The authors would like to thank reviewer Evan Goldstein for giving the constructive comments, which will definitely improve the manuscript. Below we firstly addressed each comment and also indicate changes that have been made in the revised manuscript. Notably, the page and line numbers are the ones in the attached revised manuscript.

Comment #1:

I believe this manuscript could benefit with more description as to the mechanics of sediment transport in this specific system to justify the results (Section 3.2). For instance, what drives sand transport in the modern system? Does sand come from the Baltic into the inlet? Or is the sand coming from the terrestrial setting? i.e., as a reader it would be helpful to understand in more detail how this physical system works?

Authors' reply on comment #1:

Thanks for the good points. As the catchment of the inlet is characterized with thin soil and the inlet only has a few small rivers draining into it. On one hand, we speculated that sand transportation into the inlet from the catchment could be limited. On the other hand, the sand input into the inlet from the offshore regions could be very small, as a result of the narrow and shallow sill between the inlet and the open sea water. Overall, sand and/or sediment can be transported into the inlet through both terrestrial input and offshore region with limited amount (supported by relatively low sedimentation rate, <1.5 mm yr^{-1}, during the last 1 ka). We speculated that sediment accumulated in the inlet mostly originates from the terrestrial setting, compared with the sandy offshore region.

Changes made in the manuscript based on comment #1:

Page 4, line 13: "which hinders sediment transportation between the inlet and the open water." is added after the sentence "It has a restricted water exchange with the open Baltic Sea through a narrow and shallow strait (500 m wide, <20 m deep) in the east".

Page 4, line 20: "In the shallow waters of the inlet, sandy patches can be found in addition to the rocky coast. The sediment accumulating in the inlet most likely originates from the terrestrial environment through erosion, and from land-run and river transport, instead from the open Baltic Sea. Sediment accumulation rate over the last 1000 years is generally less than

1.5 mm yr-1 in the deep basin (Ning et al., 2016).” is added after the sentence “The RSL has decreased by 17 m in…1.5 mm yr^{-1}”.

Comment #2:

Can the authors connect openness index with a near bottom water velocity and sediment transport in some way - i.e., fetch, wind speed, and water depth to calculate wave orbital motions at the bed using the relations presented in Young and Verhagen (1996)? Or perhaps the authors could relate the (spatial) change in openness index to the wind field (modern or ancient) and the fetch?

Author’s Reply on comment #2:

Thanks for the great point. It would be really interesting to relate the estimated openness index with other environmental variables to potentially explain sediment transport mechanism. However, there is a lack of reliable data on historic wind speed and direction in the Baltic Sea region. Thus, calculating wave orbital motions at the bed for the long-term scale is not possible at this moment.

As the reviewer correctly pointed out, it could be interesting to link the spatial change in the openness to the changes of wind field in the inlet, which may improve the ability of our current method in explaining sediment variation. However, since the main focus of this study is to explain the temporal dynamics of grain size changes at long-term scale, it may bring additional uncertainties to our estimations if we only use the available modern wind data for the past 5.4 ka. With availability of reliable wind data at long-term scale in future, it will definitely be interesting to explore potential impacts of wind on the grain size changes at the core site.

Changes made in the manuscript based on comment #2:

Page 8, line 18, some discussion about landward openness index with wind direction has been added.

Comment #3:

The authors focus on developing an ‘openness index’ which is the average length of line from the core site to land at a given time/sea level. Why are landward vs. seaward openness indices differentiated? And a related comment, the shifting angle is discussed only briefly. Can the authors give us some guidance on picking a starting position? Do any radial lines, at any time, make it to the open Baltic sea (i.e., do any openness measurements exceed the 8 km line segments used)? Are these lines important? (I would presume so, because these directions would permit larger waves into the system and exert more work on the bed.)

Author's reply on comment #3:

Both the seaward and landward openness indices can be linked with fetch and wave energy in the inlet, where high indices values potentially indicate relatively large bottom velocity. Thus higher openness indices in the open system lead to larger grain size in the sedimentation area. In comparison with the landward openness, the seaward openness index better reflects the morphological changes of the inlet, which is the main cause for hydrodynamic energy changes in the inlet over the last 5.4 ka. The landward index is used to describe the changes in offshore distances and it can be important if prevailing wind direction is from the land to the sea.

Thanks for the suggestions on adding comments on the shifting angle. The shifting angles of 0° to 4° have been used to test whether different starting angles influence the openness indices. The results presented in Fig. 7 showed that using 5° interval and different shifting angles, the changes in openness indices were substantial. If the interval is set as 1°, changing the shifting angle from 0° to 4° would be lead to little changes in the openness indices. Therefore using low degree interval such as 1° for calculating the openness indices is preferred. The optimal interval for estimating openness index could vary from different coastal settings and we suggest to test it before apply the index with other proxy data. In our study, using 1° interval would give the most robust results when calculating openness indices, although the computing time would be longer than larger degree intervals.

