

The Kattegat Island of Anholt: Sea-Level Changes and Groundwater Formation on an Island

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Abstract: *Fluctuations in sea level influence the condition of many coastal groundwater aquifers. A rise in sea level can result in seawater intrusion in areas where the groundwater level is near the present sea level, and it may take a long time for the boundary between salt and fresh groundwater to reach equilibrium after a rapid sea level change. In this paper, the present understanding of the palaeo-hydrology of Anholt and its dependence on the past climate and sea level history will be outlined. Anholt has a single unconfined sand aquifer which can easily be modelled. This has proven to be a case in which relatively simple models can describe the processes that take place.*

New data are presented which provide a detailed description of the last 16,000 years of climate and sea level change influence on the forces that have formed the island. This geological history can be used to provide information on the history of groundwater recharge and drainage, and the development of the salt-fresh groundwater interface under a sand island. The fact that the center of Anholt was covered by the sea 6,000 years ago, and consequently the freshwater lens, over 100 m below sea level, did not exist means that the present equilibrium between the saltwater and freshwater lens has been established in less than 6,000 years. These results can be used to give guidelines for the future administration of the groundwater resources on Anholt, but hopefully they can also help us understand the dynamics of more complicated coastal groundwater aquifers as on Zealand.

Key words: *History of groundwater recharge and drainage, climate change, sea-level change, detailed mapping, G@GPS.*

1. Introduction

This paper outlines the current understanding of the palaeo-hydrology of Anholt and its dependence on the past climate and sea level history. Anholt has proven to be a case in which relatively simple models can describe the processes that take place. Originally, the author tested the Ghyben-Herzberg law (Herzberg 1901) on the island using resistivity measurements (Schröder 1970, 1974, 1975) and found precise agreement with the law. Later the

author (Schröder and Øbro 1976) modeled the groundwater flow. The development in the groundwater table since 1973 has been in accordance with the result of the modeling.

Here, new data based on new high resolution maps and fieldwork in connection with field courses on the island (Schröder 1990), provide a detailed description of the last 16,000 years of climate and sea

level change influence the forces that have formed the island. This geological history can then be used to provide information concerning the history of groundwater recharge and drainage, and the development of the salt-fresh groundwater interface under a sand island.

Civilizations have for millennia depended on the stability of groundwater resources to survive dry or unreliable climates. While groundwater supplies are buffered against short-term effects of climate variability, they can be impacted over a longer time through climate and sea-level changes. The recharge history of a given groundwater resource is then vital for forecasting its vulnerability under future changes in the climate. Fluctuations in sea level may influence the condition of many groundwater aquifers. A rise in sea level can result in seawater intrusion in areas where the groundwater level is near the present sea level, and it may take a long time for the boundary between salt and fresh groundwater to reach an equilibrium after a rapid sea level change.

Several studies (reviewed by Essink 2001) have focused on factors influencing the behavior of the salt–fresh transition zone in coastal aquifers, including changes in the thickness and the position of the transition zone following changes in sea-level. Major



Figure 1. The island Anholt is located in the center of the red circle. Also shown is the area on the island Zealand where pilot studies on the Danian main aquifer and Quaternary palaeo-hydrological structures has been carried out (Schröder and Thorn 2015).

changes in sea level have occurred repeatedly in the past and have led to dramatic effects on groundwater discharge. Along some coasts, the groundwater system still has not reached equilibrium after the Late Pleistocene and Holocene sea-level fluctuations, as, for example, has been seen in Zealand (Schröder and Thorn 2015). Numerical modeling of groundwater flow systems can be used to calculate this relation if the local sea-level curve is known. It may also be used to estimate in which way groundwater systems adjust to a future sea-level rise.

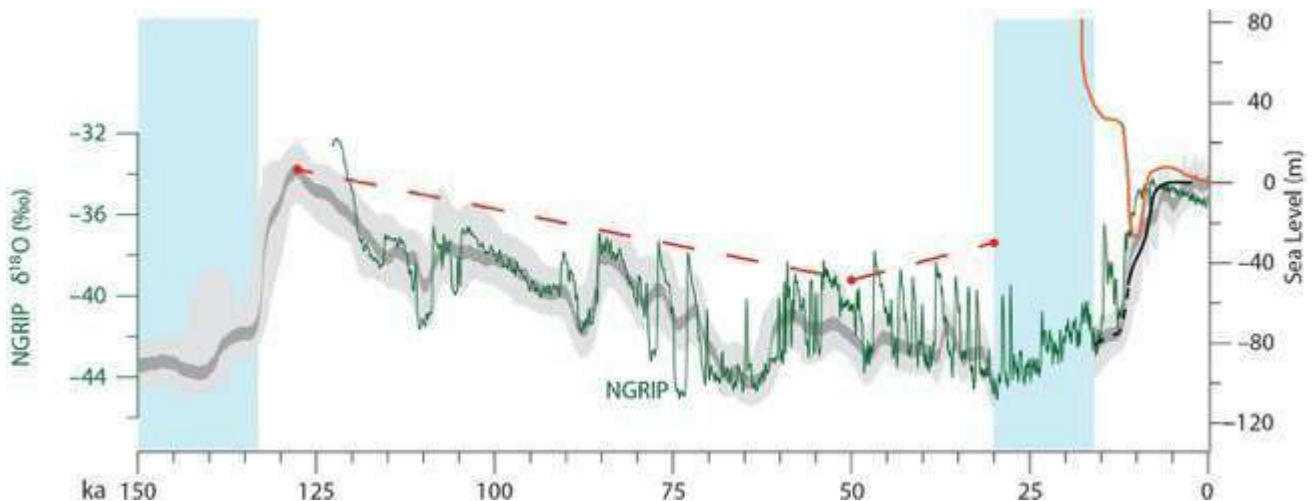


Figure 2. Sea-level history and climate change: The sea level curves of Anholt (and Kattegat) is compared with the sea-level curve from the Red Sea and the temperature signal from North Greenland (from Grant et al. 2012), probably the best palaeo-climate signals at present. Sea-level (erosion base level) in Kattegat - Anholt (red) and the probabilistic assessment of sea-level history from the Red Sea - confidence interval of 95% (light gray) and probability maximum (dark grey). The green curve represents changes in the oxygen isotopes in the ice core from North Greenland (NGRIP). Light blue areas show the periods when Anholt was covered by ice.

The G@GPS (Groundwater @ Global Palaeoclimate Signals) initiative (www.gw-gps.com) has already presented the Holocene dynamics of the salt-fresh groundwater interface under a sand island, Inhaca, Mozambique (Været *et al.* 2012). Two islands on the border of the former Scandinavian ice cap, Anholt and Zealand (see figure 1), are now included in the G@GPS palaeo-groundwater studies as they both contain a coastal aquifers system with a “palaeo-signal” potential which can be used to identify the impact of sea-level fluctuations associated with glacial transgressions and regressions in the past. In figure 2 the sea level curves of Anholt and Zealand are compared with the sea-level curve from the Red Sea (Grant *et al.* 2012) and the temperature signal from North Greenland (NGRIP members 2004), probably the best palaeo-climate signals presently available.

However the islands’ aquifers are very different. Anholt consists of a single unconfined sand aquifer which can easily be modelled, where the equilibrium was reached after a few thousand years, whereas in Zealand’s case the Danian limestone, which forms the primary aquifer, is covered by clayey tills and often also Paleocene low permeable marls. Here, the equilibrium has still not been reached after a period with very low sea levels 50,000 years ago.

2. The Hydrogeology of Anholt

The geology of Anholt is relatively well documented (see geological map of Anholt shown in Figure 3). The surface geology was already mapped by the Geological Survey of Denmark in the late 19th century (Jessen, 1897). The western glacial highland borders the Holocene beach-ridge plain with a pronounced N-S cliff. The greater part of the island (“the Dessert”) consists of raised beaches showing the positions of former coastlines.

Wells and eustatic-isostatic considerations show that the postglacial beach formation is around 30 m thick and homogeneous. In fact when new wells for the water supply of the Island were drilled in 1974, they were planned to go down to 30 m as, based on the eustatic-isostatic work of N-A Mörner (1969), it was expected that the coastal sand and gravel formation would be around 30 m thick. This was then proven by the fossil content (GEUS well nr.51.33 and 51.34, analyzed by K.S.Petersen (1974)).

The average precipitation at Anholt is about 550 mm/year. Due to the very high permeability of the soil, virtually all the precipitation infiltrates the soil and is used either by the vegetation or recharges the ground water reservoir. Consequently the surface runoff is negligible. The evapotranspiration of

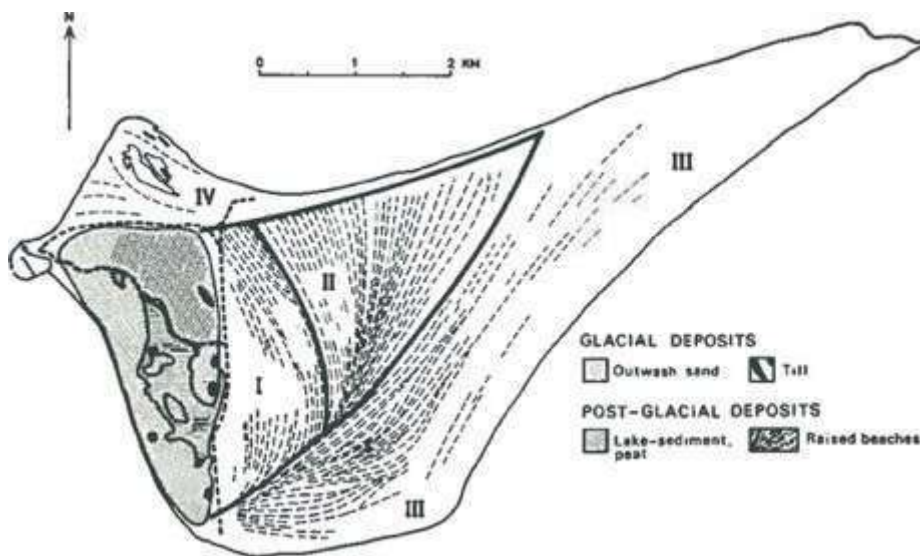


Figure 3. Geological map of Anholt showing the formations at the base of the Aeolian sands. The postglacial raised beaches are divided into four groups (I-IV) according to age. The dotted lines indicate roads. The raised beaches were in 1973 drawn based on air photos (from Schröder 1974).

