Absolute ('eustatic') sea-level changes of the Kattegat Sea shifted many times between -3.1 and +3.7 mm/year after melt down of the Scandinavian icecap – a 4900 year natural, continuous 'tide-gauge' record found

Relative sea-level reconstruction

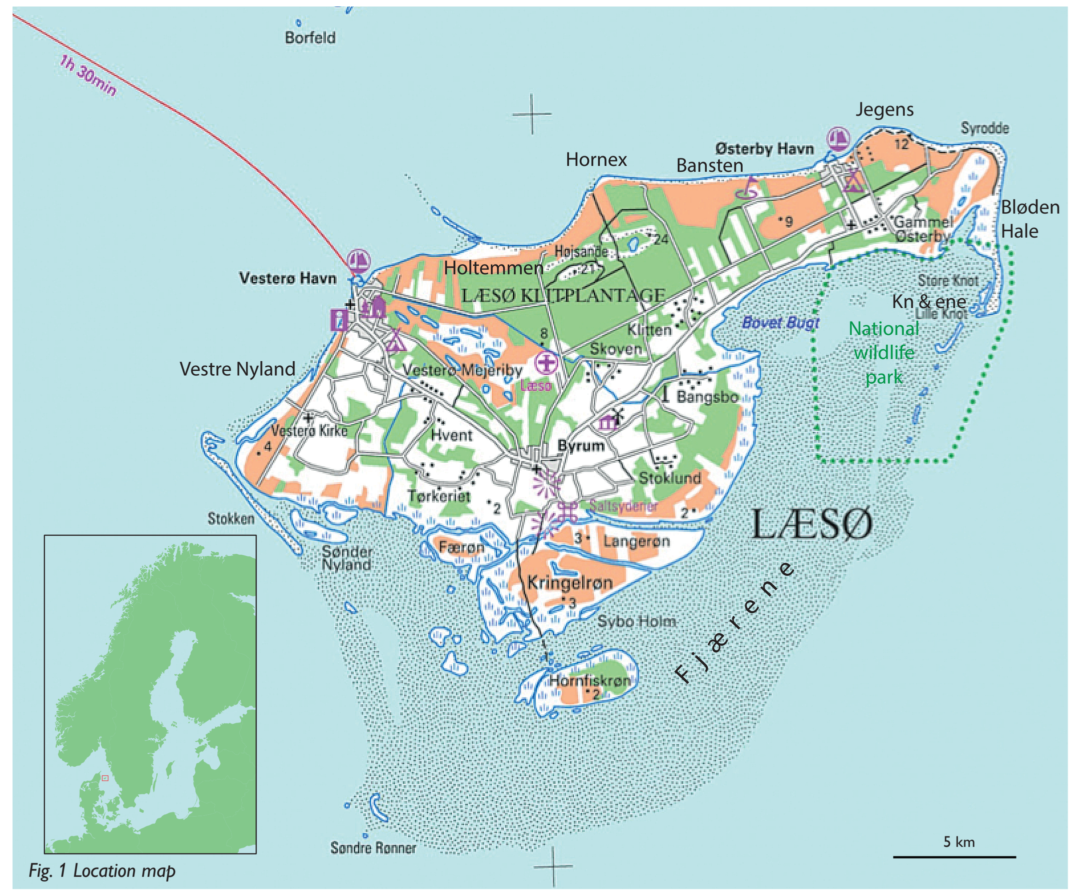

Fig. 1 Location map

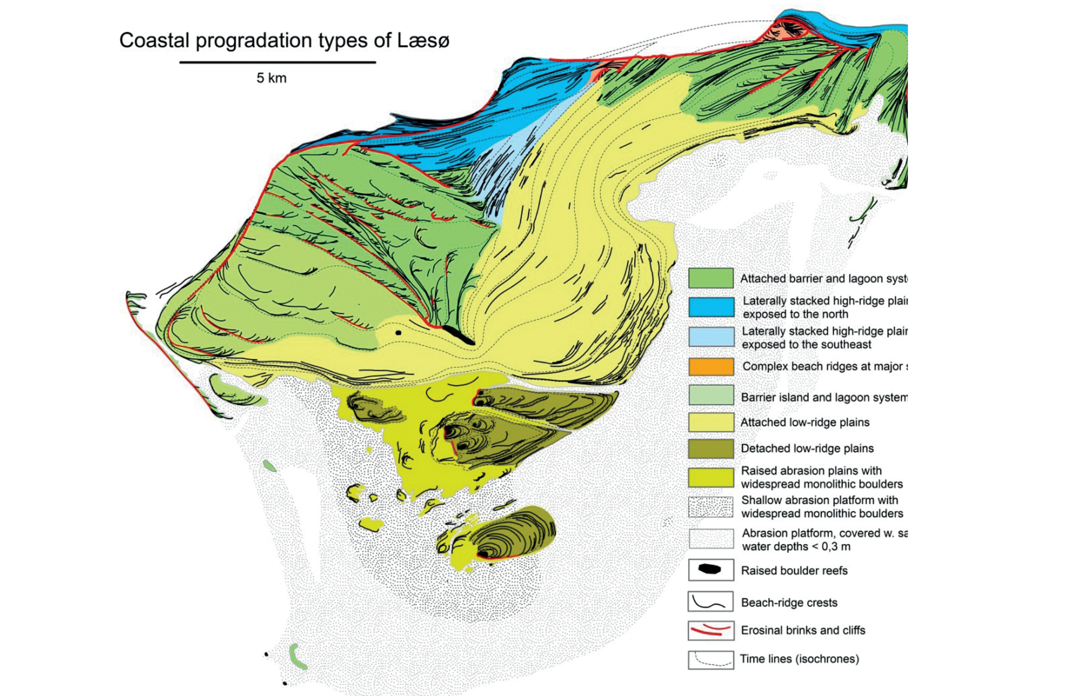

Fig. 2: Overview map of the most prominent beach ridges of Læsø, where around 4.000 km of such palaeo-shorelines are still visible. Coastal progradation types of Læsø are shown, each representing a specific type of coastal origin, morphology and landscape

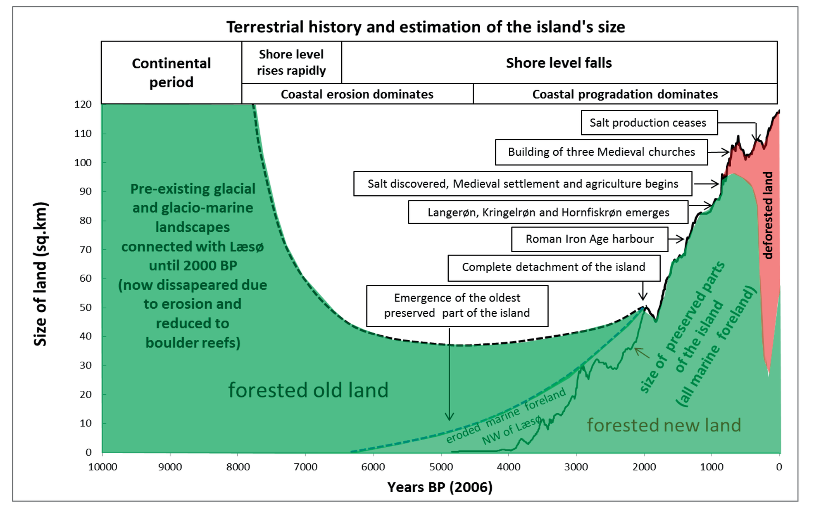

Fig. 3: Diagrammatic illustration of Læsø's terrestrial history and size as well as most important natural and cultural events. During the Boreal continental period the Læsø-region was separated from Jutland and Sweden by large rivers to the W and E, respectively, whereas the region was attached to large landmasses between the two rivers, including Sjælland and other southwestern Baltic regions. During the maximum of the Litorina transgression (at Læsø c. 6.300 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. Colored areas: Estimated size of Læsø (before 2.000 years BP including now eroded xenomorphic and marine forelands mainly NW of preserved parts of the island. Solid line: Size of preserved parts of the island. The diagram indicates that Læsø's size (including attached xenomorphic landscapes) was smallest in the period 6.000 to 3.000 years BP (around 40 sq.km or around 30% of present size), which may explain that no indications of pre-historic peasant cultures (Neolithic peasant Stone Age and all of the Bronze Age) have been found on Læsø. Reworked flint tools and ceramics found on the oldest preserved part of the island belong to a Neolithic fisher and seal-hunter culture, the so-called 'grubekeramiker' culture, which culture occurred during the late Neolithic peasant Stone Age by adaption to the contemporary and fast reduction of coastal landmasses during the Litorina transgression. The attached xenomorphic landscapes were completely eroded to sea level or lower after 2.000 years BP (now only represented by numerous boulder reefs both inside and outside Læsø's present shoreline).

