the island, and less than 100 years after the discovery of hypersaline brines three churches (1219–1250) had been built. Simultaneously, the most fertile parts of Læsø south of the sandy ‘old triangle’ and north of the saltmarshes had been cleared of forests and cultivated around the medieval churches of Byrum, Vesterø and Hals. Together, the growing number of farms and expansion of the salt industry reduced the nearly complete forest coverage before settlement began to a few hectares in 1750 AD. A consequence of this development was that wood for fences and fuel was substituted by turf (Vellev 1993; Hansen 1995), a practice that lowered the terrain of the farmlands and ultimately laid much of the cultivated land open for wind deflation.

Because of declining formation of hypersaline ground water, the salt industry declined severely from 1600 AD and ceased completely in 1652 AD (Vellev 1993, Hansen 2010), contemporaneously with man-made deforestation and climatic changes related to the last and coldest phase of the Little Ice Age (Hansen 2010). Thus, the timing of changes in salt industry and agricultural practices (Stoklund 1999) relates Læsø’s ecological and economic crises to climatic changes, consequent overpopulation and the Little Ice Age sea-level fall, which on Læsø reached two local minima, i.e. around 1300 AD and 1700 AD (Hansen *et al.* 2012).

Relative sea-level reconstruction (4900 years BP to present)

Relative sea-level changes (RSL) constitute the sum of absolute sea level (ASL) and vertical terrain changes (U and C, see section on Methods and Data). Consequently, the present RSL reconstruction is independent of data on ASL and isostatic terrain level changes. The present RSL reconstruction is mainly dependent on how base levels of beach-ridge crests (BLRC) have been measured in order to avoid effects of small dunes (D) and erosional features (E). Another main issue is how BLRC measurements have been compensated for height of swash (S). Thus, a robust reconstruction of relative sea levels on Læsø during the last 4900 years can be built on the basis of the methods described above, i.e. respecting the following:

Measurements of base levels of beach-ridge crests (BLRC).

Compensations for height of swash (run-up) according to GPR profiling, supplemented with terrain analyses and types of coastal landscape.

Observable chronology of raised beach ridges, swales, lagoons, saltmarshes, forestation and cultural history marks of the island.

Absolute age determinations of samples of sediment and fossils in beach deposits (dating emergence), in marine deposits (pre-dating emergence), and in terrestrial deposits (post-dating emergence).

No use or cautious application of level data from areas that have been ploughed and drained since the medieval settlement or exploited for intensive salt production.

Due to the different nature of barrier ridges and saltmarsh ridges the RSL reconstruction has been made in two forms: One for exposed barrier coasts (4900 years BP to present) and one for saltmarsh coasts (1500 years BP to present).

Sea-level reconstruction based on beach ridges of exposed coasts

Figure 32 shows 629 BLRC points representing exposed coasts, i.e. condensed beach-ridge, barrier-spit and barrier-island landscapes showing the RSL changes of the three main areas of the island which have continuously been exposed towards the main directions south-west, north and south-east (Fig. 4) throughout the period after 4900 years BP. RSL/age index points respect the exact formation chronologies and levels as established from the DTM. The absolute ages are modelled from the 119 absolute age determinations as described in Table 2.

The successions of the BLRC points from the three main directions of coastal growth follow the same long-term and short-term trends quite well, whereas level differences of 0.5–1.5 m between south-westerly exposed coasts (lowest) and northerly as well as south-easterly exposed barrier coasts are obvious. Of this level difference, 0.1–0.2 m is caused by isostatic south-westward tilting, whereas the remaining 0.4–1.3 m is mainly explained by differences in exposure. Thus, the fetch distances to the north are by far the largest, and fetch distances to the south-east are intermediate between those to the south-west and the north. This may explain the fact that the north, east and south-east coasts of the oldest and eastern parts of Læsø are mainly built of condensed, often coarse-grained beach-ridge plains (north) and coarse-grained barrier-spit plains (south-east and east), whereas the south-west coasts are mainly built of sandy barrier-spit and barrier-island plains.

The older part of the large plains of fine-grained condensed, low-ridge landscapes of south-eastern Læsø have not been included in the reconstruction because this part of the island has been ploughed, drained and partially used for cutting of turf through more than 600 years, which obviously has lowered and smoothed the original terrain.

Sea-level reconstruction based on saltmarsh beach ridges

Because absolute ('eustatic') sea-level oscillations during the last 1000–2000 years are generally considered to be at the scale of decimetres (see Discussion section), it is crucial to develop methods which are capable of quantifying small post-sedimentation terrain level changes at the same small scale.

In a previous study of raised saltmarshes, Hansen *et al.* (2012) have shown that the saltmarsh landscapes of southern Læsø allow extraordinarily precise determination of past sea levels due to excellent possibilities for compensation for local post-sedimentation terrain level changes, i.e. compensation for 'background noise' such as normally undetectable neo-tectonic effects, local effects of draining and ploughing and other types

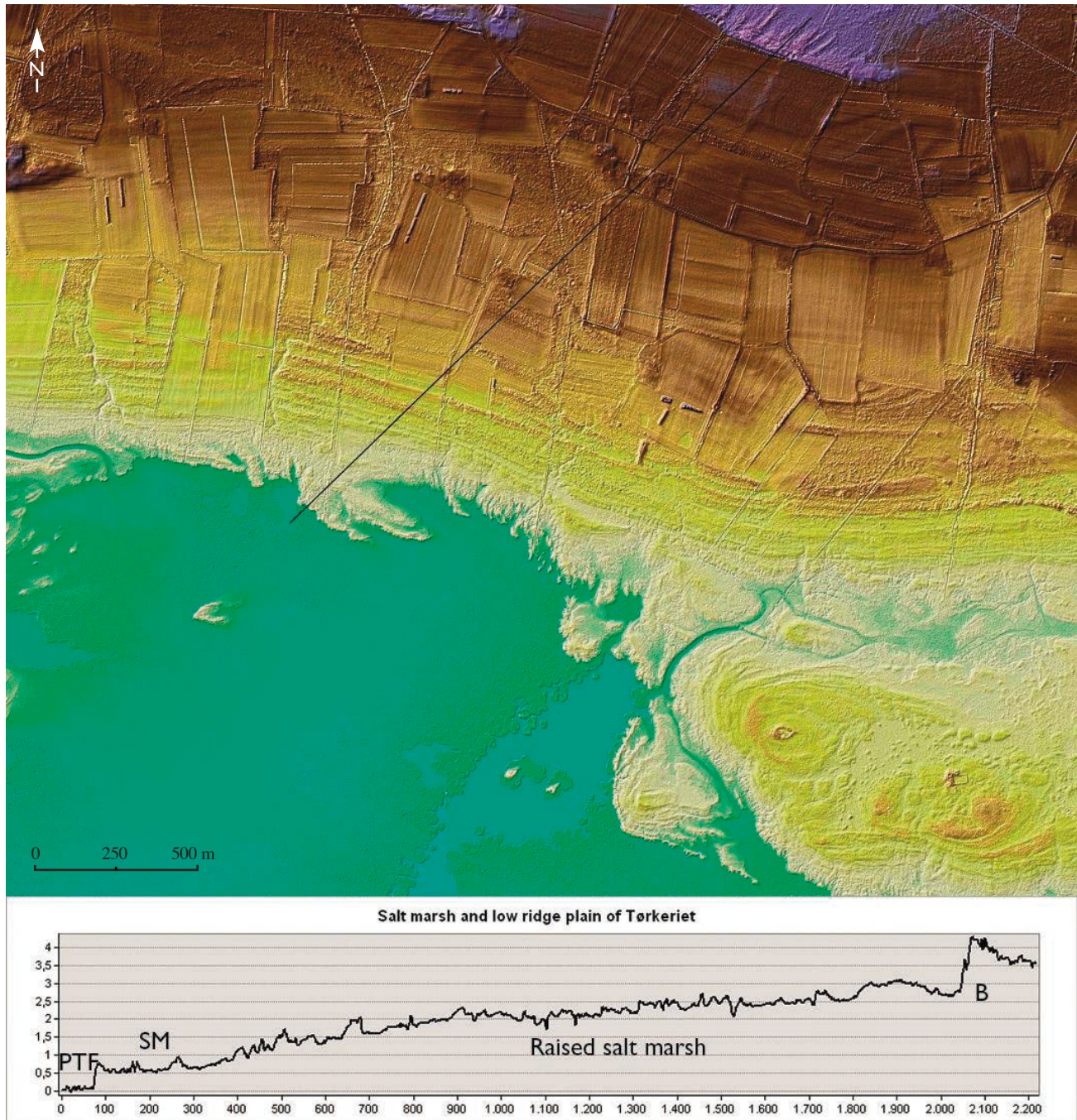


Fig. 33. Digital terrain model (DTM) of the Tørkeriet area in south-western Læsø (and Færøen, lower right) showing raised low-ridge plains (raised saltmarshes) between an older barrier (B) and the present saltmarsh (SM) fringing the pseudo-tidal flat (PTF). Levels of 35 beach ridges all 2–5 km long have been measured precisely along 381 transects each of 200 m length (Fig. 34).

of compaction. This has been done by ‘back-stripping’ of saltmarsh ridges to their original horizontal position in the reverse order of formation chronology (method in Hansen 2009; Hansen *et al.* 2012).