We have sediment data from the core site and this is also the site we are interested to investigate factors impacting sedimentation process. So it is straightforward for us to use the core site as the starting point of radial lines and the estimated changes of openness index can further link the index with other measured sediment variables.

The maximum length of 8 km line was used because it reached open water region for scenarios at the 5.4 ka ago and is recognized as a reasonable limit. For most time slices, the radial lines have already intersected with islands at less than 8 km distance from the coring site (see Fig. 4). As Fig. 4 illustrates, some lines will reach further before intersecting with land. With increasing length of radial lines, one or a few these far-reaching lines could contribute relatively more to the estimated openness index, which may increase the relative changes of the estimated openness index through the time. However, we think the changes caused by different lengths of radial lines will most probably not alter the trend which was detected with the current estimation.

Changes in the manuscript based on comment #3:

Page 6, line 18: The text of "The radial lines of 8 km were used as they can reach offshore open water region" is added after the sentence "The length of the radiating lines…was set as 1-5, 10 and 15°".

Page 8, line 5: ".Furthermore, potential effects of shifting angles (angle between the north and the nearest radial line) were tested and Figure 7 showed the cases for 5° intervals of radial lines with shifting angles of 0° to 4°. The results demonstrated that using different shifting angles can cause substantial differences in the estimated openness indices when the radial intervals are relatively large. However, if the interval is set as 1°, changing the shifting angle from 0° to 4° would result in openness indices with little very small differences in consideration of relative changes in the positions of all radial lines. Therefore using low degree interval such as 1° for calculating the openness indices is preferred and should be recommended for other similar studies, although the computing time would be longer than higher degree intervals. The landward and seaward openness indices were differentiated although they both reflect morphological changes of the inlet over the last 5.4 ka. The seaward openness index reflected more accurately the embayment process in comparison with the landward openness index, as the most distinct changes of the inlet was from the sill in the east. The landward openness index, reflecting offshore distance, could also be important for considering sedimentary grain size, especially if information describing for the past prevailing wind direction becomes available." is added after the sentence "Therefore, the associated uncertainties…openness variability."

Comment #4

The authors present Figure 6 and 7 to show there is variation in the openness index for a given degree interval (or shifting angle) at a given time. Is there a way to make this analysis more quantitative? (i.e., p5, line 9; how much 'larger'?) One suggestion to illustrate this in the figures is to plot openness variance as opposed to the raw openness index. On a related note, the authors state that they endeavor to find an optimal degree interval (p. 5 line 3). I assume 'optimal' in this context refers to a negligible variance in openness index relative to decrease computation time (associated with increasing the degree interval)? Perhaps quantifying the variation in openness index for a given degree interval will aid them in searching for an 'optimal' interval?

Author's reply on comment #4:

Different shifting angles and intervals are used to test if there is large difference among them. The results in Fig. 6 and 7 demonstrate that there are large variances among different shifting angles and intervals. We agree that it would be good to quantify the differences among different scenarios and which has now been quantified in the revised manuscript (see the changes below as well). The 1° interval is recognized as an 'optimal' interval in our study, which is based on the fact that the computing time for using 1° interval is still acceptable. If further study has large data set (i.e. processing openness index focusing on many sites), the computing time may need to take into consideration and may end up with larger intervals, e.g., 2° or 3°.

Changes made in the manuscript based on comment #4:

Page 7, line : "The calculated landward and seaward indices using 15° interval are at the maximum 7 % and 20 % larger than the 1° interval scenario." is added after the sentence "Both the seaward…the smaller degree intervals (Fig. 6)."

Page 7, line 18: "(maximum 5 %)" is added after "only minor difference".

Comment #5:

The authors present openness index data and grain size in figure 8. I believe more quantitative analysis could be performed with this data to convince the readers. For instance, what values of shifting angle and degree interval was used? Why? What is the correlation between opening index vs sand %? or openness index vs silt/clay?

Authors' reply on comment #5:

Shifting angle of 0° and interval of 1° are used in the Fig. 8 scenarios. When the interval of 1° is used, the shifting angle will only have little impact on the openness indices (see the replies on comment #3). The size of the interval indicates empties spaces without radial lines. With a reduced interval size, there is high chance to capture more detailed morphological changes and also there is less impact from the shifting angle on the estimated index.

Changes made in the manuscript based on comment #5:
To quantify the relationship between openness index with sand fraction, the R^2 with significance level was calculated to better inform the readers and has now been added in the Table 1 in the revised manuscript.

Comment #6
Has there been erosion of the islands since 5 ka? (i.e., is the present subaerial expression of the islands identical to the coastlines of the island in the past?) how could this impact your study?

Author's reply on comment #6:
Erosion from the islands since 5.4 ka most likely occurred but has been weak as these islands are mostly rocky. It may have caused a delivery of relatively large grains into the coring site during the land-uplift process. As the uplift process has been generally linear, we might expect to see a linear change in the grain size data if land uplift has played the dominant role in governing the grain size. However, the sand contents and silt/clay ratios exhibit non-linear changes, which indicate other factors than land uplifting could also participate in influencing grain-size distribution.