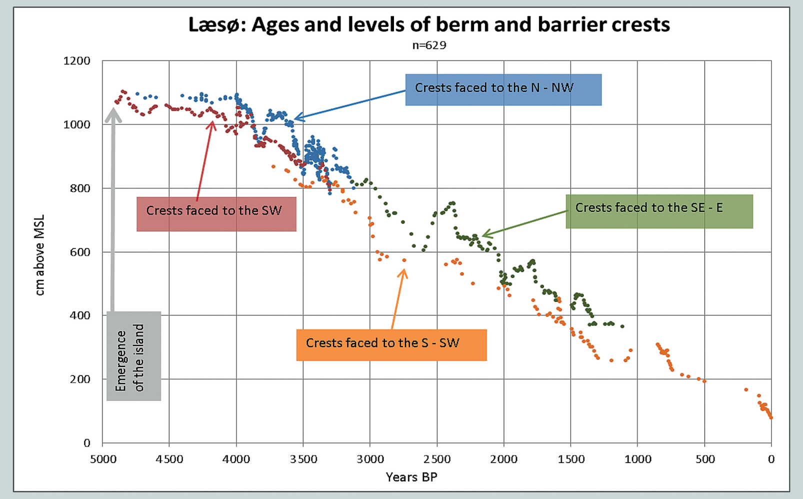

Fig. 4: Levels of raised berms, barrier-spit and barrier island beach-ridge crests measured by the BLRC-method described in the text, plotted against the ridges' age as inferred by the presented age-model of the island. Diagram shows applied measurements from areas without inland or coastal dune fields (i.e. measurements from Højsande and Bløden Hale are excluded). Colors indicate coastal exposure directions corresponding to the regions shown in Fig 3. Notice differences in levels of ridges exposed to the N, E and SE compared to ridges exposed to the SW, W and S. To some extent these level difference are caused by the general isostatic SW-tilting of the region (maximally 0,5 m) and differences in height of the swash (maximally 0,7 m). The remaining level differences is probably caused by local, geological 'background noise' (see Discussions).

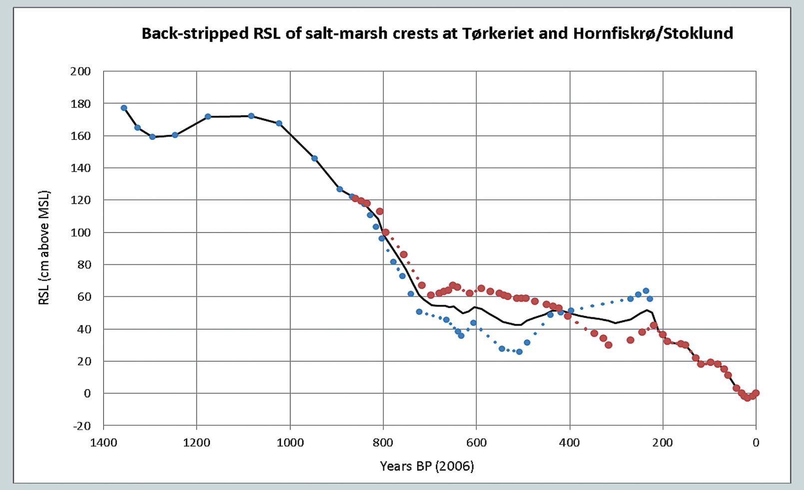

Fig. 5: RSL/age index points of raised salt-marsh crests. Brown circles: Previously published combined index points of Hornfiskrøn, Stoklund and Bangsbo, back-stripped for local geological 'background noise' (Hansen et al. 2012). Blue circles: Result of 381 new BLRC-measurements of raised salt-marsh ridges at Tørkeriet (S-SW Læsø) for comparison with the original test areas (raised salt marshes at Hornfiskrøn and Stoklund/Bangsbo) for identification of local geological 'background noise'. The index points of Tørkeriet have been back-stripped by the method described by Hansen et al. (2012), and the large blue circles show the resulting RSL-index points of 30 crests that can be traced over 2-5 km along Læsø's S-coast. Small blue and brown circles are 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).

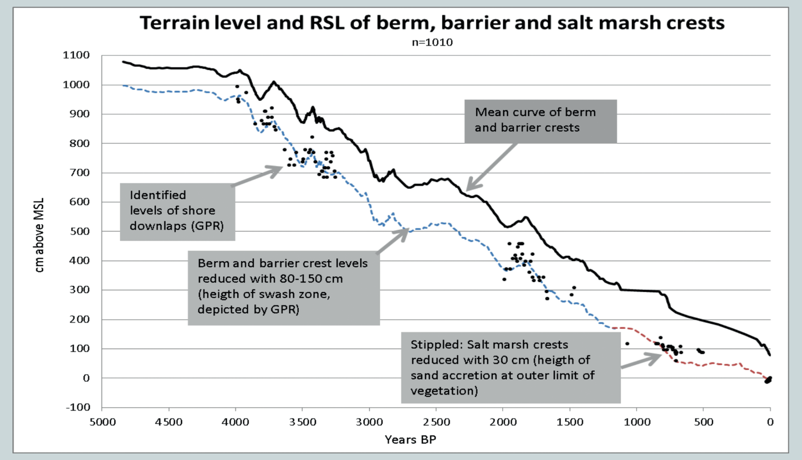

Fig. 6: Solid black line: Mean-level curve of Læsø's raised berm and barrier ridges (cf. Fig. 10). Black dots: RSLs, i.e. levels of downlap structures, determined by GPR-profiling. Dashed blue line: RSL of these SL-proxies detrended for height of swash as found by GPR-profiling and in areas without GPR-profiles by LIDAR terrain analyses (see text for methods). Dashed red line: RSL of Læsø's salt marshes (cf. Fig 8).