The area of Tørkeriet is shown in Fig. 33 and new BLRC data from this area are shown in Fig. 34. Although up to 20 cm of the observed differences in level may be explained by draining and ploughing of some parts of the area, the identified level differences (20–65 cm) of coherent ridges underline the importance of compensation for ‘geological background noise’ in studies of sea levels of the latest Holocene.

Figure 35 shows the RSL curve resulting from ‘back-stripping’ the BLRC levels (Fig. 34) as well as the result of detailed, previously published (Hansen *et al.* 2012) level studies of two other saltmarsh areas on Læsø (Hornfiskrøn and Stoklund). In each of these saltmarsh areas, many 3–5 km long, coherent saltmarsh ridges formed during the last 1000–2000 years. Compared to neighbouring swales, the ridges are very low (mostly less than 20 cm). After back-stripping, the individual ridges have vertical level differences of maximum 32 cm. The mean curve of back-stripped saltmarsh ridges from these areas is applied for the period after 1250 years BP in the reconstruction of an integral RSL curve for Læsø.

Table 4. Centennial lowstands and highstands on Læsø in the period 4000 years BP to present (Fig. 38).

High/low	Period		RSL, m	Amplitude
Highstand	4000 BP	2000 BC	9.7	
Lowstand	3800 BP	1800 BC	8.5	-0.8 m
Highstand	3700 BP	1700 BC	8.8	
Lowstand	3500 BP	1500 BC	7.2	-1.1 m
Highstand	3400 BP	1400 BC	7.7	
	to 3000 BP	1000 BC	6.3	
Lowstand	2900 BP	900 BC	5.3	>0.7 m
Highstand	2800 BP	800 BC	5.6	
Lowstand	2700 BP	700 BC	5.0	-0.5 m
Highstand	2400 BP	400 BC	5.3	
	to 2100 BP	100 BC	4.6	
Lowstand	2000 BP	0 AD	3.7	>0.6 m
Highstand	1800 BP	200 AD	4.0	
Lowstand	1600 BP	400 AD	2.6	-0.7 m
Highstand	1400 BP	600 AD	2.6	
Lowstand	1300 BP	700 AD	1.6	-0.5 m
Highstand	1100 BP	900 AD	1.7	
Lowstand	700 BP	1300 AD	0.5	-0.6 m
Highstand	450 BP	1550 AD	0.5	
	to 220 BP	1780 AD	0.5	

Amplitude of the eight lowstands are calculated as the mean difference between lowstand levels and levels of the two neighbouring highstands:

Integral age model and RSL curve for Læsø

An age model for the emergence of all parts of Læsø is presented in Fig. 36, corresponding to the growth history of the island as described above in the chapter on *Reconstruction of the emergence, growth and coastal development of Læsø* and according to the principles described in the section on *Age modelling of coastal progradation* (Table 2).

In Fig. 37 all of the 1200 RSL/age index points of exposed coasts (Fig. 32) and saltmarshes (Fig. 34) are merged into one common RSL/age curve, cf. steps 6 and 7 in Table 2. The solid line represents BLRC measurements of exposed coasts (4900 years BP to present).

The dashed blue curve in Fig. 37 represents all BLRC measurements of exposed beach ridges after reduction for height of swash (run-up) as described in the section on *Estimation of swash heights (run-up) by ground penetrating radar (GPR)*, and the dashed red line represents back-stripped BLRC measurements of the saltmarshes of southern Læsø (1250 years BP to present). The actual identification of RSL by GPR of barrier landscapes is indicated by black dots. The resulting, integral RSL curve of exposed coasts (dashed blue) is calculated on the basis of these GPR identifications in such a way that the general shape and oscillations of the BLRC curve are maintained, but lowered to a best fit with the RSL points of the GPR surveys. At stretches of the RSL curve where GPR data are not available, the inferred swash heights have been checked with terrain analyses as described in the section on *Estimation of swash heights (run-up) by terrain level analyses*.

The resulting RSL curve for Læsø is presented in Fig. 38, where also peaks of short-term highstands and lowstands have been connected above and below the RSL curve (blue band). Through this procedure, short-term (centennial) oscillations can be identified, i.e. oscillations that are normally not identified in regions of less regression and coastal growth (see Discussion). The present study suggests that short-term lowstands of 50 cm or more occurred eight times during the period 4000 years BP to present, as set out in Table 4.

Comparable observations of sea-level highstands have been published from the Swedish west coast as numbered Postglacial Transgression Maxima (PTM) (Mörner 1969, 1980). Thus, PTM 6–PTM 10 of the Swedish west coast correspond well to contemporaneous highstands identified on Læsø, whereas lowstands are more clearly developed on Læsø. This difference may be explained by the sparse sediment sources of the granitic and metamorphic bedrock terrain of western Sweden.

The RSL curve for Læsø also shows many similarities to the RSL curve of the Kattegat island of Samsø (Sander *et al.* 2015), including a relatively stable development 5000–4000 years BP, thereafter a relatively fast fall until around 3000 years BP, as well

as highstands in the period 3000–2000 years BP. As at the Swedish west coast, the lowstands at Samsø are less pronounced compared to Læsø. The difference is most probably caused by the smaller preservation potential of lowstands in less GIA-raised regions (Samsø mean 0.5 mm/year, Læsø mean 2.1 mm/year). General implications of the present identification of centennial lowstands are discussed below.

Discussion

The use of raised beach ridges as indicators of relative sea levels (sea-level proxies) of the past has a long record in modern scientific literature of Scandinavia, going back to the beginning of the 20th century. On the basis of Wilhelm Ramsay's initial ideas, Mertz (1924) and von Post (1933) began understanding how eustatic sea-level changes in combination with isostatic uplift of the Scandinavian peninsula and the Baltic region had dramatically changed sea levels of the Baltic sea and Kattegat after flooding and unloading of the region by melting of Weichselian ice caps.

A major break-through also took place when Mörner (1969), on the basis of detailed RSL/age studies of beach ridges and marine deposits of western Swedish river valleys, was able to calculate regional inclinations of raised beach ridges and thus before others became able to distinguish between the two major components of relative sea-level displacement, i.e. absolute (eustatic) sea-level changes and isostatic rebound (GIA). In later reviews, Mörner (e.g. 1980) pointed out that the beach deposits of the Kattegat region are excellent 'sea-level laboratory' objects in search for understanding the interplay between eustatic sea-level changes and post-glacial isostatic rebound.

With respect to isostatic models of the Holocene (late glacial to present) uplift, Pässe & Andersson's (2005) study of the Scandinavian peninsula is an important supplement to the observations by Mörner and other authors, resulting in many empirically documented series of the different patterns in RSL change at various positions around the centre and margins of the Weichselian glaciation of Scandinavia and the Baltic. Thus, north-east of Mörner's (1969) find of an isostatic bend perpendicular to the general Scandinavian uplift

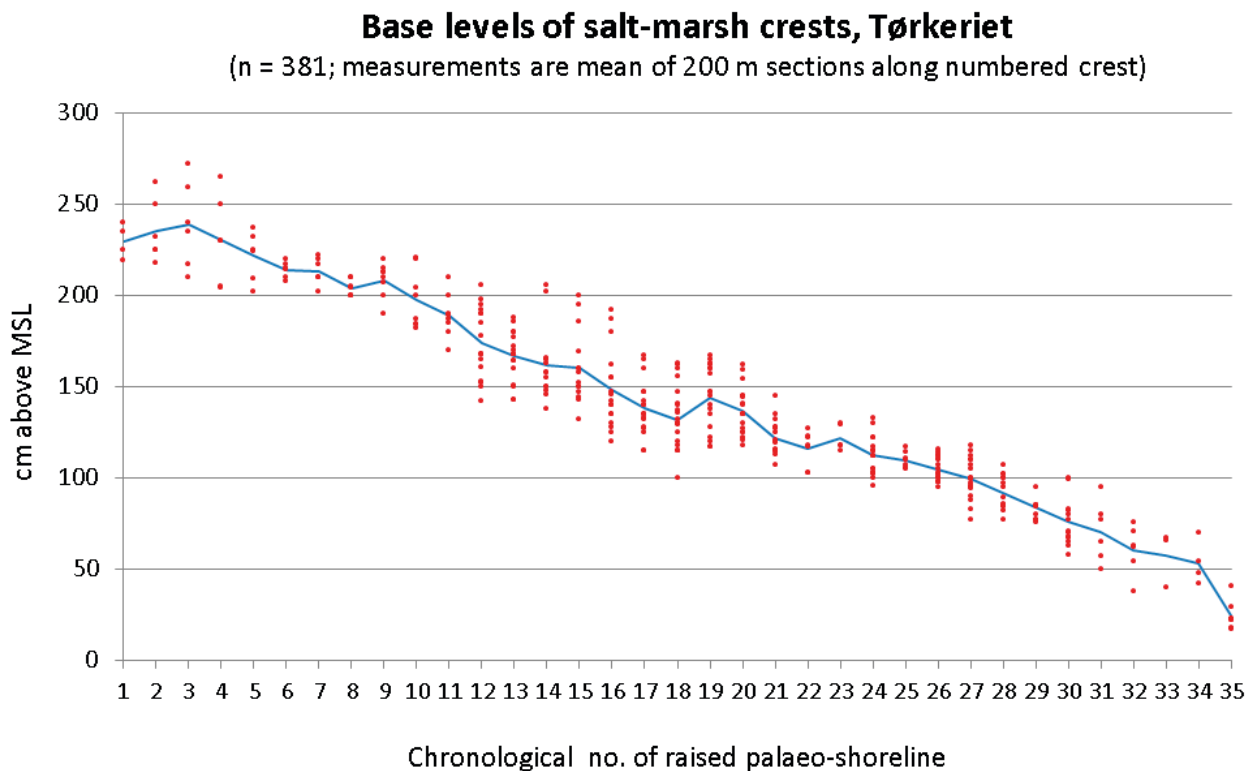


Fig. 34. Levels of 35 coherent and up to 5 km long saltmarsh crests of Tørkeriet, south-western Læsø (back-stripped curve of the measurements shown in Fig. 35). Each red dot represents the base level of ridge crests of 200 m long transects along the crest (BLRC method). The crests are arranged in chronological order according to the time of appearance (1: oldest; 35 youngest). Blue line represents the mean level of the 35 crests. The scatter of the individual crest levels varies between 20 and 65 cm and reflects local geological 'background noise', variations in the sedimentary heights of the crests (which relative to hindlying swales are about 10 cm), and a relative levelling precision between 1 and maximum 6 cm.

between the islands of Læsø and Anholt (70 km south of Læsø), Pässe and Andersson's (2005) empirical model also fits well with our RSL curve of Læsø, when our Læsø RSL/age index points are detrended for the local relaxation/uplift caused by post-Boreal erosion of the Læsø platform (Hansen *et al.* 2012).