Anholt is estimated to about 250 mm/year in the eastern, sparsely vegetated part of the island and about 350 mm/year in the western part, where the vegetation is denser. The average recharge of the ground water reservoir has therefore been estimated at 300 mm/year in the eastern part and 200 mm/year in the western part. The recharge is balanced by ground water flow to the sea, as evidenced by the map in figure 4.

The position of the boundary between fresh and salt water (defined as the level where the concentration of chloride is 300 mg/l) has been determined by resistivity soundings (Schröder 1970), a method that is still among the best for hydrogeological mapping (Schröder 2014). The result is shown in Figure 7 which indicates that the thickness of the freshwater body below sea level is approximately 30 times that above sea level, verifying the Ghyben-Herzberg Law. Normally, the interpretation of measurements is based on the assumption that the subsurface consists of two or three layers which are electrically isotropic and homogeneous. This assumption, however, is often too simple as in nature there is a continuous change in the electrical resistivity.

The Ghyben-Herzberg law was originally formulated in relation to the transition zone between fresh and saline groundwater being only a small

percentage of the thickness of the saturated freshwater body; based on their studies of the dynamics of the boundary between fresh and salt water, Underwood et al. (1992), at atoll islands, and Urish and McKenna (2004), at Cape Cod, concluded that the position of the salt/fresh interface is not very sensitive to tidal movement. But both studies found tidal movement to be decisive for the mixing process in the transition zone. However, as we know from the dispersion theory, the curve showing salinity as a function of depth will have the form of the error function, and it would be useful to approximate this continuous change as closely as possible. Therefore a set of master-curves was computed (Schröder 1970) see figure 6, making an interpretation of the variation of the chloride content possible, if the salinity distribution in the underground can be assumed to be described by the dispersion theory.

In 1972-4 a hydrogeological survey (Schröder 1974, 1975, Schröder and Øbro 1976) was undertaken on Anholt. The aims of the survey were to find the best location of ground water wells necessary for a future development of a summer house area on the island and to investigate the possibility of salt water intrusion. The survey consisted of approximately 60 resistivity soundings, systematic ground water level observations during a year and testing 2 new water supply wells in the middle of the Island.

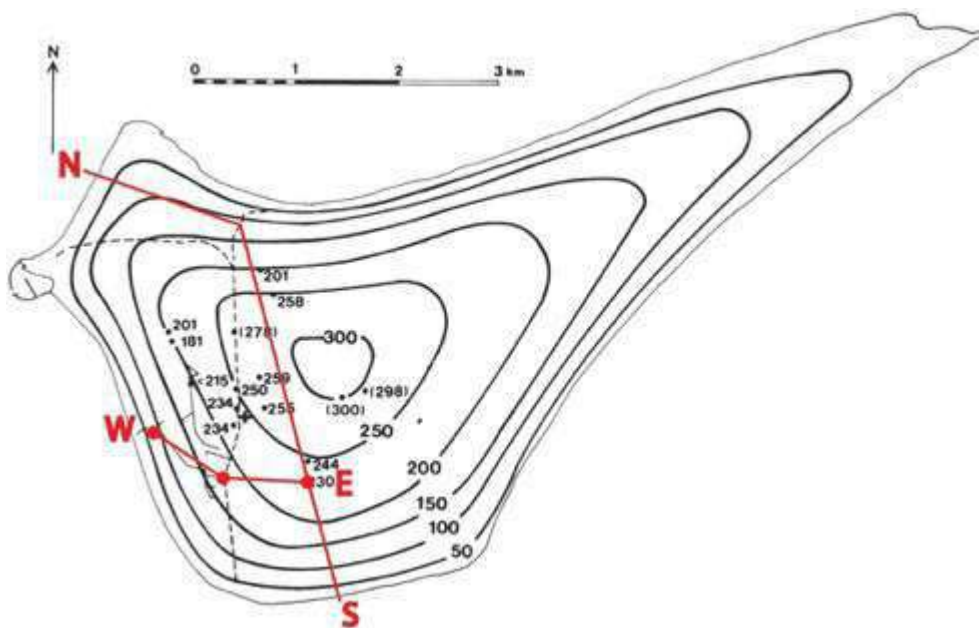


Figure 4. Observed ground water level in cm above median sea level. The E-W profile relates to the measurements in figure 5 and the N-S profile to figure 7 and 8 (modified from Schröder and Øbro 1976).

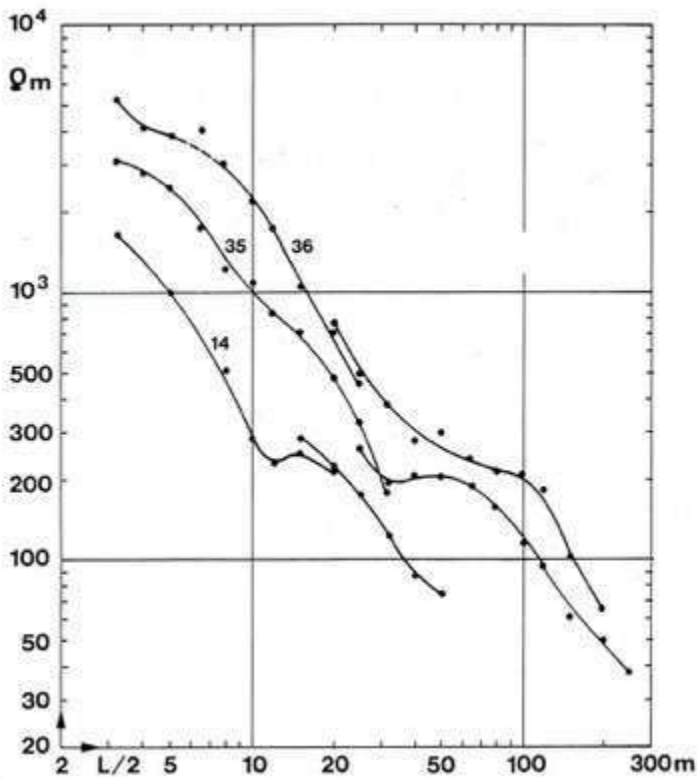


Figure 5. Three typical resistivity soundings: nr. 14, 35 and 36 from the coast to the middle of the island - for location see figure 4. The soundings represent 1: the top sand over the groundwater table with resistivities of more than 1,000 ohm-m, then 2: sand with freshwater with resistivities around 200 ohm-m and finally 3: sand with saltwater with resistivities decreasing with depth (from Schröder 1974)

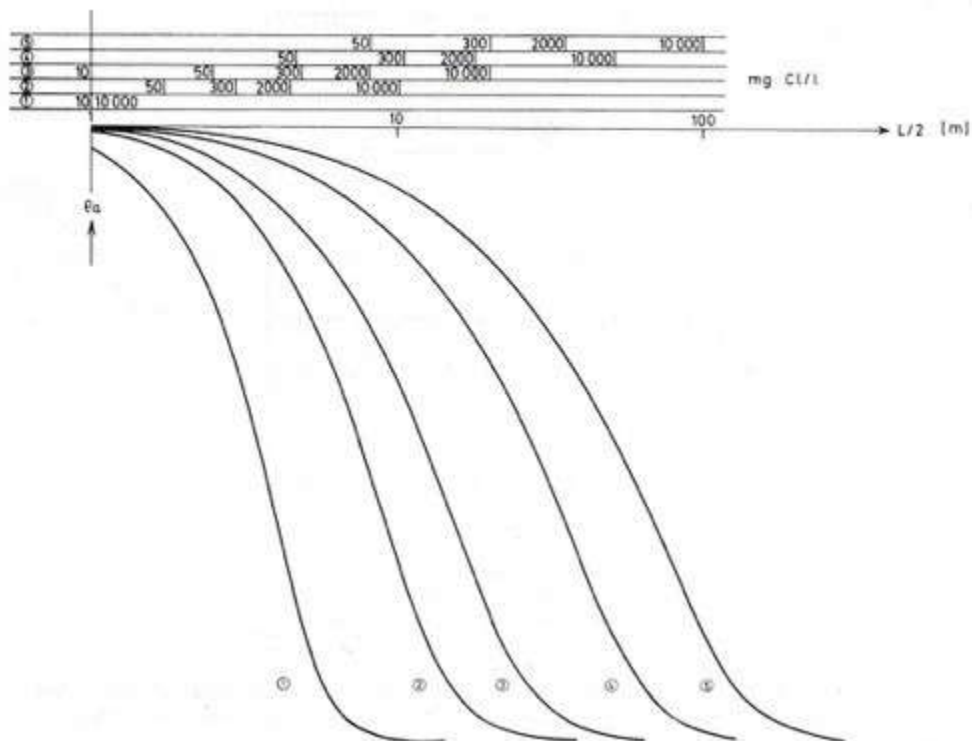


Figure 6. As we from the dispersion theory know that the curve showing the salinity as a function of depth will have the form of the error function, it is useful to approximate this continuous change as closely as possible. Therefore a set of master-curves is computed, which makes an interpretation of the variation of the chloride content possible, if the salinity distribution in the underground can be assumed to be described by the dispersion theory (Schröder 1970).

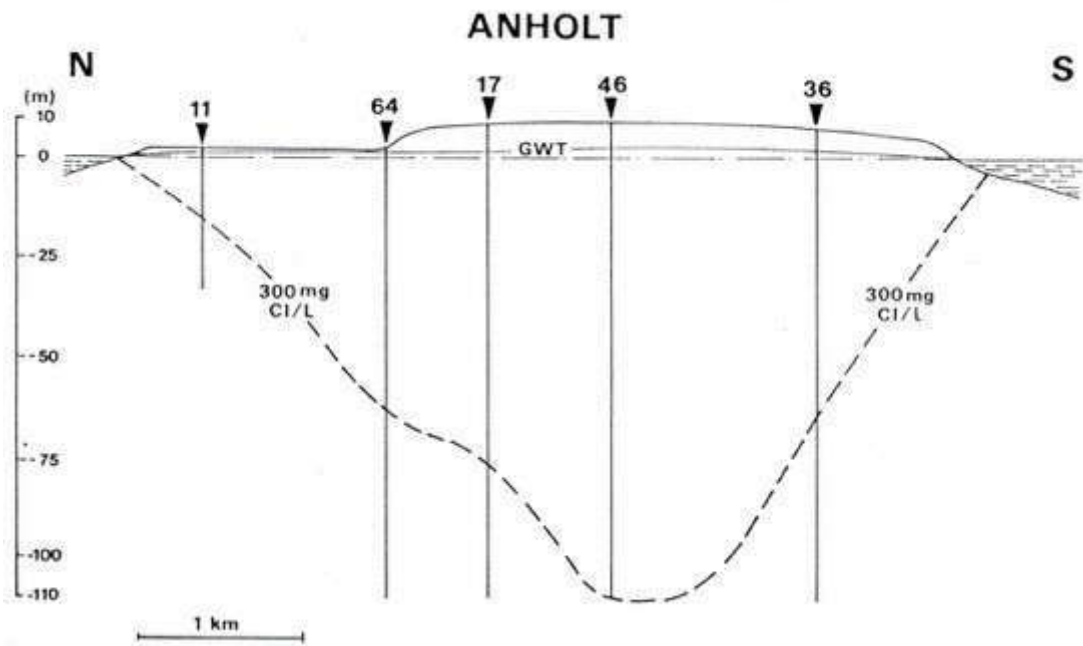


Figure 7. Cross-section through the island - for location see figure 4 - showing the position of the boundary of salt and fresh ground water (defined as the boundary level where the concentration of chloride is 300 mg/l) mapped by resistivity soundings.