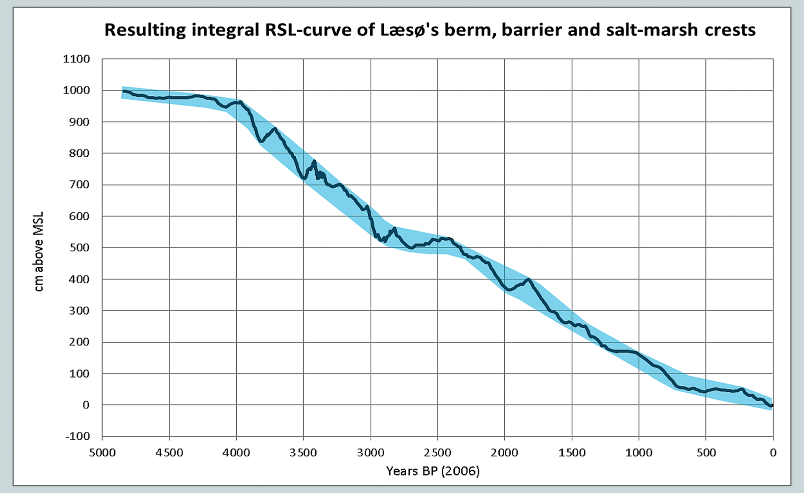

Fig. 7: Resulting integral RSL-curve of Læsø's berm, barrier and salt-marsh crests; i.e. detrended for height of swash and as far as presently possible for geological 'background noise' (cf. Figs 10 and 11). Blue band: Limits of short-term SL-oscillations over periods of mostly 200-300 years duration. Vertical widths of the blue band indicate that SL oscillated 8-9 times within limits of 0,5-1,0 m of the RSL-curve's general trend, e.g. 0,8 m during the LIA-lowstand between 850 to 250 years BP.

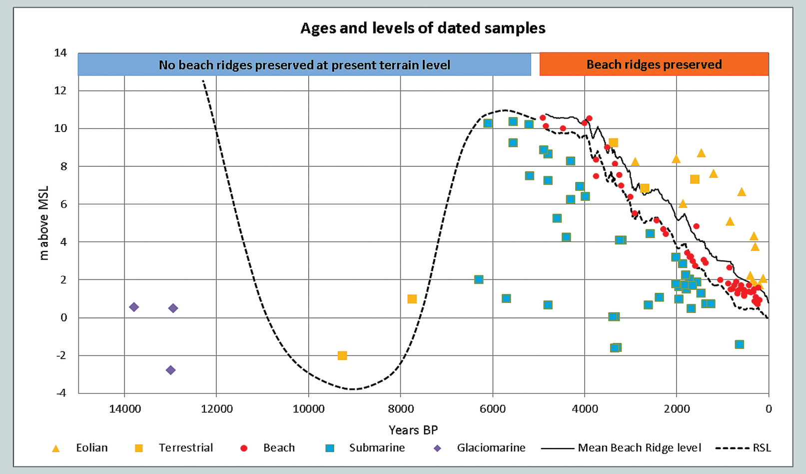

Fig. 8: Level/age diagram of all available absolute age datings (exept two older than scale permits). Results have been sorted according to interpretation of samples´ sedimentary environment. Yellow triangles: Eolian sand (i.e. fine-grained sand above beach deposits). Yellow quadrates: Peat, freshwater gyttja and trunks. Red circles: Beach deposits (i.e. mostly relatively medium to coarse-grained sand with pebbles and stones. Light blue quadrangles: Marine deposits (i.e. fossil shells, teeth of two individuals of sperm whale, or fine-grained sand without pebbles). Dark blue quadrangels: Glacio-marine deposits (i.e. fossil shells of Saxicava arctica). Solid black line: Crest level of the island's beach ridges (see text for reconstruction method). Stippled line below solid line: Reconstructed RSL (se text for transformation of crest levels to RSLs). The other stippled line: Proposed RSL of the late glacial sea, the Boreal regression, and the Litorina transgression until the preserved parts of Læsø emerged (4.900 years BP).

Short-term rates of late Holocene sea-level changes are generally underestimated because SL-proxies of lowstands normally have a much lower preservation potential than SL-proxies of highstands. Consequently, SL-changes of the instrumental period (19th century-present) may erroneously appear more dramatic than of the late Holocene pre-instrumental period, where SL-estimates are mainly based on geologically preserved highstand proxies.

In the studied region velocities of instrumentally observed SL-changes (1849-present) and SL-rise after 1970'ies are clearly within the range of often occurring SL-changes during the last 4000 years.