Changes made in the manuscript based on comment #6:
Page 10, line 3: "Erosion from the surrounding islands since 5.4 ka has most likely occurred, but could be rather limited as these islands are mostly rocky with little soil cover. It may, however, result in a flux of relatively coarser grains to the coring site during the land-uplift. As the uplift process close to be linear (see Fig. 2), we might expect to see a rather linear change in the grain size data assuming the land uplift played the dominant role. However, the sand content and silt/clay ratios exhibit strong year-to-year variations, which indicates other factors than land uplifting could also participate in influencing grain-size distribution. For instance, coarse grains, such as sand, can also be transported to the coring site through storm

events and intense wave action, sea ice or drifting sea weed. However, their impacts are not explicitly included in the openness indices.” is added after “Together with sheltered condition…in the sediments”.

Replies to the 2nd reviewer:

I would like to see a few more notes about the setting: are there only rocky coasts, or are there also patches of sandy shores? And what about shallow waters? All rocks? Some notes are found in 3.2, but more notes could be added to 2.1.

I also wonder how sand is transported to the core site. Does it happen during storms as storm sand layers? Is sand blown out on the sea ice during cold winters? Is sand transported by drifting sea weed or by drifting sea ice?

I would also like to see a few notes on the chronology of the core, at least a reference to Ning et al. (2016).

The main control on grain size distribution is distance to the shore, but this is apparently not mentioned. The closer to the shore – the more coarse-grained sediments. In Gåsfjärden, however, the sediments become more and more fine-grained as the core site moves closer to the shore. This is not surprising, because the core site at the same time becomes more and more protected. The authors have developed a novel GIS-based approach that allows them to quantify down-core changes in grain size distributions in relation to changing fetch.

Author's Reply:

Thanks for the great comments. We will first give our replies to each asked question and then list all corresponding changes have made in the revised manuscript. Notably, the page and line numbers are the ones in the attached revised manuscript.

The shallow waters and the shore are characterized with rocky coasts and some sandy patches based on observation. Inside the inlet, there is so far no data about spatial distribution of sediment grain size. The sand content in the inlet are supposed to be relatively low, due to lack of large rivers draining into the inlet and erodible soil as well as its enclosed setting.

The sand content is generally lower than 1% in our coring site. During periods with relatively high openness, storm events would most likely transport large amount of sand and silt into the coring site which is shown in Figure 8. Sand can also be transported to the coring site through sea ice and/or drifting sea weeds, although the impacts are hard to estimate.

A description on the chronology of the core has been added.

Thanks for pointing out the underlying impacts of distances on grain size distributions. We have now addressed in the revised version.

Changes in the manuscript:

Page 4, line 20: In the shallow waters of the inlet, sandy patches can be found in addition to the rocky coast. The sediment accumulating in the inlet most likely originates from the terrestrial environment through erosion, and from land-run and river transport, instead from the open Baltic Sea. Sediment accumulation rate over the last 1000 years is generally less than 1.5 mm yr-1 in the deep basin (Ning et al., 2016)."

Page 5, line 16: "Grain-size analysis" is changed to "Chronology and grain-size analysis".

Page 5, line 18: "and the age-depth model of the sediment sequence was established through a combination of ^{210}Pb and ^{14}Cs and AMS-^{14}C dating methods (Ning et al., 2016)." is added after "A 6 m sediment sequence was obtained covering the last 5.4 ka (Ning et al., 2016)".

Page 9, line 8: "The maximum sand content at the core site was only □0.4%, suggesting a relatively low bottom water velocity compared with open Baltic Sea waters (Jönsson et al., 2005). Generally, the closer to the shore, the more coarse-grained sediments can be deposited. However, the sediments in Gåsfjärden became more and more fine-grained as the coring site became shallower and closer to the shore (closer to present time, see Figs. 5 and 8), which was a result of less exposure and an increasingly protected location (reflected by the openness index).." is added after "We have…openness variations."

Page 10, line 8: "For instance, coarse grains, such as sand, can also be transported to the coring site through storm events and intense wave action, sea ice or drifting sea weed. However, their impacts are not explicitly included in the openness indices." is added before the sentence "Furthermore, the recorded large variability in the sand…from human activities".

Reference:

Ning, W., Ghosh, A., Jilbert, T., Slomp, C. P., Khan, M., Nyberg, J., Conley, D. J., and Filipsson, H. L.: Evolving coastal character of a Baltic Sea inlet during the Holocene shoreline regression: impact on coastal zone hypoxia, J Paleolimnol, 55, 319-338, 10.1007/s10933-016-9882-6, 2016.