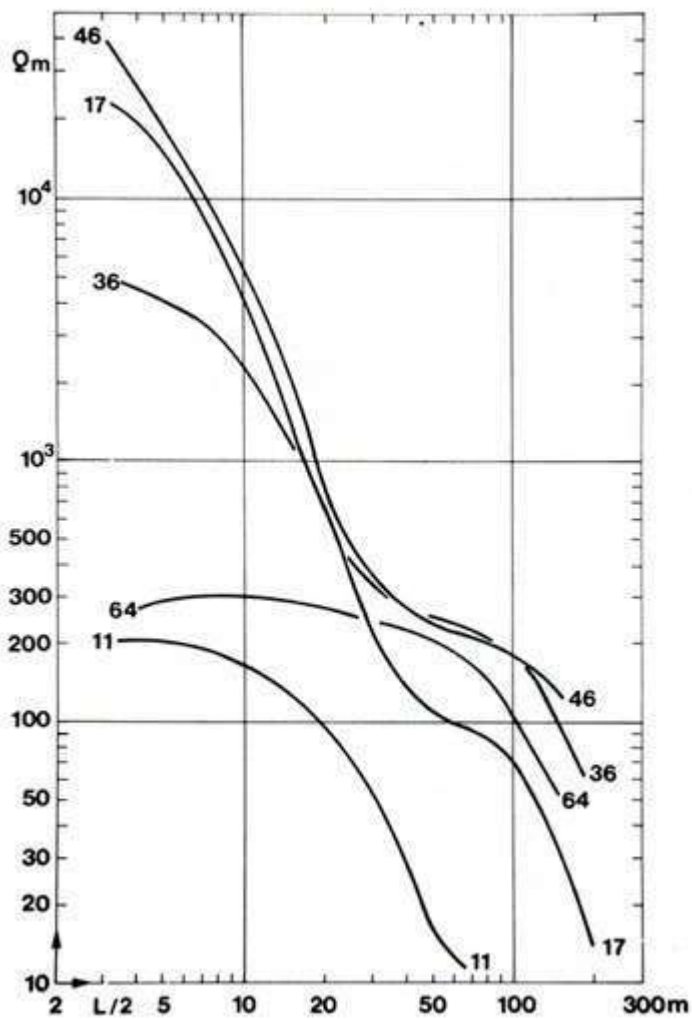


Figure 8. The soundings used for the N-S profile in figure 7.

As the maximum future ground water withdrawal was expected to be 200,000 m³/year and the recharge approx. 6 mill. m³, the problems of salt water intrusion should only be expected as withdrawal would go on mainly during the summer period and the recharge would take place during the winter months.

When the survey was completed, the municipality wanted to evaluate the feasibility of establishing a sewage system for the development areas based on septic systems instead of an expensive piped sewage system including a treatment plant etc. In order to

make sure that no effluent would flow from the septic tanks to the wells, even under extreme conditions (for instance several years of drought); a groundwater model (based on pumping tests) was developed (figure 9). The model made it quantitatively possible to appraise the response of the aquifer to pumping, drought and seeping sewage. It was used to investigate if the ground water at the planned well field might be polluted by effluent from the septic fields. Even if the model was an approximation of the real aquifer conditions, it was proved successful; the development since 1973 has been in accordance with the model.

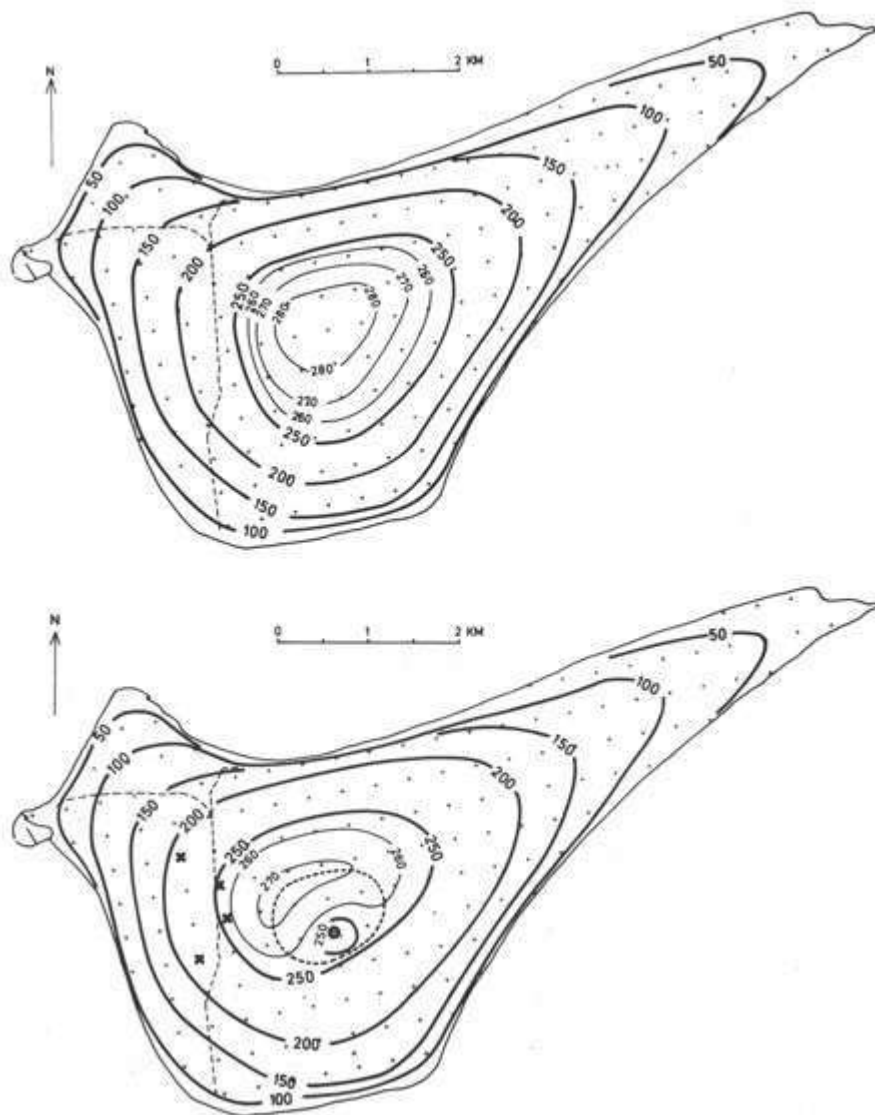


Figure 9. Computed steady-state water level in cm above sea-level.

Top: After calibration of the model.

Below: Under the assumption of withdrawal of 200,000 m³/year, from wells located in the central part of the island (indicated by a dot), while 175,000 m³/year is assumed to seep to the ground water from cesspools in the development areas (indicated by crosses). The dotted line around the wells indicates the ground water divide (from Schröder and Øbro 1976).

3. Climate and Sea-Level History

3.1 Models

When Axel Jessen (1897) published the geological map of Anholt, he was intrigued (p.33) by the fact that oldest coastlines closest to the western glacial landscape were lower (around 6 m) than the coastlines in the central part of the “Dessert” (around 9 m). As he saw the land-rise and not the sea-level rise as the dominant agent, he postulated that the coastlines close to the western highlands originally had been the highest, but that the wind had blown the material to the east. Axel Jessen did not include the general sea-level rise in his assessment.

The understanding that there had been a general sea-level rise, as well as a tilted Scandinavian uplift, was however already known to Danish geologists since the middle of the 19th century (Forchhammer 1849) - see endnote for the wording by Forchhammer.

The sea-level movements in the Kattegat area in the last 16,000 years (figure 10-12), are relatively well known and seem to be largely determined by 5 factors:

1. The climatically induced global eustatic change in ocean water volume due to accumulation/melting of ice on land.
2. The local glacio-isostatic adjustment of the lithosphere in reaction to the mass redistribution associated with changing ice volumes. (Isostatic relaxation of the Earth's surface in response to the melting of the ice sheets occurs at a rate that is governed by the mechanical properties of the Earth, in particular mantle viscosity and lithosphere thickness.)
3. Local-scale processes, such as deposition of thick layers of meltwater-sediments, can additionally influence the local sea level.
4. Global adjustment of the geoid due to global mass redistribution, associated with changing ice, water and sediment volumes.
5. Deep tectonic movements of the crust.

Eustatic curves (graphs showing the global sea-level versus time) have been calculated from various areas in the world. In the Kattegat area, N-A Mörner (1969) succeed in separating the glacio-isostatic component and the eustatic component of the sea-level change, and in this way generated a global Eustatic curve based on data from tilted shorelines.

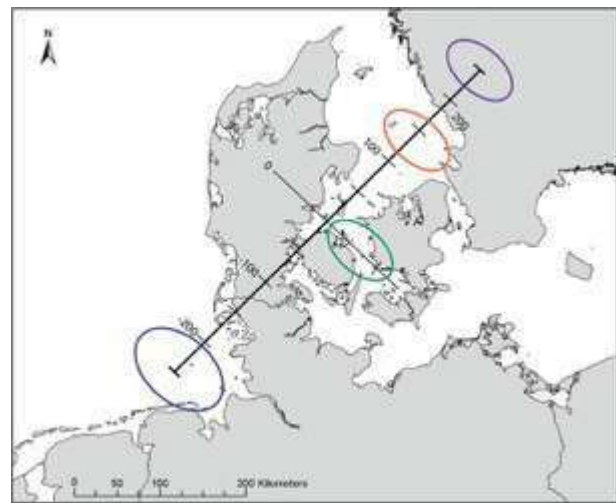


Figure 10. The thick black line indicates a profile in the direction of tilting. The colored ellipses show the areas from where the sealevel data has been collected in order to construct the diagrams in figure 11-12. The four areas are: Southern North Sea (blue), the Great Belt area (green), the Anholt area (red) and the Viskan Valley (purple).