Jens Morten Hansen
Geological Survey of Denmark and Greenland and Copenhagen University
Contact: JMH@GEUS.DK

A unique environment for SL-studies found

Continuous series of numerous, well separated sea-level proxies from both highstands and lowstands are preserved on an island in the middle of the Kattegat Sea between Denmark and Sweden at the transition between the Baltic Sea and the North Sea. Here, the post-glacial isostatic uplift (GIA) is high (presently 2,32 mm/year) and the diurnal tide amplitude is low (0,2 m).

The island's present terrain (Læsø, 118 km2, Fig. 1) is 100% built of coastal deposits and the the preserved parts of the island emerged c. 4900 years BP. Thereafter around 4000 km of still visible, successive shorelines developed as beach-ridge plains, barrier and lagoon plains, and salt-marsh plains (Figs. 1, 2). Of these 4000 km of palaeo-shorelines more than 60% are situated in never ploughed or urbanized land, thus exposing terrain levels and coastal landforms that have not been altered by human activity.

Due to a high glacial rebound (GIA), low tidal amplitudes and high supply of sediment from pre-existing glacio-marine landscapes (Fig. 3), nearby shoals and abrasion platforms, the raised beach ridges provide a unique setting for preservation of both highstand and lowstand proxies (Figs. 4, 5, 6, 7, 8), whereas lowstand proxies in most other coastal settings have been eroded by subsequent highstands forming laterally stacked highstand berms or complex, indiscriminate beach ridges mainly representing storms and highstands of relatively long periods.

Consequently, the island supplies with both highstand and lowstand proxies showing many short-term SL-oscillations not previously reported from Scandinavia and most other parts of the world. Such combined occurrence of both highstand and lowstand proxies are essential for estimating magnitudes and frequency of relatively short-term (200 - 300 years) sea-level oscillations during the late Holocene, e.g. in order to understand anomalous developments and causes of SL-changes observed during the comparatively much shorter instrumental period.

A continuous 4900-year natural 'tide-gauge' record

By means of a high resolution LIDAR model of the island (z-precision by 1-4 cm for every 3 m2), the levels and exact formation chronology of the island's previous shorelines have been identified with high confidence. By means of 118 absolute datings (14C, OSL and tree-ring datings, Fig. 10) an age model of the island has been constructed (Figs. 8, 9, 10, 11). In a datebase on more than 1200 individual SL/age-relations the shorelines' observed relative chronology has been assigned with measured and interpolate absolute ages (Figs. 4, 5).

By means of ground penetrating radar (GPR) the swash heights of any type of paleo-beach have been identified with good precision (cf. Fig. 6, and Hede et al. 2013). The GPR determinations of swash-heights have been supplemented by comparison of levels of beach-ridge crests and neighboring swales. Thereby the island's constantly rising shorelines may function as a detailed, continuous 4900-year natural 'tide-gauge' record.

Converting relative to absolute ('eustatic') sea levels

As in instrumental tide-gauge records, the island's natural long-term 'tide-gauge' record represents the relative sea level (RSL) of the recorded period. In order to convert RSL-data to absolute sea level (ASL or 'eustatic') data, the vertical geological movements of the 'station' must be known. Fig. 12 summarizes how the more than 1200 measured RSL-levels of the island have been transformed to a detailed absolute sea-level (ASL) curve by compensation for regional isostatic rates: The transformation is based on Påsse and Andersson's (2005) empirical GIA-model of Scandinavia and other types of more local terrain-level changes, which can be depicted from the LiDAR-mapping (Hansen et al. 2012). Fig. 13 shows the obtained 'eustatic' (ASL) curve of the last 4900 years and Fig. 14 summarizes the SL-changes in relation to geological periods of the Holocene as well as the island's settlement and cultural history.

Conclusions:

Calculated as a 200 year running mean of more than 1200 level/age index points the 'eustatic' ASL-curve shows these level changes of the Kattegat Sea:

4900-4000 years BP: ASL rose about 4 m with a velocity of +3.0 to +4.7 mm/year (RSL: -1.0 to +0.1 mm/year), i.e. until the Scandinavian icecap ultimately had melted back to isolated glaciers.

4000 years BP to present: After 4000 years BP the long-term general 'eustatic' sea level (ASL) stabilized around present sea level and began oscillating (seven times) in the interval between -80 cm and +70 cm during the following 4000 years. Three main phases occurred:

- 4000-2700 years BP: ASL oscillated four times between 0 and 80 cm below present MSL with ASL-change rates between -4.0 and +3.0 mm/year (RSL: -6.2 to +0.3 mm/year).
- 2700-1300 years BP: ASL oscillated twice between 0 and 70 cm above MSL with ASL-change rates between -2.2 and +3.7 mm/year (RSL: -4.5 to +1.0 mm/year).
- 1300 years BP to present: ASL oscillated 0 to 80 cm below MSL (Little Ice Age) with SL-change rates between -2.1 and +2.8 mm/year (RSL: -3.4 to +0.8 mm/year).