Long-term coastal openness variation and its impact on sediment grain- size distribution: a case study from the Baltic Sea

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Abstract. We analysed the long-term variations in grain-size distribution in sediments from Gåsfjärden, a fjord-like inlet i~~o~~n the south~~-~~west Baltic Sea, and explored potential drivers of the recorded changes in the sediment grain-size data. Over the last 5.4 thousand years (ka) in the study region, the relative sea level decreased with 17 m~~ in the study region~~, which was caused by isostatic land uplift. As a consequence, Gåsfjärden was~~has been~~ transformed from an open coastal setting ~~in~~to a semi-closed inlet surrounded ~~on the seaward side on the east~~ by numerous small islands on the seaward side. To quantitatively estimate the morphological changes in Gåsfjärden over the ~~last 5.4 ka~~investigated time period and to further link the changes to ~~our~~ the grain-size distribution data, a digital elevation model (DEM)-based openness ~~indices~~ index was~~ere~~ calculated. The highest values of the openness indices were found between 5.4 and 4.4 ka BP, which indicates relatively high bottom water energy~~ In the period between 5.4 and 4.4 ka BP, the inlet was characterised by the largest openness index~~. During the same period~~is interval~~, the highest sand content~~s~~ (~0.4%) and silt/clay ratio~~s~~ (~0.3) in the sediment sequence were

recorded. ~~, indicating relatively high bottom water energ~~After 4.4 ka BP, the average sand content was halved to ~0.2% and the silt/clay ratio~~s~~ showed a significant decreasing trend over the last 4 ka. These changes ~~are~~ were found to be associated with the gradual embayment of Gåsfjärden as represented ~~in~~ by the openness indices. The silt/clay ratios exhibited a delayed and relatively slower change compared with the sand content~~s~~, which ~~further suggest~~ indicates different grain-size sediments responses differently to the changes in hydrodynamic energy. ~~imply that finer particles such as silt and clay respond similarly to changes in hydrodynamic energy.~~ Our DEM-based coastal openness indices have proved to be a useful tool for interpreting the temporal dynamics of sedimentary grain-size ~~record~~.

1 Introduction

Sedimentary grain-size distribution provides important information ~~on~~ regarding~~the~~ depositional conditions and has been widely analysed in both modern samples and sediment cores ~~-~~(e.g., Tanner, 1992; Yang et al., 2008; Virtasalo et al., 2014). Grain-size distribution is generally governed by sediment inputs and hydrodynamic energy conditions. ~~, and~~ T~~t~~he higher the energy conditions, the ~~higher~~ larger proportion of coarse grains (Dearing, 1997; Jönsson et al., 2005). Water depth, wind direction and strength, ~~as well as~~ basin morphometry, as well as~~and~~ man-made constructions such as dam-building, could influence ~~the~~ bottom water hydrodynamics and may lead to different characteristics in grain-size distributions. The Baltic Sea is connected with the North ~~Atlantic~~ Sea ~~with~~ through the narrow Danish Straits. Although tidal activity ~~e~~ can strongly influence grain-size distribution in coastal regions, as shown by ~~(~~Zhang et al., (2002), the tidal amplitude ~~of the tide~~ recorded in the Baltic Sea is only ~~several~~ a few centimetres (Ekman and Stigebrandt, 1990) and therefore its impact on sediment grain-size is not considered in this region~~-negligible~~. Instead, w~~W~~ind conditions and coastal morphometry are considered to be ~~are probably the most~~ important factors that ~~influence~~ influencing the sedimentary grain-size distribution in the Baltic Sea coastal zone (Lehmann et al., 2002; Jönsson et al., 2005;~~The grain-size distributions~~

~~vary substantially in the Baltic Sea coastal zone as large differences in wind conditions and coastal morphometry exist among coastal sites~~ Al-Hamdani and Reker, 2007).

During the Holocene, the Baltic Sea has experienced several stages modulated by global sea-level changes as well as ~~by~~ isostatic land uplift (Björck, 1995; Andrén et al., 2011). As the Late Weichselian ice sheet retreated, land uplift during the deglaciation and the Holocene resulted in shoreline displacements in the coastal zones of the Baltic Sea. A maximum of 60 m decline in relative sea level (RSL) has been recorded over the last six thousand years (ka) in the Baltic Sea (Påsse and Andersson, 2005), leading to basin isolations and long-term changes in the coastal morphometry (Eronen et al., 2001). Ning et al., (2016) further pointed out t~~T~~hese changes in the coastal morphometry variations may potentially be linked with variations in grain-size distributions in the southwest of Baltic Sea~~,~~ ~~as shown from a coastal inlet in the south-west Baltic Sea~~ (Ning et al., 2016).