Beach ridges as relative sea-level indicators

Raised beach ridges are generally proxies of the sea level at the time of deposition, such that the crest level of a certain beach ridge minus the swash height represents sea level when the ridge was formed. In northern Denmark where the GIA has been larger than the RSL rise during the late Holocene, formation of ridge-and-swale landscapes is a general characteristic of such regressive sedimentary regimes, regardless of whether the ridges were formed as berms, barrier spits or barrier islands and the depressions between them have been formed as swales between laterally stacked berms or by growth of barrier systems.

Because the swash height may be difficult to determine without GPR or lidar, the base levels of hindlying as well as subsequent swales have often been applied in regressive sedimentary environments of the Kattegat–Skagerrak seas, e.g. in the reconstruction of the large spit Skagen Odde, the northern tip of Jutland (Nielsen *et al.* 2006; Nielsen 2008; Nielsen & Johannessen 2009, 2010; Clemmensen & Murray 2010, Clemmensen *et al.* 2012a) and the Kattegat island of Anholt (Mörner 1969; Bjørnson *et al.* 2008; Clemmensen *et al.* 2012b). Moreover, Bendixen *et al.* (2014) have shown that in a non-regressive sedimentary environment of south-east Denmark (Feddet), beach ridges represent superimposed berms of several storm surge events.

On Læsø we found that the differences between ridge and swale levels in several types of beach-ridge landscapes are smaller than indicated from GPR profiling and identification of downlap structures representing MSL of the time. This problem first and foremost relates to laterally stacked beach ridges

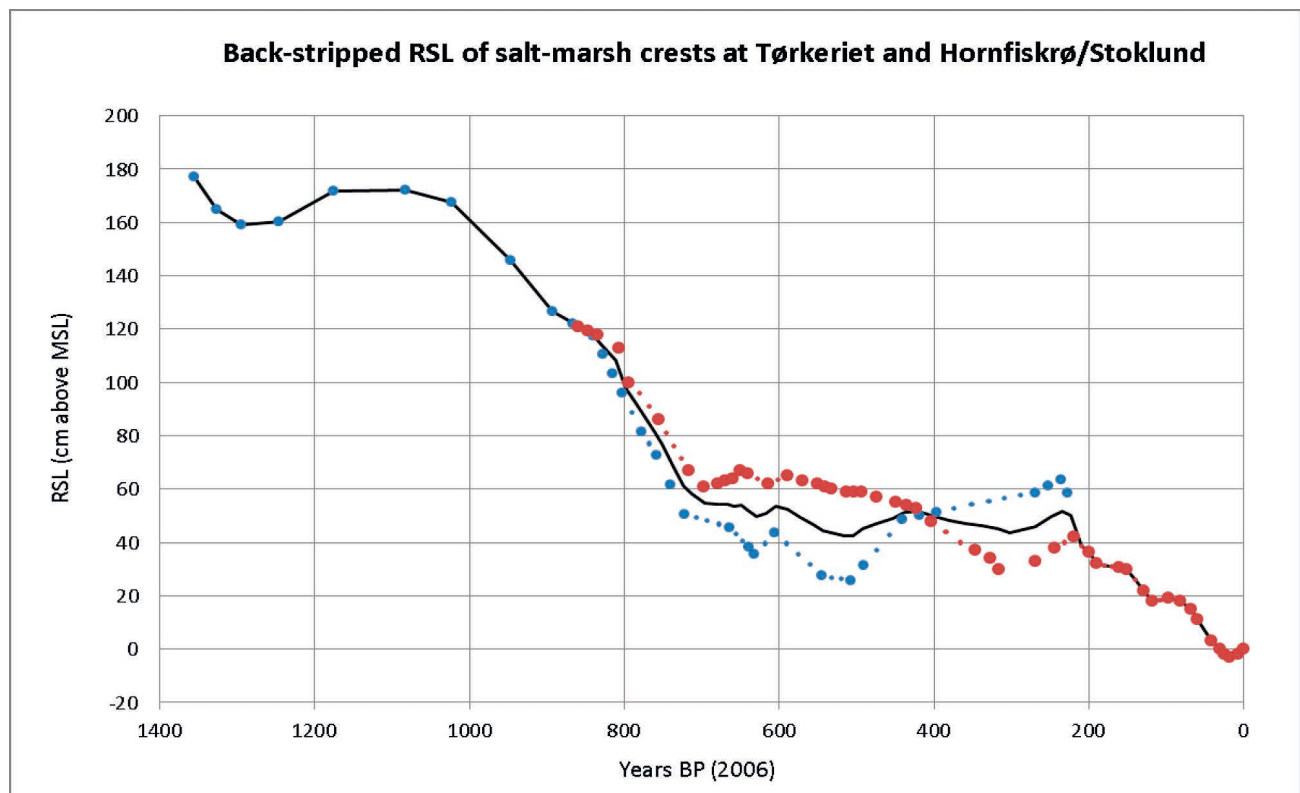


Fig. 35. RSL/age index points of raised saltmarsh crests. Brown dots: Index points of Hornfiskrøn and the Stoklund–Bangsbo area (data from Hansen *et al.* 2012). Blue dots: Result of back-stripping of 381 new BLRC measurements of raised saltmarsh ridges at Tørkeriet (Fig. 34) in comparison with the raised saltmarshes at Hornfiskrøn and Stoklund–Bangsbo, for identification of local geological ‘background noise’. The index points of all areas have been back-stripped by the method described by Hansen *et al.* (2012). The large blue dots show the resulting RSL index points of 32 crests that can be traced over 3–5 km. Small blue and brown dots are linear interpolations in order to construct the mean RSL curve (solid black line) of the two data sets that have been back-stripped for local, geological ‘background noise’ (and height of swash). The remaining RSL differences between the two data sets (mean 18 cm; max. 32 cm) are probably close to the limits of what can be compensated for in a low seismicity region with excellent representation of long, coherent and well separated saltmarsh crests.

(berms), where only incipient swales have been formed or have been partially eroded. This type of ridge-and-swale landscape forms large parts of Danish marine forelands in areas with slower coastal progradation than in the present case. On Læsø we have classified such landscapes, where swale levels may be imprecise RSL proxies, as *condensed high-ridge plains* (high-rippled washboard plains). Here, RSL identification should consequently be based on GPR profiling (cf. Hede *et al.* 2013). Also in raised saltmarsh landscapes, here classified as *condensed low-ridge plains* (low-rippled washboard plains), swale levels are generally slightly higher than the mean sea level of the time because the beach ridges are formed by vertical accretion during high water, so that the sedimentary process may

also affect the nearest hindlying swale during storm surges. In consequence we suggest that RSL/age index points obtained by lidar profiling exhibit a level difference not exceeding +0.2 m, mostly less than +0.1 m, as compared to RSL levels obtained by GPR profiling.

Exact chronology of beach ridges and uncertainty of assigned ages

The constant growth of Læsø provides two independent sources of geochronology, firstly and most importantly the exact observable order of appearance of beach ridges in each of the three main areas (Fig. 4), and secondly the laboratory age determinations listed in Table 1. The main purpose of these is to assign absolute ages to the observed chronology of