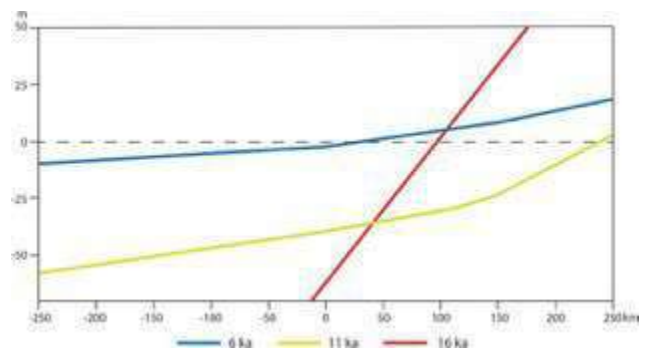


Figure 11. The lines show the tilting of the coastline (sea level) along the profile shown in figure 10: at 16 ka, 11 ka and 6 ka BP. Note that the tilted coastlines are linear over long distances

Such curves are normally obtained from so-called stable areas at long distances from the former glaciated areas.

These curves, from different places around the world, show the same general trend of a sea-level rise of about 100 m over the last 20,000 years. However, these curves differ in their details. Figure 13 illustrates this difference, where it can be seen that, though the sea-level rise is a global phenomenon, the rates and timing of which the sea-level rise takes place varies locally. In addition, one peculiarity is that about 8,000 years ago, all the curves cross each other (Mörner 1971). Note: ages in this paper will

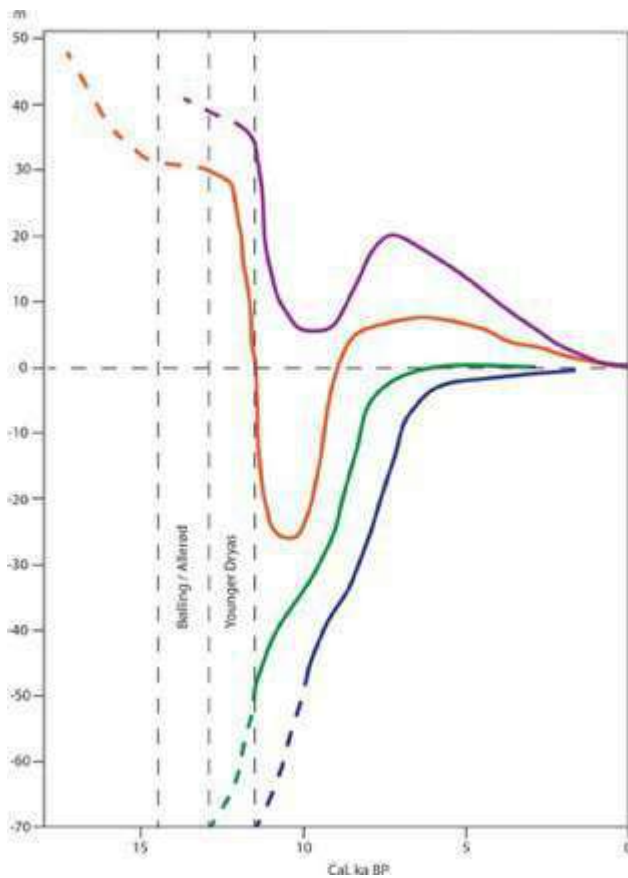


Figure 12. The curves show the sea level (coastline) history (relative to the present sea-level) of the 4 areas in figure 10, indicated with the same colors. Data for the curves: Southern North Sea: (Kiden et al. 2002, Vinka et al. 2007), The Great Belt area: (Mertz 1985, Krog1973, 1979, Christensen et al 1997, Bennike et al. 2004). The Viskan Valley: (Mörner, 1969). The Anholt area: see text.

subsequently be given in ka BP (thousands of years before present) in calibrated years (after Stuiver et al. 1998).

The feature seen in figure 13 may partly be explained by a mechanism, geoidal-deformation (Jensen 1972), an often overlooked effect of de-glaciation. When the ice melts, the change in the shape of the geoid is immediately followed up by the ocean-surface, while the yielding of the sea floor happens with a certain delay. This means that eustatic curves determined from different “stable” areas do not necessarily coincide. The parameters commanding the mechanism are not very well known. However, when a mass (the ice) is removed from a point of the surface of the Earth and a similar mass (the water) is spread over the surface, it is possible to calculate the change in the surface gravity at a certain spheri-

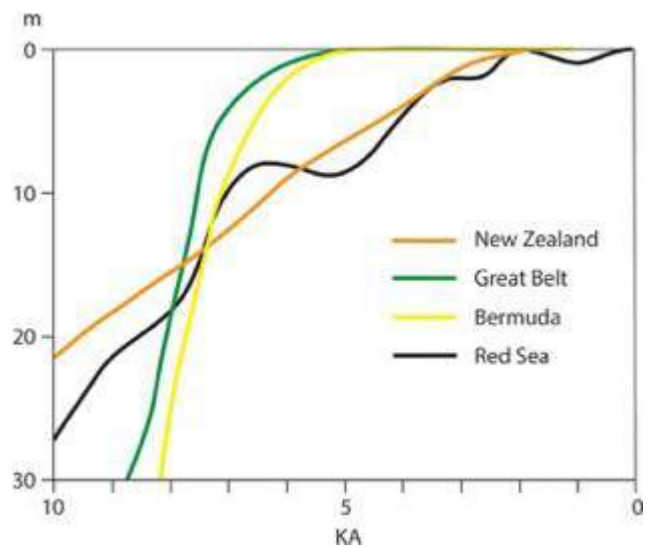


Figure 13. Sea-level history the Red Sea (Grant et al. 2012), Great Belt (Christensen et al 1997), New Zealand (Suggate 1968) and Bermuda (Newmann1969). Note that curves from New Zealand and Bermuda show a much better coincidence about 8000 years age, than before or after. The calculations carried out for Bermuda and New Zealand (Jensen 1972) – show that the difference between the eustatic curves from the two areas can partly be explained by geoidal deformation.

cal distance. Calculations carried out for Bermuda and New Zealand by the use of Stokes’s formula (Jensen 1972) – show that the difference between the eustatic curves from the two areas can (partly) be explained by this described effect. The concepts of geoidal change and geoidal-eustasy which came to change the understanding of sea level change were then developed by N-A Mörner (1976).

Local-scale processes such as deposition of thick layers of meltwater-sediments can also influence the local sea level. Amantov et al. (2011) investigated glacial erosion/sedimentation of the Baltic region and the effect on the postglacial uplift, and found that Weichselian erosion and sedimentation impact postglacial uplift. It was estimated that, in the last glacial cycle, sedimentation could result in up to 155 m of subsidence, and erosion result in as much as 32 m of uplift.

The local glacio-isostatic adjustment has not always been smooth. Especially during the late glacial melting period the adjustment has taken place as major earthquakes by reactivation of old faults (Arvidsson 1996, Jensen et al. 2002, Mörner 2008). Discussion still continues on the relative contribution on the

present uplift of Scandinavia. The question is, if it mostly is related to glacio-isostatic adjustment, or if it mostly is related to deep tectonic forces.

3.2 Regional Data

Numerous studies of Holocene sea-level change in northwest Europe have been carried out in the past century. In southern Scandinavia there are many possibilities to define sea-level changes with high accuracy as we here find many lake basins with thresholds, where marine sediments were deposited in the basin, when the sea-level reached the threshold (Christensen et al. 1997, Iversen 1973, Krog 1973, 1979, Mörner 1969, 1980, von Post 1938, 1968).

At present the late and postglacial coastlines are well determined at 4 localities perpendicular to the axis of tilting from the southern North Sea over the Great Belt and the Anholt area to the Viskan Valley in western Sweden - see figure 10-12.

Southern North Sea

Results of comparative data analysis and geophysical modeling of Holocene glacio- and hydro-isostatic crustal movements in the southern North Sea sector (Kiden et al., 2002) show that post-glacial isostatic lowering of the crust has occurred in this area. The area is close enough to the Fennoscandian ice sheet to be affected by it, whereas the glacio-isostatic effects from other ice sheets such as the Laurentide or British ice sheets can be assumed to be near to negligible.

Kiden et al. (2002) interprets the isostatic subsidence of the crust as the last phase of the collapse of a peripheral glacial forebulge around the Fennoscandian ice sheet, which was previously proposed based on models by Mörner (1980), Fjeldskaar (1994) and Lambeck et al. (1998).

Unfortunately, up to now it has not been possible to establish detailed patterns of crustal movements within the forebulge subsidence zone; especially the maximum subsidence has been difficult, due to the general scarcity of reliable sea-level data older than 8 ka BP, from the southern North Sea region. This is exactly the area and time in which the forebulge subsidence is assumed to have been greatest.

Vinka et al. (2007) included additional samples from the northwest German sector and the southern North Sea. These data show a subsidence compo-

nent, which is small on the Belgian coastal plain but increases significantly towards the northeast. Northwest Germany, for example, has been subjected to a total isostatic lowering relative to Belgium of ca 7.5m between 8 and 4.8 ka BP. These results provide new evidence from the German coastal and North Sea sectors for the post-glacial collapse of the peripheral forebulge which developed around the Fennoscandian center of ice loading during the Weichsel.

The Great Belt Area

Geological/archaeological investigations prior to the building of the Great Belt Bridge have given many data on the former sea level in the area, especially from the last 8,000 years (Mertz 1985, Krog 1973, 1979, Christensen et al. 1997). However geophysical mapping has also shown that the Great Belt area was eroded by rivers running to a late glacial Kattegat sea with a sea level below -60 m, (Bennike et al. 2004) – see figure 22 and profile (J-K) in figure 19. In figure 2 it is seen that the sea-level curve from the Great Belt area is very similar to the general eustatic curve from the Red Sea, a consequence of being at the border of the sinking forebulge and the rising Scandinavia.

The Viskan Valley

The Swedish West Coast and the Viskan Valley were studied intensively by Lennart von Post in the 1930's (von Post 1938, 1968) and by Mörner in the 1960's (Mörner, 1969). Due to the high isostatic uplift, detailed analysis of the isostatic and eustatic interaction could be studied on land. So it was possible to separate the isostatic and eustatic components.