To examine the impact of coastal morphometry changes on grain-size distribution in a long-~~temporal~~ term perspective, quantifying ~~tative estimates of~~ the ~~coastal~~ morphological changes~~metry~~, ~~including~~ e.g., water depth and cross-section areas could be useful~~are needed~~. Achieving this ~~such~~ quantification ~~estimate~~is ~~difficult~~data-demanding ~~and may cause large uncertainty~~, since it requires ~~due to:~~ 1) ~~the lack of~~ high-resolution bathymetry data, 2) right ~~difficulties in selecting the~~ cross-section area and 3) ~~unknown~~ sedimentation rates. However, all these data are difficult to obtain and makes the quantification impossible. Alternatively, through using digital elevation maps, ~~previous studies by~~ Lindgren (2011) ~~used~~ proposed a geographical information system (GIS)-based wave fetch index, ~~called~~ named filter factor, to estimate coastal morphometry. The result of the quantified coastal morphometry was found to be significantly correlated with bottom water dynamics (Persson and Håkanson, 1995) and deep~~-~~water turnover time (Persson and Håkanson, 1996). T~~T~~here are also other GIS-based indices existing for describing coastal openness and wave exposure (Ekebom et al., 2003; Tolvanen and Suominen, 2005) and these GIS-based methods have also been applied to investigate sediments grain-size distributions from lakes and coastal zones (Håkanson, 1977; Lindgren and Karlsson, 2011). However, these aforementioned indices ~~have been so fa~~are ~~r restricted~~ restricted to ~~in~~ depict~~ing~~ the modern coastal morphometry and have not yet been employed in ~~the~~a ~~context of~~ paleoenvironmental context~~studies~~.

In this study, ~~our approach of~~ we ~~calculating~~ proposed an openness index using ~~a~~ Digital Elevation Model (DEM) data~~-based method~~ and ~~as~~ this approach –could ~~may~~ provide an opportunity to estimate long-term coastal morphometry variations for the Holocene. Furthermore, we innovatively used the coastal openness index for grain-size data interpretations. The aim of the study is to: (1) present a method for quantifying openness changes in coastal region that experienced large relative sea level as well as ~~and~~ shoreline changes, and (2) link the estimated openness index with the long-term sediment grain-size distribution.

2 Materials and methods

2.1 Study area and digital elevation model

Gåsfjärden is a semi-enclosed fjord-like inlet located on the south~~-~~east Swedish Baltic Sea coast (Fig. 1a). It has a restricted water exchange with the open Baltic Sea through a narrow and shallow strait (~500 m wide, <20 m deep) in the east, which hinders sediment transport between the inlet and open waters. The surface area of Gåsfjärden is 22 km^2 and the mean and maximum water depths are 10 m and 51 m, respectively. The RSL has decreased by 17 m in the region over the last 5.4 ka as a result of isostatic land uplift (Fig. 2) and the present land uplift rate is ~1.5 mm yr^{-1} (Påsse & Andersson 2005). The catchment of Gåsfjärden is characterised by very thin soils (<1 m) and exposed pre-Cambrian bedrock. Arable land is sparsely distributed in the lowlands and ~~the~~ vegetation mainly consists of coniferous forest (Fig. 1b). Small-scale human activities existed in the region as early as 2 ka ago, although substantial expansion has occurred since the 1700s (Karlsson et al., 2015; Ning et al., 2016). In the shallow waters of the inlet, sandy patches can be found in addition to the rocky coast. The sediment accumulating in the inlet most likely originates from the terrestrial environment through erosion, and from land-run and river transport, instead from the open Baltic Sea. Sediment accumulation rate over the last 1000 years is generally less than 1.5 mm yr^{-1} in the deep basin (Ning et al., 2016). ~~The catchment of Gåsfjärden is characterised by very thin soils (<1 m) and exposed pre-Cambrian bedrock. Arable land is sparsely distributed in the lowlands and the vegetation mainly consists of coniferous forest (Fig. 1b). Small-scale human activities existed in the region as early as 2 ka ago, although substantial expansion has occurred since the 1700s (Karlsson et al., 2015). The RSL has decreased by 17 m in the region over the last 5.4 ka as a result of isostatic land uplift (Fig. 2) and the present land uplift rate is ~1.5 mm yr^{-1} (Påsse & Andersson 2005).~~

~~In the shallow waters of the inlet, sandy patches can be found in addition to the rocky coast. There is a general lack of erodible soil and subsequent sediment transportation into the inlet. Even so, sediment accumulated in the inlet is expected to originate mostly from the terrestrial setting, instead of from the open Baltic Sea. Sediment accumulation rate over the last 1 ka is generally less than 1.5 mm yr^{-1} in the deep basin (Ning et al., 2016).~~

The Light Detection And Ranging (LiDAR)-based DEM data of the study region (Fig. 1c) were obtained from the Swedish mapping agency, Lantmäteriet (http://www.lantmateriet.se/). The horizontal and vertical resolutions of the DEMs are approximately 2 m and 0.1 m, respectively. The data are in the Swedish national coordinate system (SWEREF99 TM).

2.2 Chronology and g~~G~~rain-size analysis

Sediment cores were collected at Station VG31 (57°34'21.3" N, 16°34'58.4" E) in August 2011 on the R/V *Ocean Surveyor* ~~ship~~. A 6 m sediment sequence was obtained and the ~~covering the last 5.4 ka .~~ age-depth model was established through a combination of ^{210}Pb, ^{137}Cs and AMS-^{14}C dating methods (Ning et al., 2016). For the grain-size analysis, ~~O~~organic ~~matter~~carbon, calcium carbonate, and biogenic silica were removed from the sediment samples using procedures by Van Hengstum et al. (2007). To obtain enough minerogenic material, a mixed sediment sample of about 13 g, with ~~a~~ core sections of a maximum of 7 cm (covering ~60 years), was used. The sand particles (>63 µm) were sieved, dried and weighed. The mass fraction of sand was calculated by dividing the dried sand weight with the original dry sample weight before any chemical treatment. The mass fraction of clay (<2 µm) and silt (2-63 µm) from particles less than 63 µm were obtained with a Micromeritics Sedigraph III Particle Size Analyser at the Department of Geology, Lund University, Sweden.