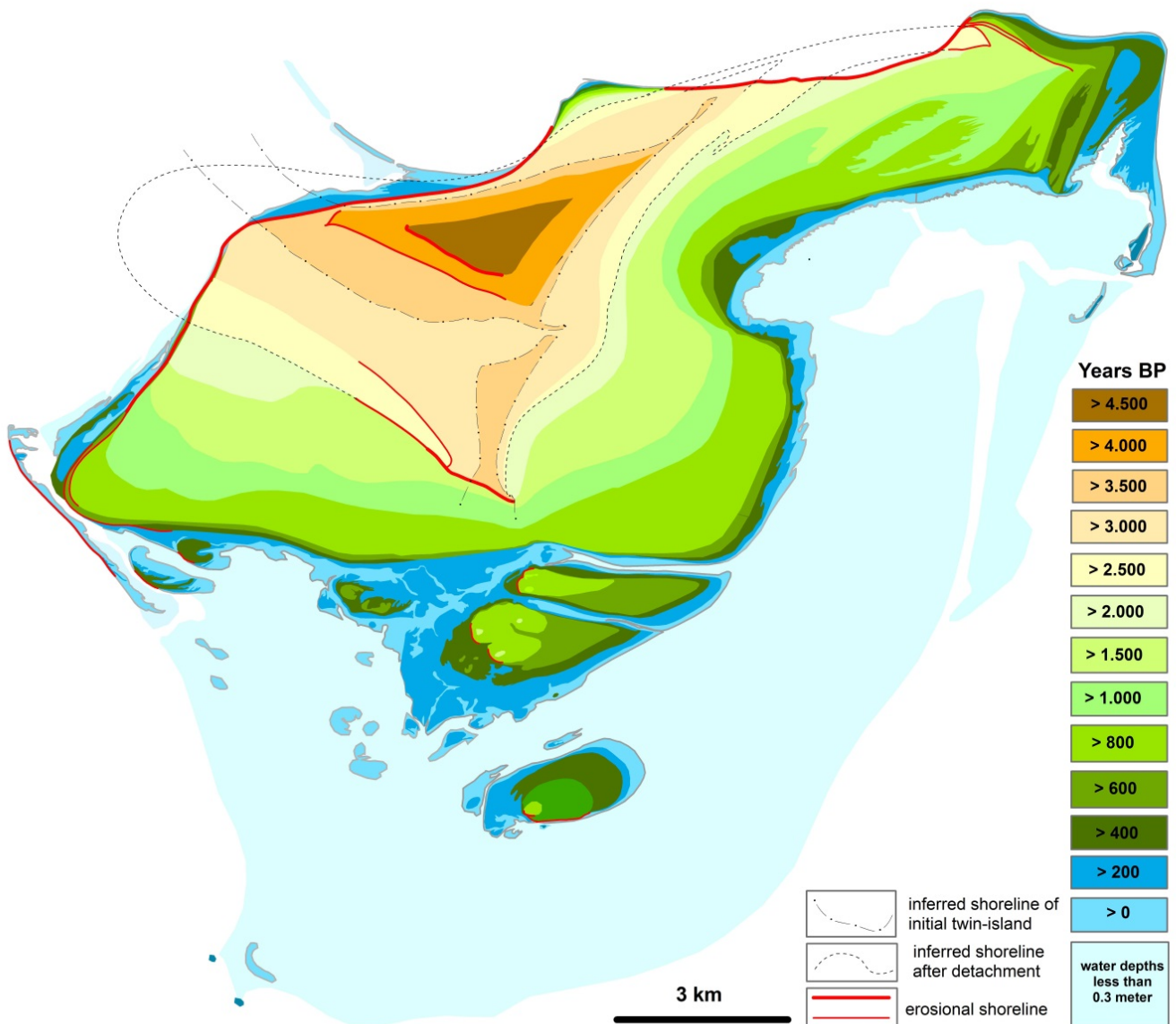


Fig. 36. Age model of the older, still preserved shorelines on Læsø. See text for description of the construction method.

palaeo-shorelines (cf. the section on *Age modelling of coastal progradation*). If two laboratory age determinations oppose the observed chronological order, then the observed chronology ranks above laboratory measurements and, consequently, analytical uncertainties of the relevant samples must be considered. The 1200 RSL/age index points respect this elementary principle of stratigraphical ranking and are further supported by the procedure of age modelling in which the assigned age of each index point is proportional to the distances between beach ridges.

The analytical uncertainties of all absolute age determinations are listed in Table 1, and the mean uncertainty of laboratory datings is 7.2 % of the assigned ages. However, the absolute age modelling is based on 12–37 samples within each time interval of 1000 years. Consequently, the uncertainties of ages assigned to the RSL curve (Fig. 38) are considered to be much lower than those of the individual samples. Moreover, the chronological order of index points is exact (certain). We consider the uncertainty of assigned ages to be <100 years for the period 5000–2000 BP, <50 years for the period 2000–1000 BP, and <25 years for the period 1000 BP to present.

Identification of geological ‘background noise’ in a low seismicity region

In sea-level reconstructions, the conclusion of Moucha *et al.* (2008) on long-term sea-level modelling has often been cited: “There is no such thing as a stable continental platform”. As any large long-term change is composed of smaller short-term changes, Moucha *et al.*’s (2008) conclusion also applies to late Holocene sea-level reconstructions.

Hansen *et al.* (2012) showed that geological ‘background noise’ is a crucial parameter for reconstruction of the last 900 years of absolute sea-level changes, because amplitudes of late Holocene sea-level changes (Woodworth *et al.* 2009; Cronin 2012) are comparable to amplitudes of normal geological background noise in regions of low seismicity such as Denmark (Andersen *et al.* 1974; Lykke-Andersen & Borre 2000; Khan *et al.* 2006), other parts of Scandinavia (Bungum *et al.* 2010; Hill *et al.* 2010), Central Europe (Scheck-Wenderoth & Lamarche 2004), and the east coast of north America (Engelhart *et al.* 2009). The present study correlates well with these and our previous findings of geological background noise and demonstrates how causes and magnitudes of relatively

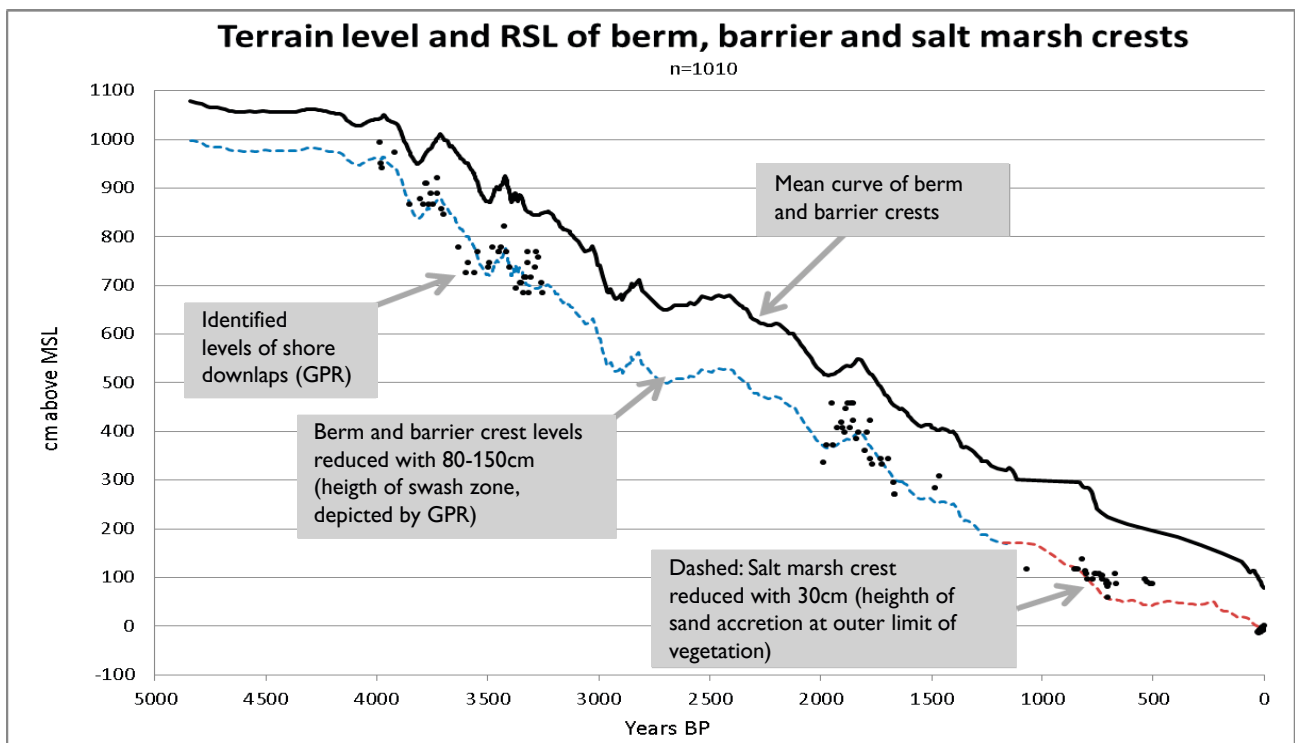


Fig. 37. Solid black curve: Mean level of raised berm and barrier ridges on Læsø (Fig. 32). Black dots: RSL levels of downlap structures determined by GPR profiling. Dashed blue curve: RSL of these sea-level proxies detrended for height of swash as found by GPR profiling. Dashed red curve: RSL of saltmarshes on Læsø (Fig. 35). The RSL curve of raised barriers is detrended for height of swash in such a way that the shape of the curve is maintained, but the curve is lowered to best fit with the RSL points as identified by GPR profiling.

short-term land-level changes of the Kattegat region may provide a better understanding of small relative sea-level changes.

Consequently, even along passive continental margins problems may arise for reconstruction of reliable late Holocene sea-level curves from areas where possibilities for multi-site, precise and coherent levelling of sea-level proxies are not at hand. Thus, except for a few cases of detrending for sediment compaction (e.g., Horton & Shennon 2002; Edwards 2006), published sea-level curves for low seismicity regions are not detrended at all for geological background noise. Compensations for tectonic background noise have mainly been done in regions of higher seismicity, e.g. Lambeck *et al.* (2004) in a study of Italy and in many studies of the north American west coast. Proportional differences between sea-level index points and sea-level curves from different locations may therefore be large compared to the general conception of small sea-level changes during the last 2000 years.