Present SL-changes: After culmination of the Little Ice Age lowstand c. 700 years BP (at 0.8 m below MSL) ASL has been changing with rates between -0.9 and +2.7 mm/year (RSL: -1.1 to +0.8 mm/year), i.e. rising through the last 700 years with a mean rate of +1.2 mm/year as also observed during the last 160 years in 29 long tide-gauge measurements of the eastern North Sea – central Baltic region (Påsse & Andersson 2005; Hansen et al. 2012; Nielsen et al., in press).

References

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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(9), 1238-1246.

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Absolute »eustatic« sea-level reconstruction

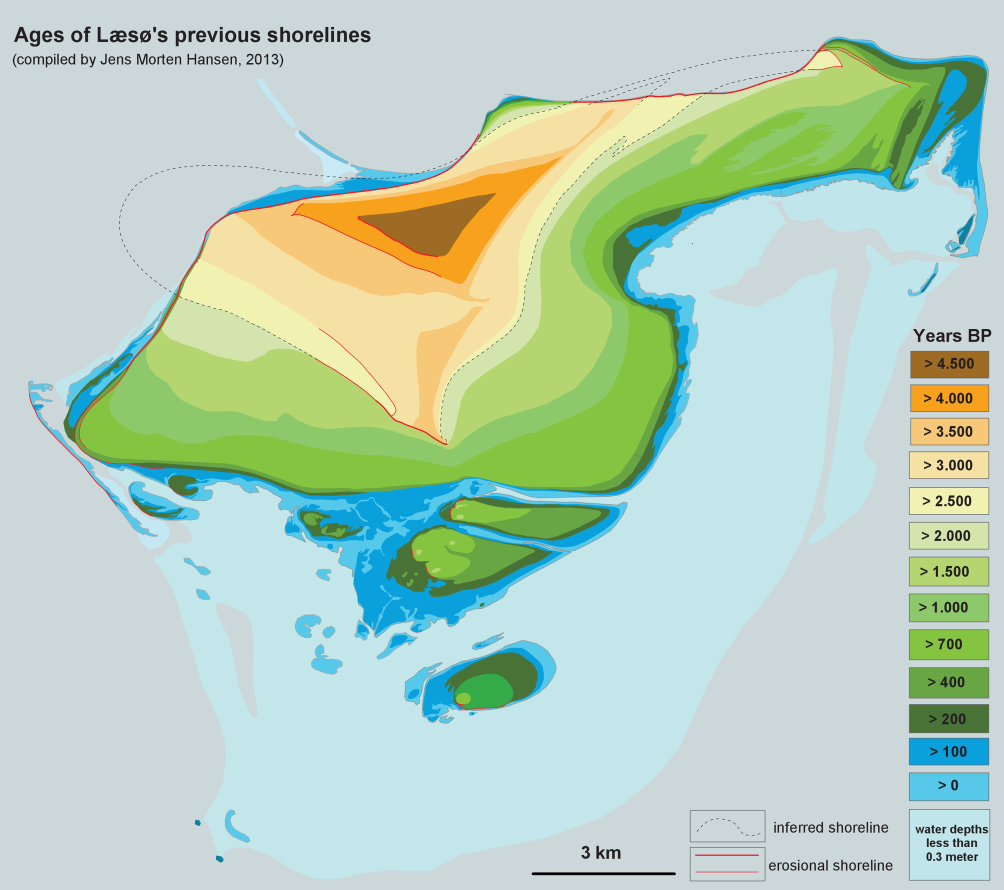

Fig. 9: Age-model of Læsø's previous, still preserved shorelines. See text for detailed description of how the age-model has been constructed.