~~2.3 DEM data~~

~~The Light Detection And Ranging (LiDAR)-based DEM data of the study region (Fig. 1c) were obtained from the Swedish mapping agency, Lantmäteriet (http://www.lantmateriet.se/). The horizontal and vertical resolutions of the DEMs are approximately 2 m and 0.1 m, respectively. The data are in the Swedish national coordinate system (SWEREF99 TM).~~

2.34 Openness index ~~calculation~~

The calculation of the openness index (Fig. 3) has been modified on the basis of the method described by Lindgren (2011) and the fetch-length method of Ekebom et al. (2003)~~ (Fig. 3)~~. The following steps for estimating openness index variations were taken in ArcGIS 10.3:

1) The coring site was identified in the DEM.
2) Using the coring site as starting point, two sets of 180° circles of radiating lines were created. One set of ~~radical~~radial lines was towards the east (seaward) and the other was towards the west (landward), with an interval of Δ degree (generated by the Python scripts in Supplement S1). The length of the radiating lines was set as 8 km and the interval Δ was set as 1-5, 10 and 15°. The ~~radical~~radial lines of 8 km were used as they can reach offshore open water. The ~~radical~~radial lines with a 5° interval but with different shifting angles θ (1-4°) were also created (~~see~~ Fig. 3a).
3) The RSL changes with a 100-year interval were applied to the present-day DEM. For every 100 years, a new DEM was generated and the RSL changes were based on the age-RSL relationship in Fig. 2.

4) For every 100 years, the grid cells in the generated DEM were classified as sea or land based on the elevation.

5) The raster DEMs were converted to land and sea polygons for vector calculation in ArcGIS, and the radiating lines generated in Step 2) were divided into smaller segments when the lines were intersected by the land polygons.

6) The lines originating from the coring site and that came into contact with the land were selected (see Figs. 4 and 5). The seaward and landward openness ~~index~~ indices were~~as~~ calculated as the average length of the selected radiating lines.

7) ~~The seaward and landward openness indices were obtained accordingly (Figs. 4, 5).~~

3 Results and Discussion~~s~~

3.1 Estimated openness indices under different scenarios

The openness indices with different intervals have been estimated in order to determine an optimal interval for applying this index for the study region. ~~We calculated openness index under different scenarios in order to determine the optimal interval for the~~ openness index ~~application of the openness index. Both~~ T~~t~~he seaward and landward openness indices, calculated with 15° and 10° intervals, exhibited relatively large year-to-year deviations~~ as~~ , compared with the ~~openness~~ indices ~~calculated~~ using the relatively smaller degree intervals (Fig. 6). The calculated landward and seaward indices using the 15° interval are at the maximum 7 % and 20 % larger than the 1° interval scenario. Only minor differences (maximum 5 %) were observed between the openness indices calculated using 1, 2 and 3° intervals. Generally, t~~T~~he larger degree intervals, such as 5°, 10° and 15°, resulted in fewer ~~radical~~radial lines; as a consequence, the weights of a few very long or short ~~radical~~radial lines on the average length will be relatively larger compared with the estimation using smaller intervals. Therefore, the associated uncertainties in the estimated openness index ~~may~~ will be larger when using ~~radical~~radial lines with larger intervals. The high frequency of ~~radical~~radial lines, e.g., using a 1° interval, ensures a higher possibility for capturing the details of the coastal openness variability. ~~Furthermore, using less frequent radical lines, e.g., 5° interval in Fig. 7 could be easily influenced by the shifting angles. As the shifting angle varies among 0° to 4°, substantial differences are observed among the calculated openness indexes.~~ Furthermore, potential effects of shifting angles (angle between the north and the nearest radial line) were tested and Figure 7 showed the cases for 5° intervals of radial lines with shifting angles of 0° to 4°. The results demonstrated that using different shifting angles can cause substantial differences in the estimated openness indices when the radial intervals are relatively large. However, if the interval is set as 1°, changing the shifting angle from 0° to 4° would result in openness indices with very small differences in consideration of relative changes in the positions of all radial lines. Therefore using low degree interval such as 1° for calculating the openness indices is preferred and should be recommended for other similar studies, although the computing time would be longer than higher degree intervals. The landward and seaward openness indices were differentiated although they both reflect morphological changes of the inlet over the last 5.4 ka. The seaward openness index reflected more accurately the embayment process in comparison with the landward openness index, as the most distinct changes of the inlet was from the sill in the east. The landward openness index, reflecting offshore distance, could also be important for considering sedimentary grain size, especially if information describing ~~for~~ the past prevailing wind direction becomes available. Seaward ~~-~~ and landward openness indices have ~~shown~~ ~~demonstarted~~demonstrated a continuous decline over the last 5.4 ka (Fig. 6), ~~reflecting the embayment process~~ caused by isostatic land uplift and the embayment process. The decreasing rate of the seaward openness index was generally more pronounced during 5.4-4.4 ka BP than during 4.4-0.1 ka BP. In contrast, the decline in the landward openness index was relatively smoother and no drastic transition was recorded ~4.4 ka BP.