Obviously, this lack of detrending is a problem when hypotheses on a rapidly rising present sea level, as seen from tide gauge records, are based on the untenable concept of a relatively stable sea level during the last 1000–2000 years. Detailed and robust measurements

of the magnitude of sea-level oscillations prior to any substantial present sea-level rise are therefore required.

Unique representation of short-term lowstands

Another general problem of sea-level reconstructions is that it is a matter of discussion whether transgressive, stable and slightly regressive environments are capable to produce or preserve visible or separate sea-level proxies of short-term (multidecadal to centennial) lowstands. Even in micro-tidal environments, sea-level oscillations merely produce and preserve relatively high, complex berms which have mainly been formed over decades or centuries by storm surges (Bendixen *et al.* 2014). Consequently, sea-level curves based on such relatively stable isostatic environments may only illustrate sea-level highstands or storm surge levels, whereas short-term lowstands are missing or blurred. Unawareness of this situation may lead to unrealistic conceptions of short-term sea-level stability of the past (cf. Table 4).

Due to strong isostatic uplift, micro-tidal conditions, excessive supply of sediment and shallow surroundings, the horizontal coastal growth of Læsø (mean 2 m/year) has been enhanced by a

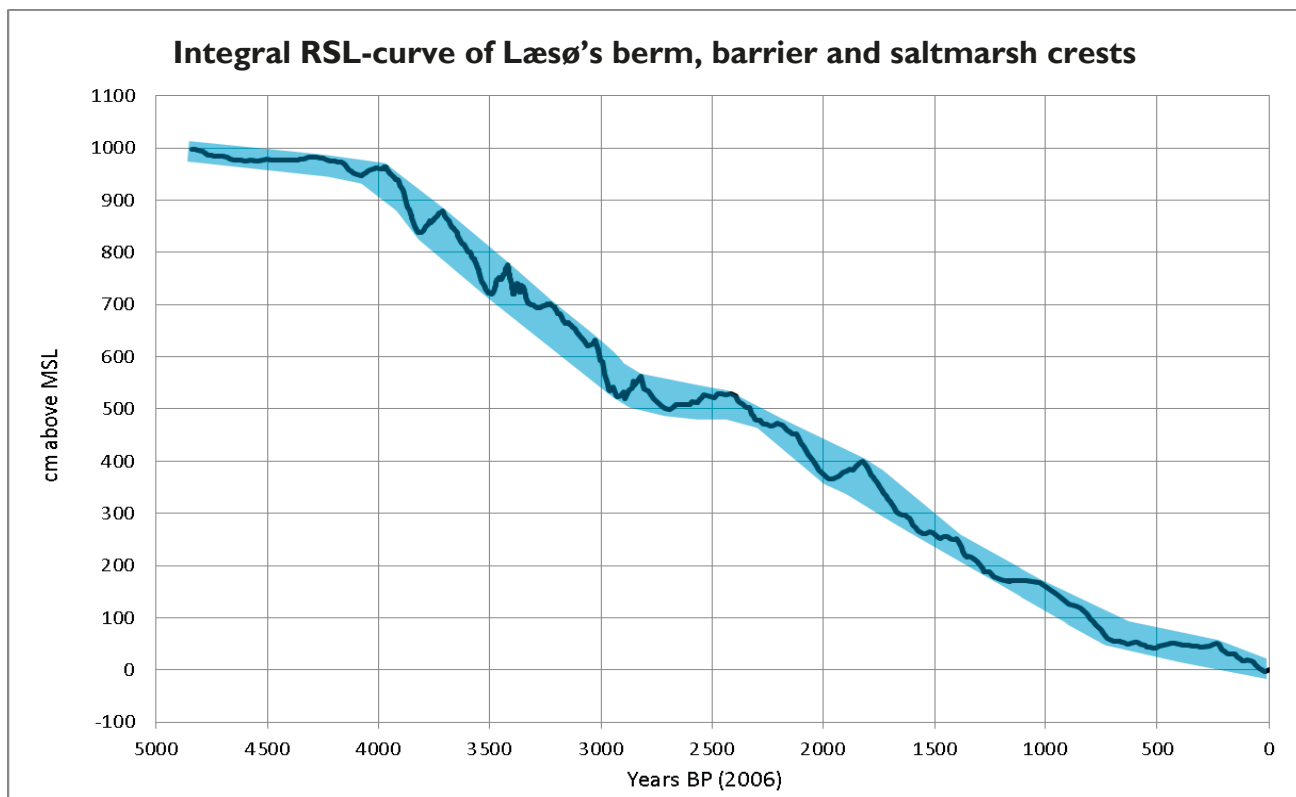


Fig. 38. Integral RSL curve of berm, barrier and saltmarsh crests on Læsø. The curve is detrended for height of swash and geological 'background noise' (Figs 32 and 35). Blue band: Limits of short-term sea-level oscillations. The vertical widths of the blue band indicate that the sea level oscillated many times within limits of 0.5–1.1 m of the general trend of the RSL curve, e.g. 0.6 m during the Little Ice Age lowstand between 850 to 200 years BP (1250–1800 AD).

continuously regressive environment where oscillations between short-term lowstands and subsequent highstands generally have not caused widespread erosion or produced large complex berms obscuring the directly observable beach-ridge chronology. Consequently, we consider the beach-ridge systems of Læsø to represent a unique micro-tidal and strongly regressive environment where proxies of both short-term sea-level highstands and lowstands have been preserved, and where short-term (multidecadal to centennial) sea-level oscillations and variability can be reconstructed for the last 4900 years in beach-ridge landscapes and most precisely for the last 2000 years in saltmarsh landscapes (Fig. 38 and Table 4).

Conclusions

Due to strong isostatic uplift, surplus of sediment, micro-tidal amplitudes and shallow water depths, the island of Læsø provides an excellent environment for reconstruction of continuous records of sea-level changes during the late Holocene. We show that this mid-Kattegat setting has created at least three simultaneously developing systems of beach ridges during the last 4900 years. Increasingly large parts of the island have been formed as raised saltmarshes during the last 3000 years. Thus, all periods of the last 4900 years are covered by at least three and up to eight separate, coherent and continuous sea-level records,