3.3 Anholt Data

The Raised Beaches

The sea level in the Anholt area has been dated by ¹⁴C by Mörner (1969, 2008), mainly at the Bjäre peninsula having the same isostatic history as Anholt in the Postglacial - see figure 20, and by OSL measurements on samples from Anholt by the Nordic Laboratory for Luminescence Dating (Bjørnsen et al. 2008, Clemmensen et al. 2012). In OSL (Optically Stimulated Luminescence dating), the amount of energy absorbed by a mineral since it last was exposed to daylight is used as a chronometer.

Axel Schou (1945) studied the beach-forming forces, and used Anholt as an example. Here it was determined that the waves are the predominant force. The

factors on which the wave-power depends are the velocity, the direction and the duration of the wind and the fetch. Schou's direction-resultant showed, in spite of its simple construction, to be very useful. It was determined that the linear form of a coast it not affected by erosion, because the regression will be uniform in the total length of the coast. If it is a short coast-line, the coast-line is often orientated at a right angle to the resultant of all wave work.

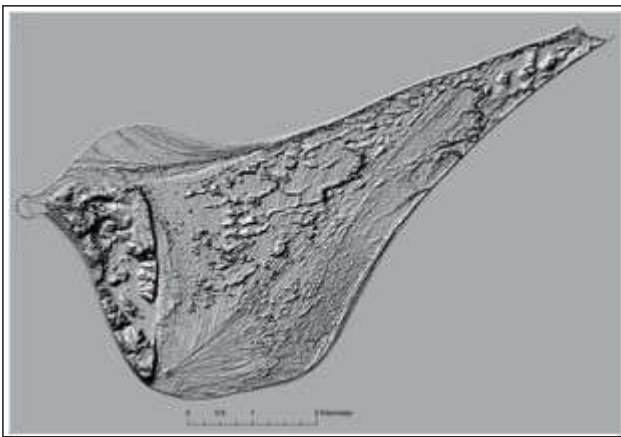


Figure 14. Shadow map of Anholt based on detailed radar mapping of the topography (accuracy <math><0,2\text{m}</math>) from www.kortforsyningen.dk (2014). Detailed maps as this based on airborne laser scanning, show clearly the high-lying glacial landscape to the west and the beach-ridge plain to the east. Despite the cover of Aeolian deposits the beach ridge and swale topography is easily recognized, better than on air photos as in figure 3.

This study has analysed the detailed topographical maps based on airborne laser scanning. As seen in figure 14-15, the high-lying glacial landscape is clearly seen in the west and to the east, despite the cover of Aeolian deposits, the beach ridge and swale topography are easily recognized. As beach-ridges under stormy conditions could be formed up to 2m above sea level, the swale elevation is used in the reconstructions as a measure for past sea levels. By drawing topographical curves below a maximum value, it has been possible to reconstruct the swale and coastline of Anholt, corresponding to the different sea levels (figure 17).

Figure 16 shows details in the reconstruction process (curves up to 6 m and 7m). The top reconstructions show the growing of the first spit from the north, corresponding to lower swale elevations in the southern part of the spit; whereas the bottom reconstruction shows the spit growing from the south indicating that the dominant wind must have shifted from NW to SW. The red dots in the reconstruction are registered finds of flint tools and flint tool workshops from the "grubekeramiske" culture - data from <http://www.kulturarv.dk/fundogfortidsminder/> (2014).

Probably the "grubekeramiske" (pitted ware culture) people lived permanently in Western Sweden, and only visited Anholt during the summer for seal hunting, fishing and collecting flint for tool making.

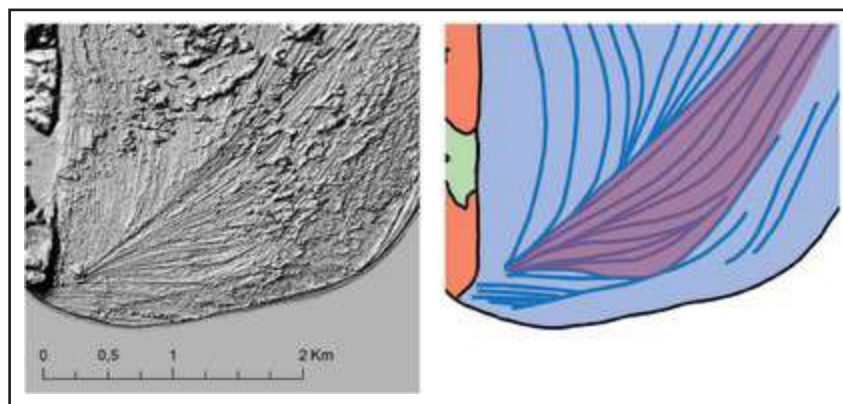


Figure 15. Detail of figure 14, showing the southern part of the island with an interpretation of the area. The dominant ridges are shown as dark blue. The violet area was deposited between 4.5 ka BP and 3.5 ka BP. The beach-ridge relief here has much higher amplitudes compared to other parts of the island. The ridge complex developed in this time indicates that the dominant wind direction had changed back from SW to NW. In the "Desert" (the beach-ridge plain) iron-manganese concretions - so called "Dværgkrukker" - are found. The violet area seems also to be the area where the concentrations of

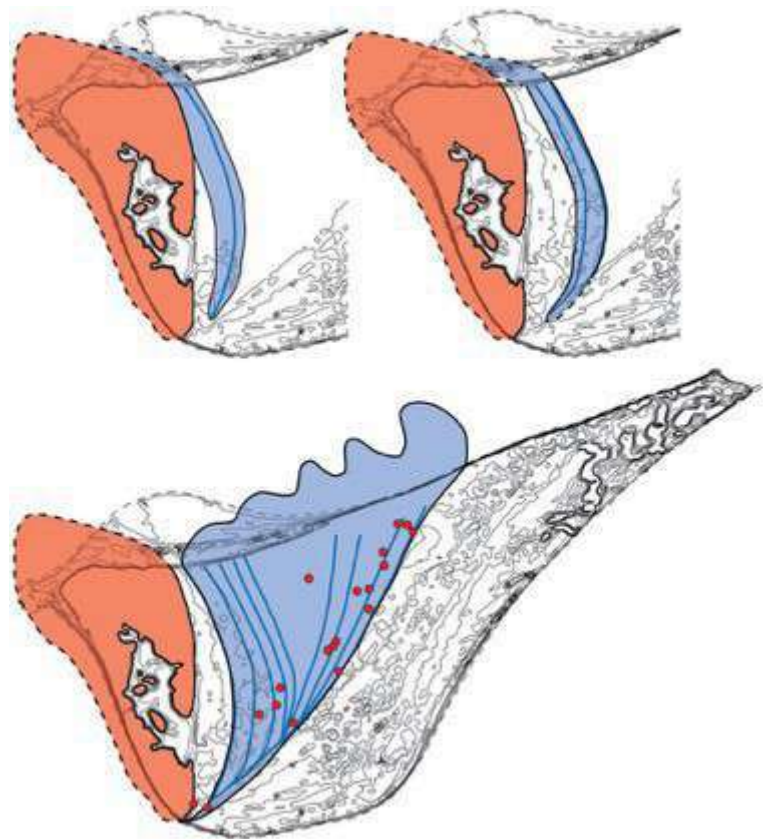


Figure 16. As beach-ridges under stormy conditions could be formed up to 2m above sea level, the swale elevation is chosen a measure for past sea levels. By constructing topographical curves below a maximum value it is possible to reconstruct the coastline corresponding to that sea level. At the top of the figure curves up to 6m and 7m are shown, and at bottom, curves up to 7 m are shown. The top reconstructions show the growing of a spit from north, corresponding to lower swale elevations in the southern part of the spit. Whereas the bottom reconstruction shows the spit growing from the south indicating that the dominant wind must have shifted from NW to SW. The red dots in the reconstruction are registered finds of flint tools and flint tool workshops from the "grubekeramiske" culture - data from <http://www.kulturarv.dk/fundogfortidsminder/> (2014).

As seen from the reconstruction of the coastline, their boats could at that time find a natural harbor sheltered by the spit.

The beach-ridge relief has extra high amplitudes between 4.5 ka BP and 3.5 ka BP (figure 15). The ridge complex developed in this period indicates that the dominant wind direction changes back from SW to NW. Iron-manganese concretions - so called "Dværgkrukker" (Gnome – pots) – are often found in the beach-ridge plain. The high relief part of the beach-ridge plain created between 4.5 ka BP and 3.5 ka BP seems also to be the area where the concentration of concretions is the highest (Schröder 1990). This could indicate that Kattegat, in this period, had a higher tidal range than present, giving rise to more oxidation of the ground water and precipitation of iron-manganese, which is similar to observations

in Cape Cod (Urish and McKenna 2004). At present there is virtually no tide at Anholt. It is hoped that future investigations will answer this question. The bottom curve of dominant wind direction in figure 18 is deduced from changes in the coastline as reconstructed in figure 17, whereas the curve of July temperature is deduced from palaeo-botanical studies (Iversen 1973).