3.2 Implications for sediment grain-size distributions

The openness indices calculated with 1° interval and 0° shifting angle were plotted along with the grain size data (Fig. 8). Correlations (r^2) between the openness indices and grain size data range between 0.47 and 0.65 ($p<0.01$) (Table 1). This suggests changes in coastal openness are important factor influencing the sedimentary grain size. Both the seaward openness index and sand content~~s~~ had the highest values between 5.4 and 4.4 ka BP ~~(Fig. 8)~~,~~.~~ and there is~~We have noted~~ a synchronous large decline in seaward openness and sand content~~s~~ around 4.4 ka BP (Fig. 8)~~,~~. ~~which~~ This further indicates a connection between the depositional environment and coastal openness variations. The maximum sand content at the core site was only ~0.4%, suggesting a relatively low bottom water velocity compared with open Baltic Sea waters (Jönsson et al., 2005). Generally, the closer to the shore, the more coarse-grained sediments can be deposited. However, the sediments in Gåsfjärden became more and more fine-grained as the coring site became shallower and closer to the shore (closer to present time, see Figs. 5 and 8), which was a result of less exposure and an increasingly protected location (reflected by the openness index)~~.~~ ~~This is because the core site becomes more and more protected even though it moves clooer to the shore.~~ At present, the sea-floor outside Gåsfjärden is characterised by sandy sediments, whereas gyttja clay is deposited in the sheltered Gåsfjärden (Al-Hamdani and Reker, 2007). The modern grain-size difference between the areas inside and outside Gåsfjärden is linked ~~with~~ to the different hydrodynamic statuses. The relatively higher sand content during 5.4 and ~~-~~4.4 ka BP may also be associated with the increased sand transport when Gåsfjärden had a relatively larger cross-sectional area. ~~However, T~~the ~~maximum sand content~~ at the core site ~~was only ~0.4%, suggesting a relatively low bottom water velocity compared with open Baltic Sea waters (Jönsson et al., 2005).~~ Based on an analysis of 201 sites along the Swedish coast characterised by complex bathymetry, Lindgren and Karlsson (2011) concluded ~~have estimated~~ that the mean critical depth separating the depositional areas from the erosion and transport areas i~~wa~~s located at 19 m. At ~~P~~present, ~~ly~~ our core~~ring~~ site has a water depth of 31 m. The relatively deeper water depth (sediment dominated by transport, instead of erosion) ~~. T~~together with sheltered ~~condition,~~condition resulted in the low sand content~~s are expected in the sediments~~.

Erosion from the surrounding islands since 5.4 ka has most likely occurred, but could be rather limited as these islands are mostly rocky with little soil cover. It may, however, result in a flux of relatively coarser grains to the coring site during the land-uplift. As the uplift process close to be linear (see Fig. 2), we might expect to see a rather linear change in the grain size data assuming the land uplift played the dominant role. However, the sand content and silt/clay ratios exhibit strong year-to-year variations, which indicates other factors than land uplifting could also participate in influencing grain-size distribution. For instance, coarse grains, such as sand, can also be transported to the coring site through storm events and intense wave action, sea ice or drifting sea weed. However, their impacts are not explicitly included in the openness indices. Furthermore, the recorded l~~L~~arge variability in the sand content~~s~~ ~~has been recorded~~ within the last millennium~~, which~~ may be linked with catchment disturbance from human activities (Karlsson et al., 2015; Ning et al., 2016).

The s~~S~~ilt/clay ratios can also reflect bottom water energy, with higher values indicating higher energy conditions. The silt/clay ratio was ~0.3 between 5.4 and 4.0 ka BP, and exhibited a continuous decline from 4.0 ka BP. The different pattern between the silt/clay and sand content~~s~~, particularly during the period when Gåsfjärden was relatively open, between 5.4 and 4.0 ka BP, suggested~~s~~ that different grain-size sediments ~~classes~~ respond differently to the changes in hydrodynamic conditions in this region. ~~Although~~ The ~~large~~ decrease of sand content~~s~~ ~~decreased~~ from 5.4 to 4.4 ka BP~~,~~ indicates ~~ing~~ a decline in bottom water velocity~~energy~~. However, ~~Even so,which~~the declined bottom water velocity ~~, the energy~~ was probably still high enough to maintain the silt/clay ratios, as silt and clay might have responded similarly to the changes in hydrodynamics. The~~at~~ ~~D~~different grain-size classes respond~~ing~~ differently to hydrodynamic changes ~~were were~~are also reported in two coastal sites in Italy (Molinaroli et al., 2009), where positive correlations between current velocities and silt (8-63 µm) and fine sand (63-105 µm) fractions were found in the two lagoons. The changes in landward openness, which reflect the offshore distance~~water depth changes~~~~embayment process~~, seem to follow the silt/clay ratios ($r^2 = 0.65$). In our data, the silt/clay ratios exhibited a significant decreasing trend (p<0.01, Mann-Kendall test) between 4.0 and 0.1 ka BP, which indicates a long-term impact of ~~lowered~~ decreased coastal openness on the grain-size distribution~~s~~.