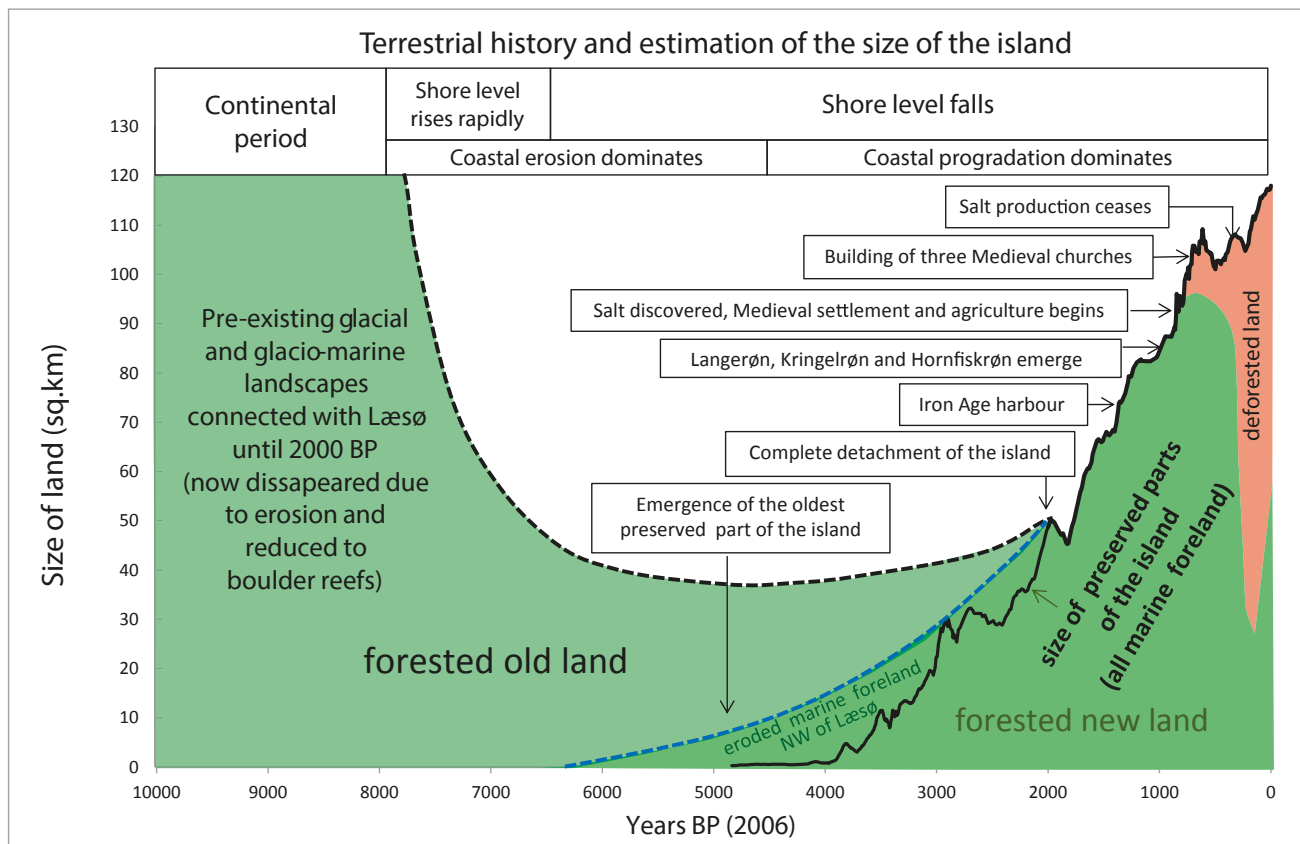


Fig. 39. Diagrammatic illustration of the coastal history and size of Læsø with indications of significant natural and cultural events. During the Boreal continental period, the Læsø-region was separated from Jutland and Sweden by large rivers to the west and east, whereas the region was attached to large landmasses between the rivers. During the maximum of the Litorina transgression (at Læsø c. 6300 years BP), all parts of present middle and northern Kattegat were flooded by the sea except for areas around the islands of Læsø and Anholt. Coloured areas: Estimated size of Læsø (before 2000 years BP, including now eroded glacio-marine landscapes and marine forelands mainly northwest of the preserved parts of the island). Solid curve: Size of preserved parts of the island; the curve is constructed by reversing the RSL curve in Fig. 38 and fitting it to the size of land areas in Fig. 36. The diagram indicates that the size of Læsø (including attached glacio-marine landscapes) was smallest in the period 6000 to 3000 years BP (around 40 km² or 30% of the present size), but large enough for survival of a stock of large herbivores (e.g. red deer) until after medieval settlements, and large enough for survival of mature, light-open forests including the Læsø pine (*Pinus silvestris* var. *laesoensis*), which became extinct elsewhere in the Baltic region. The attached glacio-marine landscapes were completely eroded to sea level or lower after 2500–2000 years BP and are now only represented by numerous boulder reefs both inside and outside of the present shoreline of Læsø.

i.e. continuous records of beach-ridge coasts exposed to the north, south-east to east, and south-west (4900 years BP to present) and saltmarsh coasts exposed to the south-east (3000 years BP to present) and south (2000 years BP to present).

Not only proxies of sea-level highstands are represented – as in less regressive environments – but also proxies of sea-level lowstands have often been preserved. This situation is mainly caused by strong uplift and the unique hydrographic setting of the island. Thus, the identified general RSL fall of 10.3 m (Fig. 38) reveals a mean vertical regression rate of 2.1 mm/year and a mean horizontal regression rate of 2 m/year, and eight short-term sea-level oscillations in the range of 0.5–1.1 m during the last 4900 years (Table 4), corresponding to short-term (centennial) absolute ('eustatic') sea-level changes.

Origin, coastal progradation and detachment from pre-existing landscapes

The present study explains how the island of Læsø emerged from a pre-existing, now eroded glacio-marine landscape and how the coastal development during the last 4900 years is related to a strongly regressive sedimentary environment, sea-level oscillations and changes in exposure, water depths and sedimentary sources. A summarizing figure of the above described pre-history, emergence, coastal growth, forestation, settlement, salt industry, deforestation and land-use is shown in Fig. 39 where the main events of the coastal history are highlighted.

Identification of geological 'background noise'

The coastal landscapes of Læsø make it possible to reconstruct several independent sea-level curves from closely spaced, but separate areas of the same low seismicity region. Because normal tectonic level changes, as well as terrain level changes due to land-use practices, by definition are local, this situation provides a rare opportunity for identification of small-scale terrain-level changes, which are likely to appear in all cultivated landscapes and most low seismicity areas such as Scandinavia, other parts of north-western Europe and eastern north America. From such assumed stable geological environments, similar small local changes usually cannot be detected.

Continuous record of sea-level changes during the last 4900 years

Many studies of beach ridges and other sea-level proxies of the Kattegat Sea have given both coherent and detailed knowledge about early Holocene (late glacial) and mid Holocene relative sea-level changes, while understanding of the late Holocene, in particular the last 2000 years, has been at a less

coherent and precise level. The island of Læsø has been formed after 4900 years BP by continuous coastal progradation, forming more than 4000 km of well separated, still visible barrier and saltmarsh beach ridges. Thus, a coherent and detailed record of Late Holocene RSL changes can be constructed on the basis of 1200 RSL/age index points, including the last 2000 years about which knowledge on European and American sea-level changes is generally incomplete because of lack of studies on lowstand proxies. For the last 1000 years the sea-level curve of Hansen *et al.* (2012) is supplied with many new RSL/age index points displaying a 80 cm RSL fall (1200–1300 AD) at the onset of the Little Ice Age.

Centennial sea-level oscillations of 0.5–1.1 m

The strongly regressive regime, shallow surrounding waters and continuous surplus of sediment in combination with a micro-tidal amplitude of only 0.2 m has created a unique sedimentary environment, where proxies of short-term sea-level oscillations of the last 4900 years have continuously been preserved in the form of both highstand and lowstand proxies, while lowstand sea-level proxies in less regressive environments appear to have been eroded or obscured by subsequent highstands in most other parts of north-western Europe and north-eastern America. By comparing the detailed RSL curve with its general trends (Fig. 38), eight short-term (centennial) sea-level oscillations can be identified, showing that RSL oscillated 0.5–1.1 m around the generally falling RSL (Table 4).

Acknowledgements

We are indebted to Geocenter Denmark for grants to the Refleks project and for discussions with its other participants including Morten Pejrup, Lars Clemmensen, Mikkel Hede, Nanna Noe-Nygaard, Andrew Murray, Lars Henrik Nielsen and Peter Johannessen, who worked at other coastal sites. We are also indebted to Eigil Holm for providing excellent aerial photographs, Lasse Gudmundsson for both photographs and inspiring assistance with OSL sampling, Frank Andreasen for his large pioneer work on Læsø with GPR profiling, Peter Roll Jacobsen for assisting with supplementary GPR profiling (2010), to Benny Scharck for preparing illustrations, to two anonymous reviewers, and to the editor (Lotte Melchior Larsen) for careful reading and clarification, constructive suggestions on the structure and focus of the article. The Carlsberg Foundation and the Danish Council for Independent Research supplied grants for OSL dating. GEUS is thanked for general support and technical assistance.

References

- Andersen, O. B., Kejlso, E. & Remmer, O. 1974: Secular movements within Jutland as determined from repeated precise levellings 1885–94 and 1943–53. *Geodætisk Instituts Skrifter* 3, 1–70.
- Andersen, S.T. 1970: The relative pollen productivity and pollen representation of north European trees, and correction factors for tree pollen spectra. *Danmarks Geologiske Undersøgelse Række 2 No. 96*, 99 pp.
- Andreasen, F. 1986: Rapport over prospektering efter sten og grusforekomster på Læsø. *Fredningsstyrelsen*. (Unpublished data report with app. 50 km of GPR profiles).
- Bahnsen, H. 1986: Lithologisk undersøgelse af materiale fra seks boringer på Læsø. *Danmarks Geologiske Undersøgelse Series D 6*, 7–23.
- Bahnsen, H., Knudsen, K. L. og Hansen, J. M. 1986: Bidrag til Læsøs geologi. *Danmarks Geologiske Undersøgelse Series D 6*, 72 pp.
- Bendixen, M., Clemmensen, L.B. & Kroon, A. 2014: Sandy berm and beach-ridge formation in relation to extreme sea levels: A Danish example from a micro-tidal environment. *Marine Geology* 344, 53–64.
- Berthelsen, A. 1978: The methodology of kineto-stratigraphy as applied to glacial geology. *Bulletin of the Geological Society of Denmark* 27 (special issue), 25–38.
- Bird, E. 2008: Coastal geomorphology. An introduction. *Wiley & Sons*, 411 pp.
- Bjørnsen, M., Clemmensen, L.B. & Murray, A. 2008: New evidence of the Littorina transgressions in the Kattegat: Optically Stimulated Luminescence dating of a beach-ridge system on Anholt, Denmark. *Boreas* 37, 157–168.
- Bradshaw, R., Hansen, J.M. & Møller, P.F. 1999: Om begrebet natur. Natur versus menneske i Kvartærtid. *Skoven 3/99*, 117–121.
- Bungum, H., Olesen, O., Pascal, C., Gibbons, S., Lindholm, C. & Vestøl, O. 2010: To what extent is the present seismicity of Norway driven by post-glacial rebound? *Journal of the Geological Society of London* 167, 373–384.
- Christensen, C. 1995: The Littorina transgressions in Denmark. In: Fischer, A. (ed.), *Man and Sea in the Mesolithic – Coastal Settlements Above and Below Present Sea Level*. *Oxbow Monograph*, Oxford, 15–22.
- Clemmensen, L.B. & Murray, A.S. 2010: Luminescence dating of Holocene spit deposits: an example from Skagen Odde, Denmark. *Boreas* 39, 154–162
- Clemmensen, L.B. & Nielsen, L. 2010: Internal architecture of a raised beach-ridge system (Anholt, Denmark) resolved by ground-penetrating radar investigations. *Sedimentary Geology* 223, 281–290.
- Clemmensen, L.B., Murray, A.S. & Nielsen, L. 2012a: Quantitative constraints on the sea level fall that terminated the Littorina Sea Stage, southern Scandinavia. *Quaternary Science Reviews* 40, 54–63.
- Clemmensen, L.B., Nielsen, L., Bendixen, M. & Murray, A. 2012b: Morphology and sedimentary architecture of a beach-ridge system (Anholt, the Kattegat sea): a record of punctuated coastal progradation and sea level change over the past ~1000 years. *Boreas* 41, 422–434.
- Cronin, T.M. 2012: Rapid sea level rise. *Quaternary Science Reviews* 56, 11–30.
- Edwards, R.J. 2006: Mid- to late-Holocene relative sea level change in southwest Britain and the influence of sediment compaction. *The Holocene* 16, 575–587.
- Engelhart, S.E., Horton, B.P., Douglas, B.C., Peltier, W.R. & Törnqvist, T.E. 2009: Spatial variability of late Holocene and 20th century sea level rise along the Atlantic coast of the United States. *Geology* 37, 1115–1118.
- Fredericia, J. 1985: Hydrogeologisk basisdatakort, Læsø. *Danmarks Geologiske Undersøgelse, Hydro-geological basis data map series*.
- Fredericia, J. & Grambo-Rasmussen, A. 1985: Kortlægning af kvartære gasfund i Vendsyssel. Fase 2. (2 volumes), 126 pp. Fase 3. rapport, 13 pp. *Danmarks Geologiske Undersøgelse, report series*.
- Gregersen, S. & Voss, P.H. 2014: Review of some significant claimed irregularities in Scandinavian postglacial uplift on timescales of tens to thousands of years – earthquakes in Denmark? *Solid Earth* 5, 109–118.
- Hansen, J.M. 1977: Sedimentary history of the island Læsø. *Bulletin of the Geological Society of Denmark* 26, 217–236.
- Hansen, J.M. 1980: Læsøs postglaciale udvikling i relation til den Fennoskandiske Randzone. *Dansk Geologisk Forening, Årsskrift for 1979*, 23–30.
- Hansen, J.M. 1986: Læsø: Et resultat af forkastningsbevægelser, jordskælv og niveauforandringer? *Danmarks Geologiske Undersøgelse Series D 6*, 47–72.
- Hansen, J.M. 1994: Læsøs tilblivelse og landskaber – om øen der rokker og hopper. *Danmarks Geologiske Undersøgelse & Geografforlaget*, 56 pp.
- Hansen, J.M. 1995: En ø's opståen, kystdannelse og vegetationsudvikling: Naturlige og menneskeskabte landskaber på Læsø. *Geologisk Tidsskrift* 2, 1–74, 2 folded maps.
- Hansen, J.M. 2009: On the origin of natural history: Steno's modern, but forgotten philosophy of science. *The Geological Society of America, Memoir* 203, p. 159–178.
- Hansen, J.M. 2010: The salt industry on the Danish Kattegat Island of Læsø (1150–1652): Hypersaline source, climatic dependence, and environmental impact. *Danish Journal of Geography* 110, 1–24.
- Hansen, J.M. 2011: Læsøs strandlinier – i lokalt/globalt og historisk/fremtidigt perspektiv. *Geologisk Nyt* 2011/6, 26–37.
- Hansen, J.M. 2015: Læsøs forhistorie og ældste stadier. *Museumsforeningen for Læsø, Årsskrift for 2014*, 12–25.
- 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, 180–208.
- Hede, M.U., Bendixen, M., Clemmensen, L.B., Kroon, A. & Nielsen, L. 2013: Joint interpretation of beach-ridge architecture and coastal topography show the validity of sea level