Mörner (1980, 2008) has, based on changes in coastal dynamics and shore morphology on the Bjäre peninsula, also constructed a curve over the dominant wind direction over the last 10,000 years. The curve in figure 18 only covers the last 8,000 years; however the dominant wind direction before 8 ka BP must have been from the east, as the western glacial highland borders the beach-ridge plain with a pronounced N-S cliff. The Anholt curve of

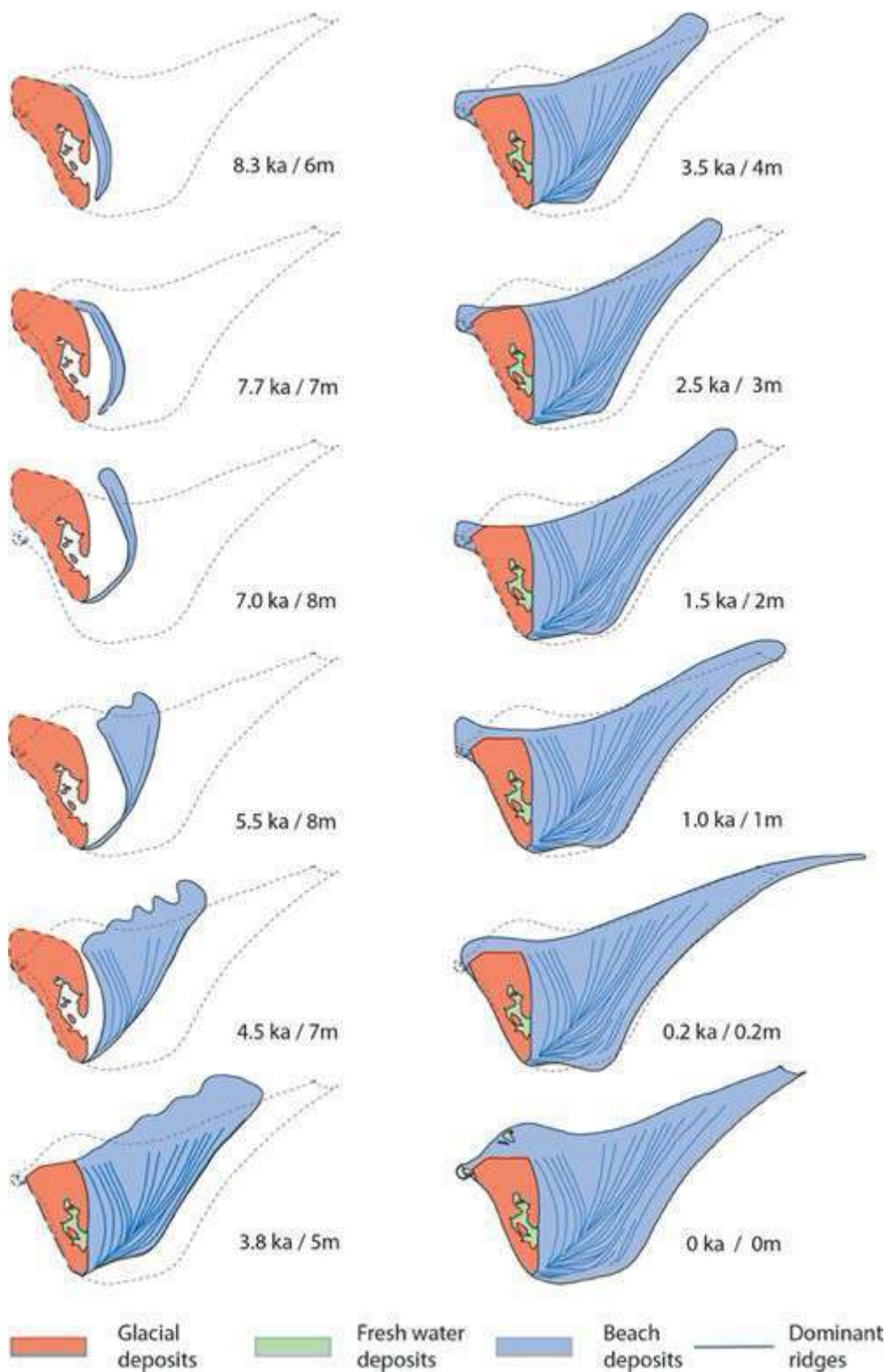


Figure 17. Using the method shown in figure 15-16, it has been possible to reconstruct the coastline of Anholt during the last 8 ka. Around 8-7 ka BC a spit consisting of beach sand and gravel started to grow from the NE corner of Anholt, generated by wind-systems where NW winds were more dominant than today. From 7-4.5 ka BP the spit grew from the south corner of the island and developed a fan shape, probably caused by SW winds being more dominant than to-day. After 4.5 ka BP the north coast is strongly eroded under a wind regime not very different from today, however the coastal evolution after 2.5 ka seems to indicate a period with more northern winds, continuing until a few hundreds year ago.

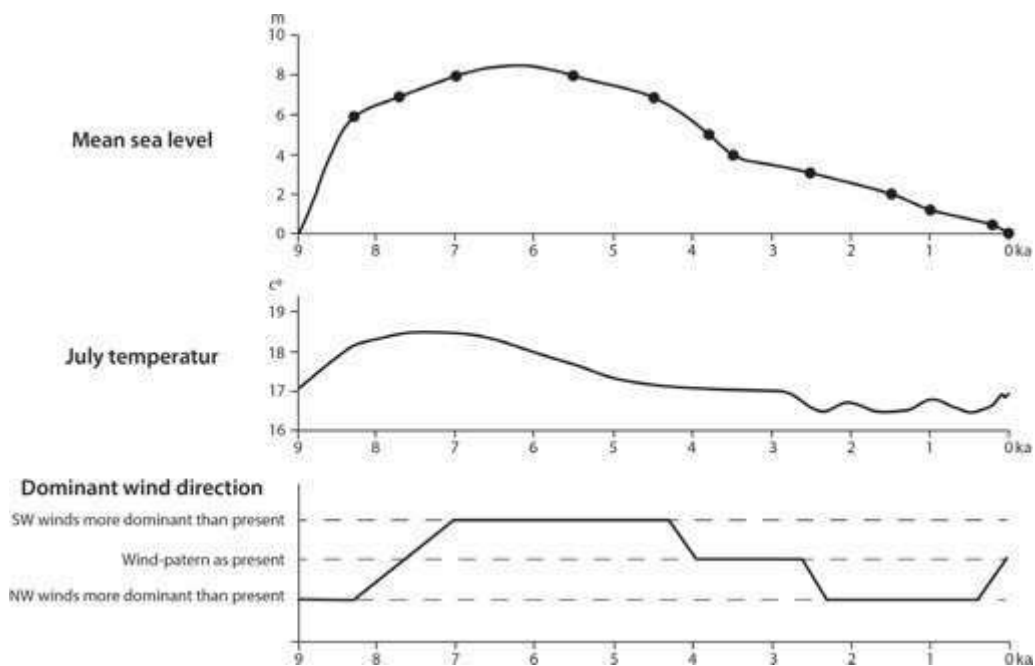


Figure 18. The dots on the upper curve correspond to the maps in figure 17. The curve of July temperature is deduced from palaeobotanical studies (Iversen 1973). The bottom curve of dominant wind direction is deduced from changes in the coastline..

dominant wind direction in figure 18 is in good but not complete agreement with the results gained from Bjäre; this may be explained by the fact that Bjäre is a peninsula whereas Anholt an island situated in the middle of the sea. The coastal changes on Anholt during the last hundreds of years are mostly due to lee side erosion of costal constructions (the lighthouse and the harbor) Schröder (1990) and Clemmensen *et al.* (2011). A more detailed record of late Holocene sea-level change has been obtained from Læsø archipelago in the Kattegat Sea (Hansen *et al.* 2012).

Data from Kattegat

The late and postglacial development of Kattegat has been reviewed by Mörner (1969), Houmark-Nielsen *et al.* (2012) and Larsen *et al.* (2009). Data from marine geology and geophysics work around Anholt have been presented by Bergsten and Nordberg (1992), Christiansen *et al.* (1993), Conradsen (1995), Jiang and Klingberg (1996). Jiang *et al.* (1997,1998), Bennike *et al.* (2000), Jensen *et al.* (2002), Leth and Novak (2010) and Bendixen *et al.*(2013). Based on these this data from Kattegat and data from the Swedish west coast (www.sgu.se, Mörner1969) and North Zealand (www.geus.dk, Schröder 1992, Schröder *et al.* 2004) it has been possible to reconstruct the Late- and Post – glacial development of Kattegat

(figure 19-22). The late glacial Kattegat is characterized by the deposition of thick layers of varved clays and silt (figure 19), seen in the seismic sections as patterns with parallel reflections. Also in the lobe in the northern part of Roskilde fjord, these patterns have been reported (Bondesen and Schröder 1979).

The Glacial Landscape and the Data from Boreholes As there are no precise dates of the late-glacial coast-lines older than 11 ka BP at Anholt, the late-glacialpart of the Anholt curve has to be established by extrapolation from the Viskan Valley curve. However there is also another well dated late-glacial sea-level curve from the western rim of the ice-sheet, from the island Sotra west of Bergen (Lohne *et al.* 2007) (see figure 23). The relative sea-level curve from Sotra has a pronounced low point in late Allerød, which is followed by a pronounced sea-level rise. This indicates that the isostatic rebound ceased or possibly was slightly reversed in Western Norway during this time span, which can only be explained by an increased ice load to the east of the Sotra Island. There is no proof of a sea-level low point in late Allerød from Denmark, however the famous archaeological/geological profile at the coastal cliff at Nørre Lyngby (Fisher *et al.* 2013), indicates that the sea-level drop also occurred here.

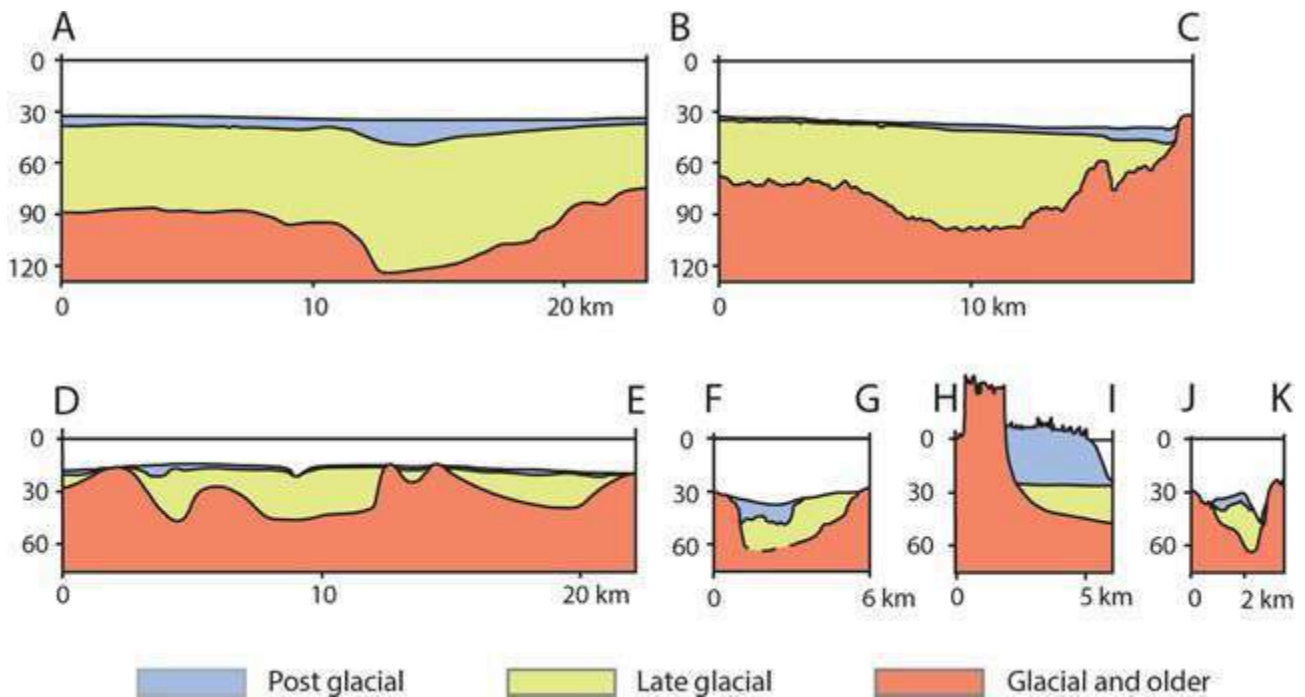


Figure 19. Geological profiles - see figure 20-21 for locations. Profile (H-I) is based on Anholt wells. The marine profiles show interpretations of geophysical and geological data from the Kattegat based on: Bennike et al. (2000, 2004), Jensen et al. (2002), Leth and Novak (2010), Bendixen et al. (2013). Post glacial deposits are younger than 11 ka BP. Late glacial deposits is deposited between 17-11 ka.