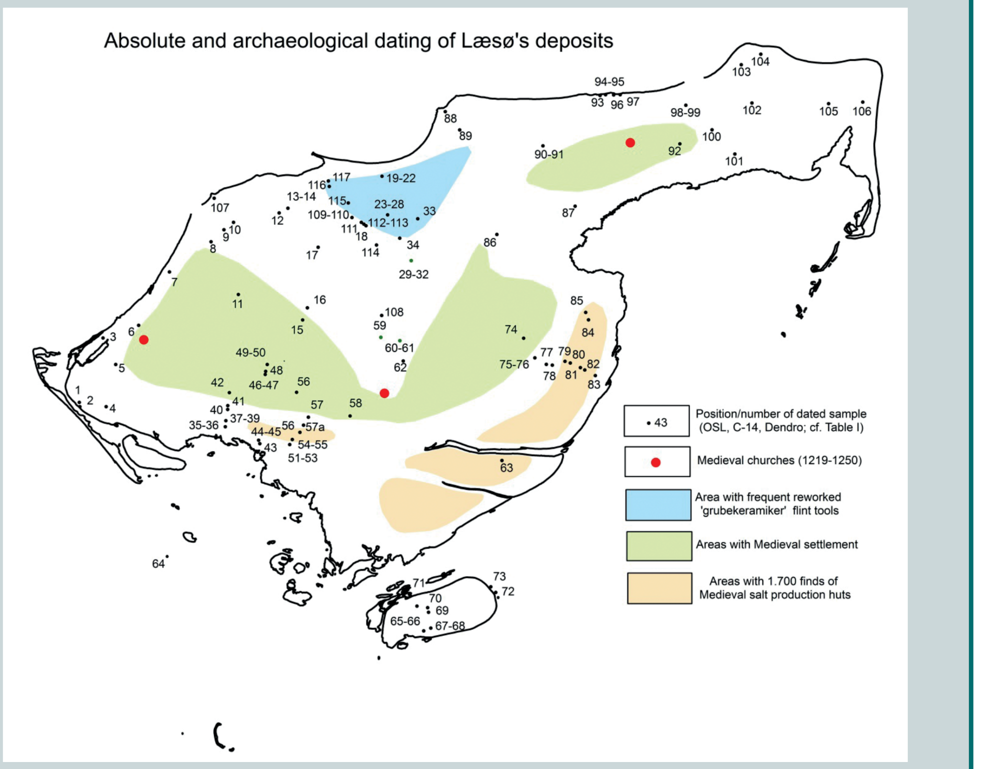

Fig. 10: Positions of absolute age-dated sediment samples and positions of age-related settlements, buildings and industrial land-use.

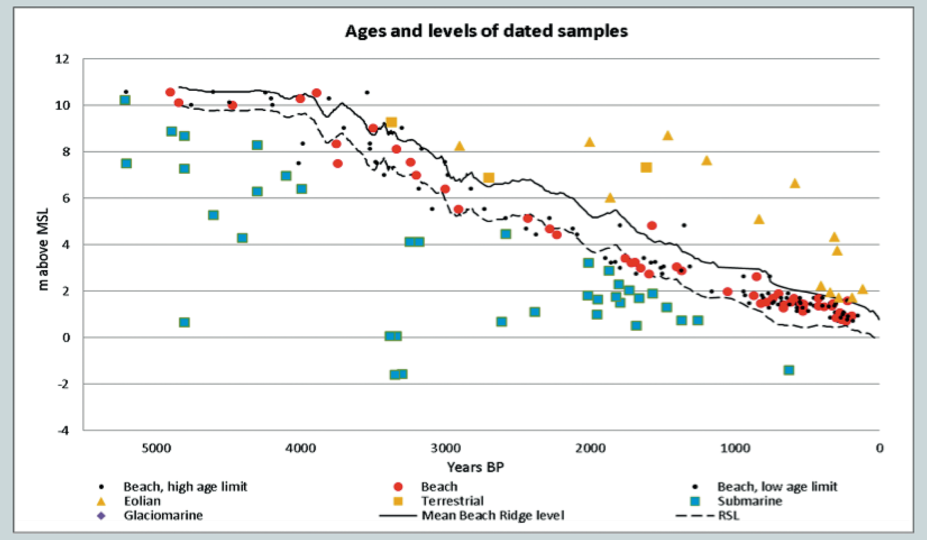

Fig. 11: Fraction of Fig. 8 showing older and younger age-limits of absolute age-dated beach-deposit samples. According to depositional theory, the RSL-curve (stippled) must be below the younger age-limits of dated samples, while the crest-level curve (solid) must be above the older age-limits of dated samples. Similarly, the younger age-limits of marine samples (blue) must be below RSL-curve, while the older age-limits of terrestrial/eolian samples must be above the crest-level curve (cf. Fig 9). These theoretical requirements are actually seen to be fulfilled.