- markers observed in ground-penetrating radar data. *The Holocene* 23, 1238–1246.
- Hede, M.U., Sander, L., Clemmensen, L.B., Kroon, A., Pejrup, M. & Nielsen, L. 2015: Changes in Holocene relative sea-level and coastal morphology: A study of a raised beach ridge system on Samsø, southwest Scandinavia. *The Holocene* 25, 1402–1414. DOI: 10.1177/0959683615585834.
- Hill, E.M., Davis, J.L., Tamisiea, M.E. & Lidberg, M. 2010: Combination of geodetic observations and models for glacial isostatic adjustment fields in Fennoscandia. *Journal of Geophysical Research* 115, B07403, doi:10.1029/2009JB006967.
- Horton, B.P. & Shennan, I. 2002: Compaction of Holocene strata and the implications for relative sea level change on the east coast of England. *Geology* 37, 1083–1086.
- Houmark-Nielsen, M. 2003: Signature and timing of the Kattegat Ice Stream: onset of the LGM-sequence in the southwestern part of the Scandinavian Ice Sheet. *Boreas* 32, 227–241.
- Houmark-Nielsen, M. 2004: The Pleistocene of Denmark: a review of stratigraphy and glaciation history. In: Ehlers, J. & Gibbard (eds): *Quaternary glaciations – Extent and Chronology*. Elsevier, Amsterdam.
- Houmark-Nielsen, M. & Kjær, K.H. 2003: Southwest Scandinavia 40–15 ka BP: Palaeogeography and environmental change. *Journal of Quaternary Science* 18, 769–786.
- Iversen, J. 1967: Naturens udvikling siden sidste istid. In: Arne Nørvang & Torben J. Meyer (eds): *Landskabernes opståen*. Danmarks Natur 1, 345–445. Politikens Forlag.
- Japsen, P. & Britze, P. 1991: Det danske Bassin, Kalk Gruppen. Kort over den vertikale tykkelse (The Danish Basin, Chalk Group, Isochore map). *Danmarks Geologiske Undersøgelse Map Series* 29.
- Jensen, P., Aagaard, I., Burke Jr., R.A., Dando, P.R., Jørgensen, N.O., Kuijpers, A., Laier, T., O'Hara, S.C.M. & Schmaljohann, R. 1992: 'Bubbling reefs' in the Kattegat: submarine landscapes of carbonate-cemented rocks support a diverse ecosystem at methane seeps. *Marine Ecology Progress Series* 83, 103–112.
- Jessen, A. 1897: Beskrivelse til geologiske Kort over Danmark. Kortbladene Læsø og Anholt. *Danmarks Geologiske Undersøgelse*, 2. Række 4, 48 pp., 2 maps.
- Jessen, A. 1922: Stenalderhavets Udbredelse i det nordlige Jylland. *Danmarks Geologiske Undersøgelse*, 2. Række 25, 112 pp.
- Jessen, A. 1936: Vendsyssels Geologi. *Danmarks Geologiske Undersøgelse*, 5. Række 2, 195 pp.
- Jørgensen, N.O. 1980: Gypsum formation in recent submarine sediments from Kattegat, Denmark. *Chemical Geology* 28, 349–353.
- Jørgensen, N.O. 1992: Methane-derived carbonate cementation of marine sediments from the Kattegat, Denmark: Geochemical and geological evidence. *Marine Geology* 103, 1–13.
- Khan, S.A., Knudsen, P. & Tscherning, C.C. 2006: Crustal deformations at permanent GPS sites in Denmark. In: Sanso, E. (ed.): *A Window on the Future of Geodesy*, 556–560. Springer, Berlin.
- Krog, H. 1965: On the Post-Glacial development of the Great Belt. *Baltica* 2, 47–60.
- Krog, H. 1968: Late-Glacial and Postglacial Shoreline Displacements in Denmark. In: R.B. Morrison & H.E. Wright Jr. (eds): *Means of correlation of Quaternary successions* 8, 421–135.
- Laier, T. 1992: Shallow gas in northern Kattegat and southern Skagerrak. Meeting Proceedings, *Geologiska Foreningen i Stockholms Förhandlingar* 114, 235–251.
- Laier, T., Jørgensen, N.O., Buchardt, B., Cederberg, T. & Kuijpers, A. 1992: Accumulation and seepages of biogenic gas in northern Denmark. *Continental Shelf Research* 12, 1173–1186.
- Lambeck, K., Antonioli, F., Purcell, A. & Silenzi, S. 2004: Sea level change along the Italian coast for the past 10,000 years. *Quaternary Science Reviews* 23, 1567–1598.
- Larsen, G., Bauman, J. & Bjørn, O. 1986: Kvartærgeologiske forhold under havbunden i Læsø Rende. *Dansk Geologisk Forening, Årsskrift for 1985*, 39–46.
- Lykke-Andersen, A.-L. 1990: Foraminiferal stratigraphy of Quaternary deposits in boring no. 51.12 Anholt, Kattegat. *Danmarks Geologiske Undersøgelse, Series B* 15, 40 pp.
- Lykke-Andersen, H. 1992a: Massebevægelser i Vendsyssels og Kattegats kvartære aflejringer. *Dansk Geologisk Forening, Årsskrift for 1990–1991*, 93–97.
- Lykke-Andersen, H. 1992b: Nogle hovedtræk af Kattegats kvartære geologi. *Dansk Geologisk Forening, Årsskrift for 1990–1991*, 57–65.
- Lykke-Andersen, H. & Borre, K. 2000: Aktiv tektonik i Danmark – der er liv i Sorgenfrei-Tornquist Zonen. *Geologisk Nyt* 6/2000, 12–13. Copenhagen: Geological Survey of Denmark and Greenland.
- Lykke-Andersen, H., Knudsen, K.L. & Christiansen, C. 1993a: The Geokat project - a study of the Late Quaternary evolution of the Kattegat Sea. *Boreas* 22, 267–268.
- Lykke-Andersen, H., Knudsen, K.L. & Christiansen, C. 1993b: The Quaternary of the Kattegat area, Scandinavia: a review. *Boreas* 22, 269–281.
- Lysdahl, P. 1985: Minder fra Læsøs oldtid. *Museumsforeningen for Læsø, Årbog for 1984*, 8–12.
- Lysdahl, P. 1987: Et stenalderkar. *Museumsforeningen for Læsø, Årbog for 1986*, 35–36.
- Læsø Kommune, Nordjyllands Amt og Skov- og Naturstyrelsen 1989: Råstofkortlægning på Læsø, 96 pp. (Municipal decision paper).
- Mertz, E.-L. 1924: Oversigt over de sen- og postglaciale niveauforandringer. *Danmarks Geologiske Undersøgelse*, 2. Række 41, 50 pp.
- Michelsen, O. 1967: Foraminifera of the late-quaternary deposits of Læsø. *Meddelelser fra Dansk Geologisk Forening* 17, 205–264.
- Moucha, R., Forte, A.M., Mitrovica, J., Rowley, D.B., Quéré, S., Simmons, N.A. & Grand, S.P. 2008: Dynamic topography and long-term sea level variations: There is no such thing as a stable continental platform. *Earth and Planetary Science Letters* 271, 101–108.
- Mörner, N.-A. 1969: The late Quaternary history of the Kat-