At Viskan Valley, the isostatic rebound apparently continued during the Allerød-Younger Dryas (YD), but much more slowly during this period than before or after, indicating that the Swedish part of the ice-cap was thinning even during the YD cold period. So most probably the dominant plateau that is seen in the western glacial landscape at Anholt (around 30 m) is also created in Allerød-YD (see figure 24).

On the southwestern coast of Anholt, the winter storms 2013-15 have opened new profiles at the base of Sønderbjerg. The photo in figure 25 shows that the glaciofluvial deposit, which constitutes the dominant part of the glacial West Anholt, are folded, most probably by an ice advance from the south. The indicator erratics (rocks transported via ice) found on Anholt are mostly of Norwegian or Baltic origin, but also some Swedish blocks are found (Jessen 1897, Gripp 1967, observations by the author). The photos in figure 26-27 (added in proof) show the folded glaciofluvial deposits eroded by the sea, and covered by beach-ridges around 2.5 ka, when a period with more northern winds started.

The Quaternary sequence in borings 350 m NE of the harbor has been reported by Lykke-Andersen (1990) and Seidenkrantz (1992). Here both marine and non-marine sediments are found from a time interval from the Saalian to Holocene. In 1943a prospecting well (GEUS no. 51.12), 230 m in depth was carried out, however the quality of the samples from this well were very poor, so new borings were established here in 1990 in order to study the Quaternary sequence. The Eem interglacial is represented by a 3 m thick marine layer situated about 70 m below surface. At 50 m depth, marine clay (2 m in thickness), which can be correlated to the Middle Weichselian, is also found. Otherwise, the remaining sequence is predominately sand of non-marine origin and the top 2 m represent the Holocene coastal deposits.

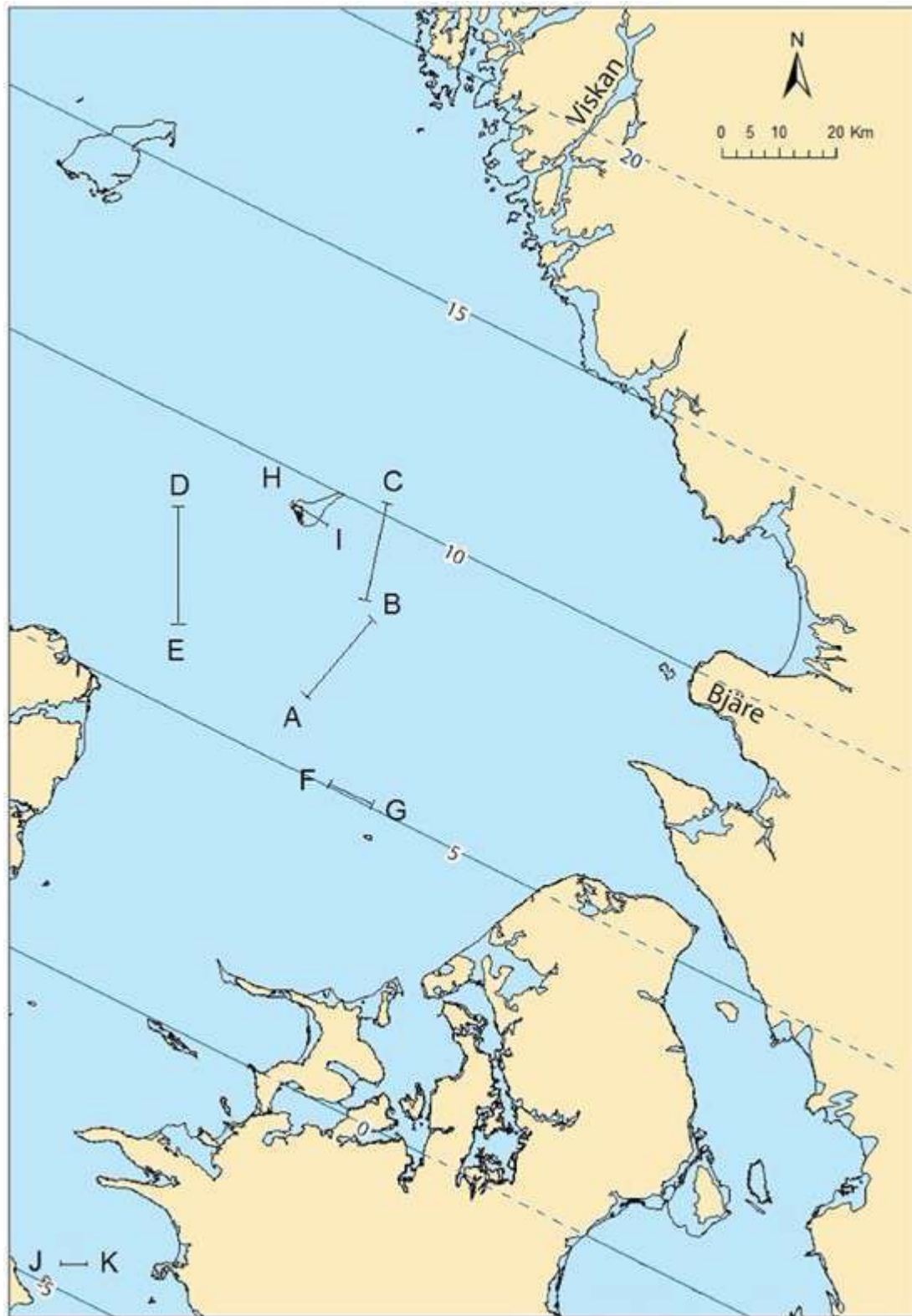


Figure 20. The sea level in Kattegat at 6 ka. The thin parallel lines indicate the sea-level at 6 ka (based on the curves in figure 10-11). The coastline is approximately the coastline at 6 ka. However the coastline is mapped as the maximum postglacial sea-level, that is asynchronous as the time for maximum sea-level is very different in the Anholt and the Great Belt regions - see figure 12..

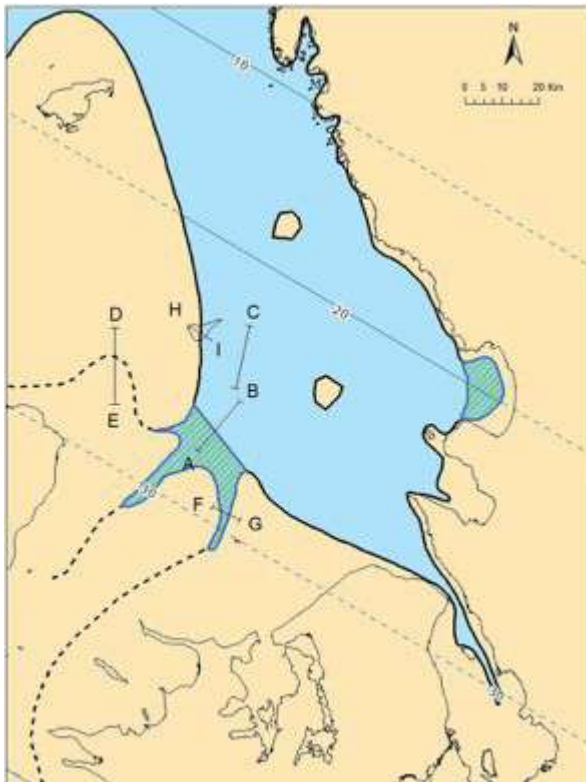


Figure 21. The sea level in Kattegat at 11 ka. The thin parallel lines indicate the sea-level at 11 ka (based on the curves in figure 10-11). The coastline is approximately the coastline at 11 ka. The blue-green areas represent lagoons (from Jensen et al. 2002 and Mörner 1969).

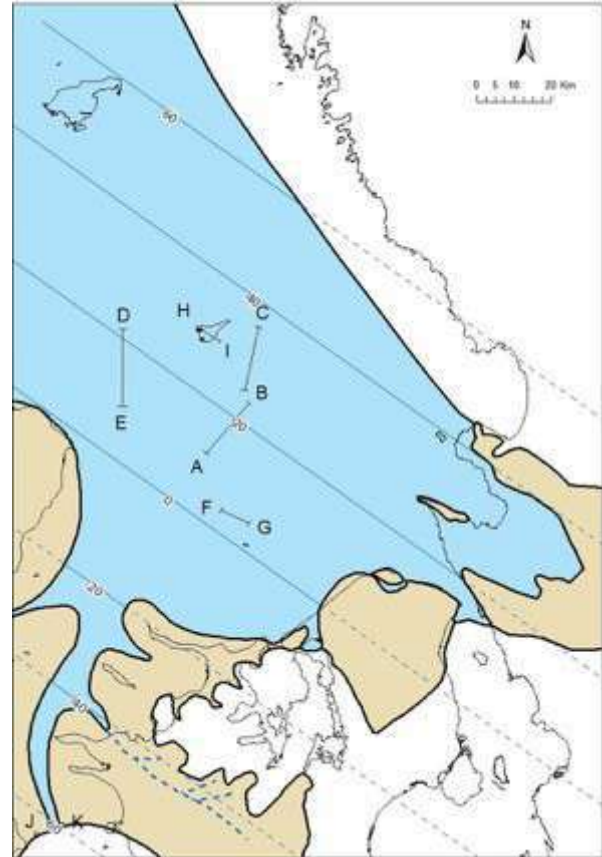


Figure 22. The sea level in Kattegat at 16 ka. The thin parallel lines indicate the sea level at 16 ka (based on the curves in figure 10-11). The coastline is approximately the coastline at 16 ka. The light red area represents a mixture of glacial materials and dead-ice (see also Schröder et. al 2004). The late glacial Kattegat is characterized by deposition of thick layers of varved clays and silt (figure 19).