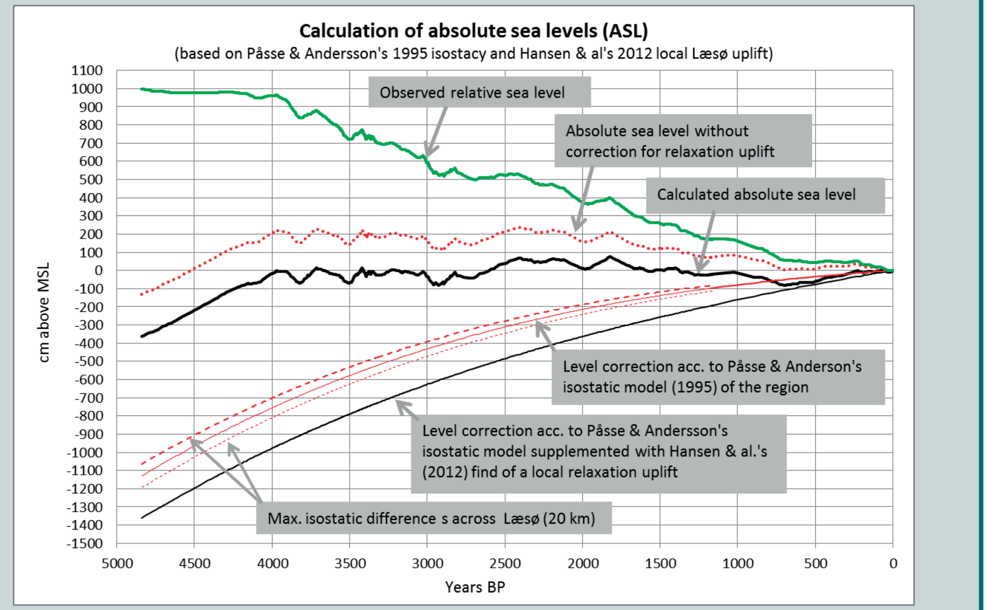

Fig. 12: Transformation of RSL curve to ASL ('eustatic') curve. The RSL curve (green) is subtracted by the sum of Påsse & Anderssons (2005) GIA-curve and Hansen et al.s (2012) curve for local relaxation uplift caused by preceding erosion, resulting in the ASL ('eustatic') curve of the Kattegat Sea (fat black curve).

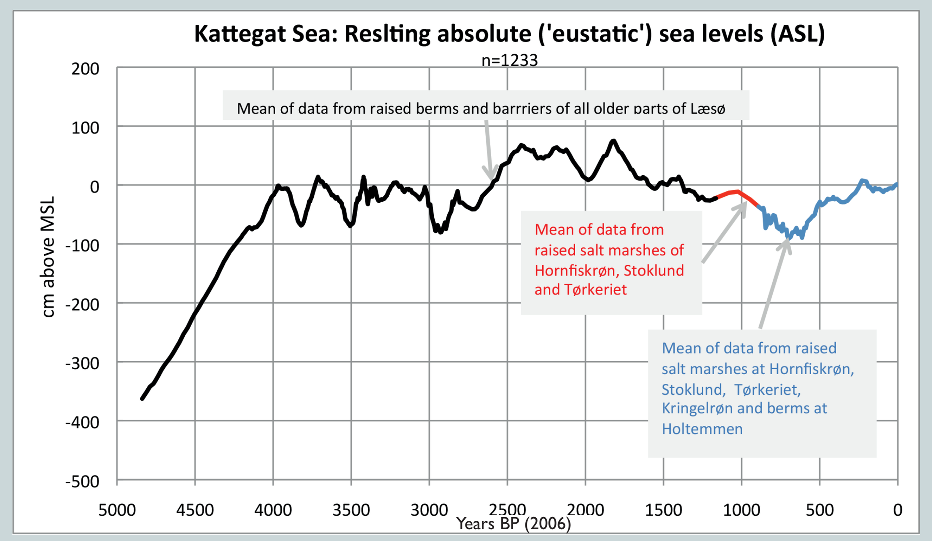

Fig. 13: Resulting absolute ('eustatic') curve of the Kattegat Sea – i.e. the transitional sea between the Baltic and North Seas.

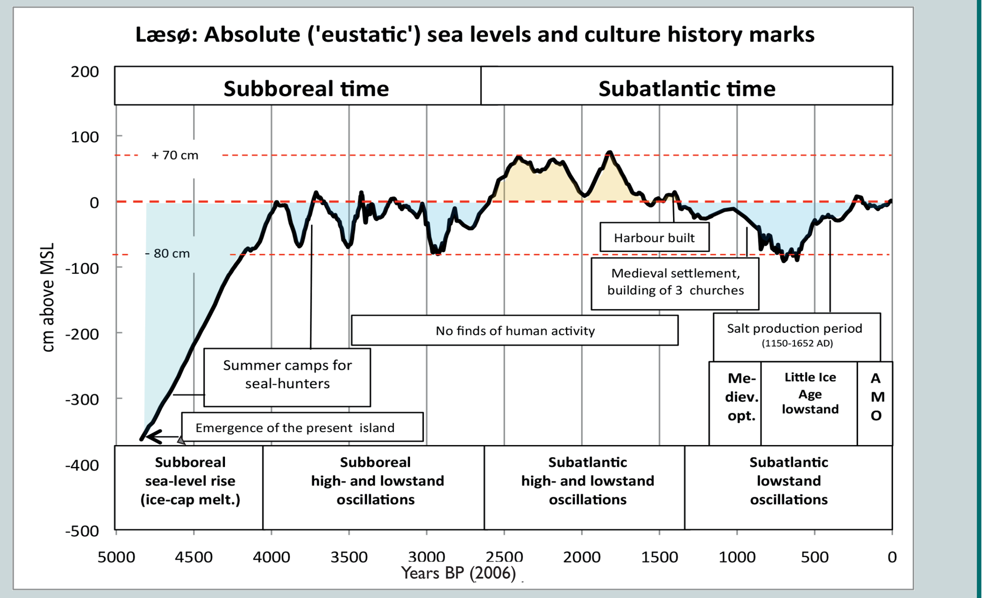

Fig. 14: Resulting ASL ('eustatic') curve and the region's time scale, hydrographic events and some cultural history marks.