- tegat Sea and the Swedish west coast. *Sveriges Geologiska Undersökning, Series C 640*, 487 pp.
- Mörner, N.-A. 1978: Faulting, fracturing and seismic activity as a function of glacial isostasy in Fennoscandia. *Geology* 6, 41–45.
- Mörner, N.-A. 1980: The northwest European “sea level laboratory” and regional Holocene eustacy. *Palaeogeography, Palaeoclimatology, Palaeoecology* 29, 281–300.
- Mörner, N.-A. 1995: Palaeoseismicity – The Swedish case. *Quaternary International* 25, 75–79.
- Mörner, N.-A. 2014: An $M > 6$ Earthquake ~750 BC in Sweden. *Open Journal of Earthquake Research* 3, 66–81.
- Nielsen, A.H. 2008: On the evolution of beach-ridge plains – Luminescence dating, geomorphology and soil development at the Jerup beach-ridge plain, Denmark. Ph.D. thesis, Copenhagen University, 129 pp.
- Nielsen, A., Murray, A.S., Pejrup, M. & Elberling, B. 2006: Optically stimulated luminescence dating of a Holocene beach-ridge plain in northern Jutland, Denmark. *Quaternary Geochronology* 1, 305–312.
- Nielsen, L. & Clemmensen, L. 2009: Sea level markers identified in ground-penetrating radar data collected across a modern beach-ridge system in a microtidal regime. *Terra Nova* 21(6), 474–479.
- Nielsen, L.H. & Johannessen, P.N. 2009: Facies architecture and depositional processes of the Holocene–Recent accretionary forced regressive Skagen spit system, Denmark. *Sedimentology* 56, 935–968.
- Nielsen, L.H. & Johannessen, P.N. 2010: Accretionary, forced regressive shoreface sands of the Holocene–Recent Skagen Odde spit complex, Denmark – a possible outcrop analogue to fault-attached shoreface sandstone reservoirs. *Norwegian Petroleum Society, Special Publications* 10, 457–472.
- Noe-Nygaard, N., Knudsen, K.-L. & Houmark-Nielsen, M. 2006: Fra istid til og med Jægerstenalder. In: Larsen, G. (ed.): *Naturen i Danmark. Geologien*. Gyldendal, København, 303–332.
- Nordmann, V. 1903: En Klump sammenkittede Molluskskaller fra Havbunden ved Læsø. *Meddelelser fra Dansk Geologisk Forening* 9, 37–44.
- Olesen, M. (ed.) 2005: *Naturforholdene i havet omkring Læsø. Pilotprojekt Marin Nationalpark Læsø. Report for the working group on national parks*, 129 pp.
- Paradeisis-Stathis, S. 2015: *Evolution of a Barrier Island, Vegetation Cover and Climate Change – A Case Study of Stokken, Læsø*. Copenhagen University, Faculty of Science, 91 pp. (unpublished Master Thesis).
- Pedersen, S.A.S., Laier, T., Hansen, J.M. & Petersen, K.S. 1989: *Maringeologisk undersøgelse ved Læsø Rende. Dykkerundersøgelse af kalkcementering ved gasudstrømning i NV-Kattegat*. Danmarks Geologiske Undersøgelse Report series 35, 30 pp.
- Pässe, T. & Andersson, L. 2005: Shore-level displacement in Fennoscandia calculated from empirical data. *Geologiska Föreningen i Stockholms Förhandlingar* 127, 253–268.
- Sander, L., Hede, M.U., Fruergaard, M., Nielsen, L., Clemmensen, L.B., Kroon, A., Johannessen, P.N., Nielsen, L.H. & Pejrup, M. 2015: Coastal lagoons and beach ridges as complementary sedimentary archives for the reconstruction of Holocene relative sea-level changes. *Terra Nova (early view)*, DOI:10.1111/ter.12187.
- Sarmaja-Korjonen, K., Vasari, Y. & Hæggstrom, C.-A. 1991: *Taxus baccata* and influence from Iron Age man on the vegetation in Åland, SW Finland. *Annales Botanica Fennici* 28, 143–159.
- Scheck-Wenderoth, M. & Lamarche, J. 2004: Crustal memory and basin evolution in the Central European Basin System – new insights from a 3D structural model. *Tectonophysics* 397, 143–165.
- Schou, A. 1945: *Det marine Forland*. 236 pp. Copenhagen: Hagerups Forlag.
- Schou, A. 1969a: Danmark – et morænearkipel. In: Nørvang, A. & Meyer, T.J. (eds): *Kyst, Klit og Marsk*. Danmarks Natur 4, 9–17. Copenhagen: Politikens Forlag.
- Schou, A. 1969b: Kysten – kampzonen mellem hav og land. In: Nørvang, A. & Meyer, T.J. (eds): *Kyst, Klit og Marsk*. Danmarks Natur 4, 30–37. Copenhagen: Politikens Forlag.
- Schou, A. 1969c: Kystprofilen og dets udformning. In: Nørvang, A. & Meyer, T.J. (eds): *Kyst, Klit og Marsk*. Danmarks Natur 4, 52–58. Copenhagen: Politikens Forlag.
- Schou, A. 1969d: Det marine forland – de havskabte kystsletter. In: Nørvang, A. & Meyer, T.J. (eds): *Kyst, Klit og Marsk*. Danmarks Natur 4, 66–71. Copenhagen: Politikens Forlag.
- Schou, A. 1969e: Materialevandringen langs kysten. In: Nørvang, A. & Meyer, T.J. (eds): *Kyst, Klit og Marsk*. Danmarks Natur 4, 71–81. Copenhagen: Politikens Forlag.
- Schou, A. 1969f: Kystudligningen. In: Nørvang, A. & Meyer, T.J. (eds): *Kyst, Klit og Marsk*. Danmarks Natur 4, 81–85. Copenhagen: Politikens Forlag.
- Schou, A. 1969g: Hævede kystlinjer. In: Nørvang, A. & Meyer, T.J. (eds): *Kyst, Klit og Marsk*. Danmarks Natur 4, 187–190. Copenhagen: Politikens Forlag.
- Stoklund, B. 1973: *Tømmerskuderne fra Læsø. Et kapitel af skudehandelens historie*. Handels- og Søfartsmuseets Årbog for 1972.
- Stoklund, B. 1980: *Bosættelse og bebyggelse på Læsø*. Vendsyssel Årbog 1980. Historisk Samfund for Vendsyssel, 7–56.
- Stoklund, B. 1986: *Hakkemøg, foldtørv og træk*. *Tidsskrift for Folkelivsgranskning* 29, 51–69.
- Stoklund, B. 1990: *Tørvegødning – en vigtig side af hedebondens driftsystem*. *Landbohistorisk Tidsskrift* 1990(1), 47–72.
- Stoklund, B. 1999: *Turf Manuring in the Danish Island of Læsø*. *Geografisk Tidsskrift, Special Issue* 1999(1), 209–214.
- Stoklund, B. 2007: *Fra salt til tømmers*. In: Nielsen, H.G. (ed.): *Fra Reformation til Enevælde. Renæssancen i Nordjylland 1536/1600*. Hals, Nordjyske Museers Østkystnetværk, 339–366.
- Tamura, T., Fumitoshi, M., Futoshi, N., Kazuaki, W. & Yoshiki, S. 2008: Ground-penetrating georadar profiles of Holocene raised beach-ridge deposits in the Kujukuri strand plain, Pacific coast of eastern Japan. *Marine Geology* 248, 11–27.

- Vangkilde-Pedersen, T., Lykke-Andersen, H. & Lind, G. 1993: Dislocated Quaternary deposits in southeastern Kattegat – a glacial or gravitational phenomenon? *Boreas* 22, 329–336.
- Vejbæk, O.V. & Britze, P. 1994: Top præ-Zechstein. Toppen af bjergarter ældre end Zechstein, Strukturelt tidskort (Top pre-Zechstein, Structural time map). Danmarks Geologiske Undersøgelse, Map Series 45.
- Vellev, J. 1991: Die Salzproduktion in Dänemark – besonders auf der Insel Læsø. In: Ingenhaeff, W. (ed.): *Das Salz in der Rechts- und Handelsgeschichte*, 413–438. Hocquet & Palme.
- Vellev, J. 1993: Saltproduktion på Læsø, i Danmark og i Europa. Hikuin, 108 pp.
- Vellev, J. 2001: Salt på Læsø. In: Poul Christensen (ed.): *Læsø Salt – i Røg og Damp*. Læsø Produktions-skole og Saltsyderi, 31–52.
- von Post, L. 1933: A Gothiglacial Transgression of the Sea in South Sweden. *Geografiska Annaler* 15, 225–254.
- Woodworth, P.L., White, N.J., Jevrejeva, S., Holgate, S.J., Church, J.A. & Gehrels, W.R. 2009: Evidence for accelerations of sea level on multi-decade and century timescales. *International Journal on Climatology* 29, 777–789.