4. Conclusions and Recommendations

The dynamics of the boundary between fresh and salt water depends mainly of the variation in rainfall, sea-level and permeability. Even if it is possible to reconstruct temperature and dominant wind direction for Anholt during the Holocene it is not possible to reconstruct the variation in rainfall.

However, it has been possible to reconstruct the coast, wind and sea level history of Anholt with a high degree of accuracy over the last 8000 years using detailed topographical maps based on airborne laser scanning (figure 14-18). And the compiling of recent data from marine geology and geophysics work around Anholt has made it possible to determine the sea level history since the melting of the Fennoscandian ice-cap (figure 19-22). The entire island (up to 48 m above present sea-level)

was flooded by the sea when the ice-cap around 17 ka BP melted away from the area, and around 16-12 ka BP the sea-level was slowly falling and only a very small part of the glacial landscape was above the sea. Thereafter, isostatic land-rise was dominant, and around 11 ka BP the sea-level was 25 m below the present. From 11-6 ka BP the sea-level rise was dominant and at 6 ka BP most of the island, except the western glacial hills, was covered by the sea. Thus in the Holocene, Anholt switches from terrestrial to marine and back to terrestrial conditions. This has affected the interface position much more than the variations in rainfall. The fact that the center of Anholt was covered by the sea at 6 ka BP, and consequently the freshwater lens did not exist, means that the present equilibrium with a freshwater lens exceeding 100 m is less than 6000 years old. Also on the sandy island of Inhaca, Mozambique (Været

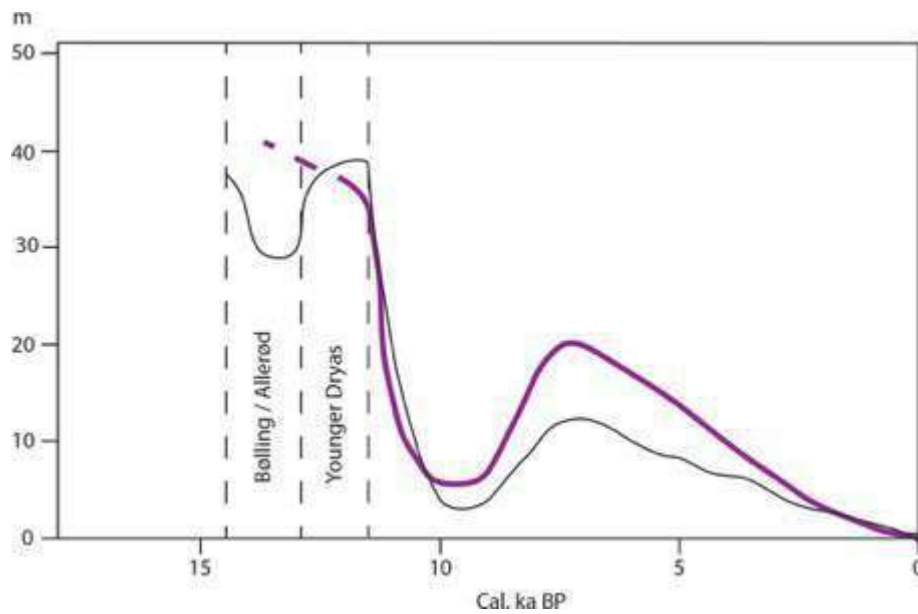


Figure 23. The relative sea-level curves for the Viskan Valley (purple), and the island Sotra (black) west of Bergen (Lohne et al. 2007). The relative sea-level curve from Sotra has a pronounced low point in late Allerød, which is followed by a pronounced sea-level rise. This is in accordance with the conclusion that the Norwegian west coast had no isostatic uplift between the Allerød low-stand and the YD high-stand. This indicates that the isostatic rebound was slightly reversed in Western Norway during this time span, which only can be explained by an increased ice load to the east of the Sotra Island. At Viskan Valley (and probably Anholt) the isostatic rebound apparently continued during the YD, though at a slower pace than before and after resulting in the 30 m terrace at Anholt.

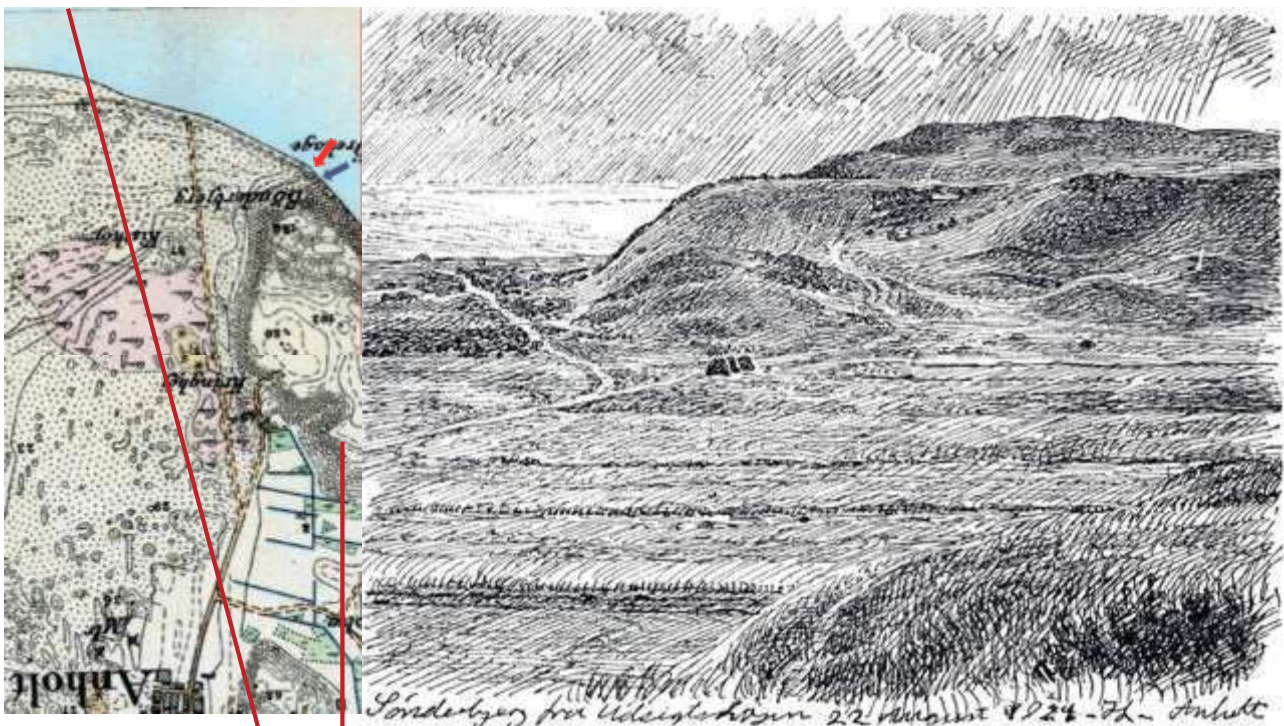


Figure 24. Drawing of Sønderbjerg which is the highest part of the glacial landscape. In 1924 the artist Johannes Larsen visited Anholt. At that time the western part of the Island was without trees, and a terrace at around 30 m over present sea level is clearly seen, indicating that the late glacial sea for a long time had a sea level around 30 m. Also the very top of Sønderbjerg (48m) is seen as a flat plateau, so probably also all of Anholt was flooded by the sea when the ice melted from the area. Red lines on the map aside show the area seen in the drawing. Also shown on the map is the location of the photos of figure 25 (blue arrow) and figure 26 (red arrow).



Figure 25. At the SW coast the winter storms 2013-15 have opened new profiles at the base of Sønderbjerg. The photo shows that the glacio-fluvial deposits, which constitute the dominant part of the glacial West Anholt, are folded, probably by an ice advance from the south.



Figure 26. The photos here (02.05 2015) 50 meter south of the photo in figure 25 shows the folded glaciofluvial deposits eroded by the sea, and covered by beach-ridges around 2.5 ka, when a period with more northern winds started (see figures 17-18).

et al. 2012), it was shown that less than 1000 years was needed to reach equilibrium after the preceding rapid sea-level rise.

Numerical modelling can be used as a tool to analyze processes which threaten fresh groundwater supplies in coastal areas, and as seen for Anholt, even primitive two-dimensional models can successfully be used when the geology is simple.

At present, three-dimensional modelling of solute transport is the state of the art from a salt water intrusion modelling point of view. Nevertheless, there are some restrictions in modelling salt water intrusion in three dimensions (Essink 2001). The most important restriction is that reliable and accurate data, which are required for calibration and verification of the models, are not available in more complex geological settings. But coastal well systems have to be safeguarded to prevent them from salinization. Monitoring the quality of groundwater on a regular basis is important in coastal areas where salt water intrusion may be expected. The conventional way is to analyze the salinity of samples and registration of piezometric heads. Besides this, geophysical exploration techniques have proven to be useful. The application of an electrical resistivity method is also useful in combination with observation wells. A network of observation wells around the well system should be set up and groundwater samples and piezometric heads should be analyzed.

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Note

The words of Forchhammer on sea level change in Denmark in 1849 (in Danish):

"Medens den store skandinaviske hævnning især forandrer det nordlige og østlige Europas kyster, har Nordsøsækningen forandret især det vestlige og sydvestlige Europa; medens den skandinaviske hævnning har været langsom, og vedbliver endnu, synes Nordsøsækningen, at have været pludselig, og har for længe siden allerede ophørt at virke. De nordlige og østlige dele af Danmark, og den sydlige del af Skåne har været påvirket af begge disse niveauforandringer, og deres modsatte virkninger berede ofte den iagttagende geognost store vanskeligheder".

(in English):

"While the uplift of Scandinavia changes the North-eastern parts of the coasts of Europe, the lowering of the North Sea has changed the Western and South Western coasts of Europe. Whereas the Scandinavian uplift has been slow, it seems that the lowering of the North Sea was quick, and has long ago stopped to be active. The Northern and Eastern parts of Denmark, and the Southern part of Scania has been affected by both of this sea-level changes, and the opposite effects often cause great difficulties for the observing geologist."

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