4 Conclusions

Our DEM-based calculations of coastal openness ~~indexes~~indices have shown to be a useful tool when interpreting ~~in the interpretation of~~ long-term sedimentary grain-size data. A ~~relatively~~ high relative sea level wa~~i~~s linked with~~ a~~ large coastal openness ~~-~~and higher hydrodynamic energy, which in turn wa~~i~~s well reflected in the seaward openness index. The higher values of both sand content~~s~~ and the seaward openness index were recorded in the early part of the record, indicating that coastal ~~openness~~ morphology (presented by openness index) strongly influenced~~s~~ sand ~~grain-size~~ distribution. The differences in temporal dynamics of ~~t patterns for~~ sand content~~s~~ and silt/clay ratios~~-~~ indicate different grain-size sediments responds differently to hydrodynamic energy. ~~imply that finer particles~~ we~~are less sensitive to changes in hydrodynamic energy~~. The significant decline in silt/clay ratios between 4 and 0.1 ka ~~shows~~ demonstrated that a ~~coastal openness had a~~ long-term impact~~influence~~ of coastal openness on this finer grain-size sediment distributions. ~~The~~ Our DEM-based openness index can be easily applied to other coastal settings that have experienced large sea-level changes over time. The index could also be further used in predicting future dynamics by combing information about sea-level changes in a warmer future.

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Tables and Figures

Table 1. Correlation (r^2) matrix for the grain size data and the calculated openness indices

Index	Sand	Silt/clay
Landward openness	0.48	0.65
Seaward openness	0.47	0.56

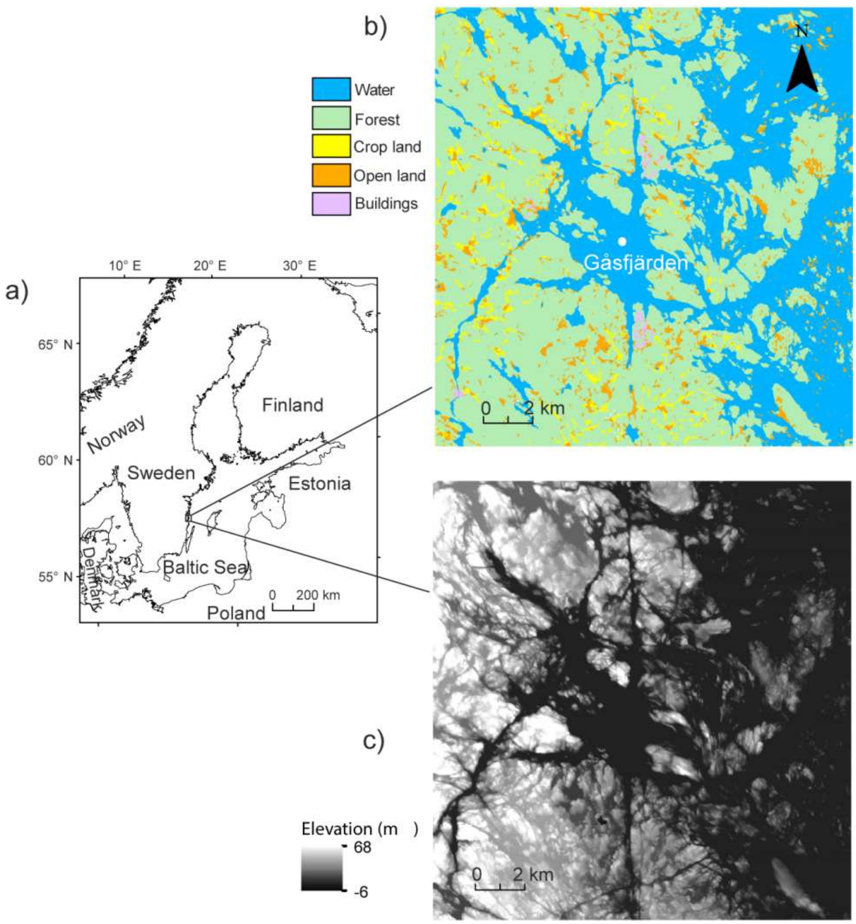

Figure 1 (a) Overview of the Baltic Sea region and the location of Gåsfjärden; (b) vegetation in the study region and the coring site (white filled circle) and (c) digital elevation model of the study region.

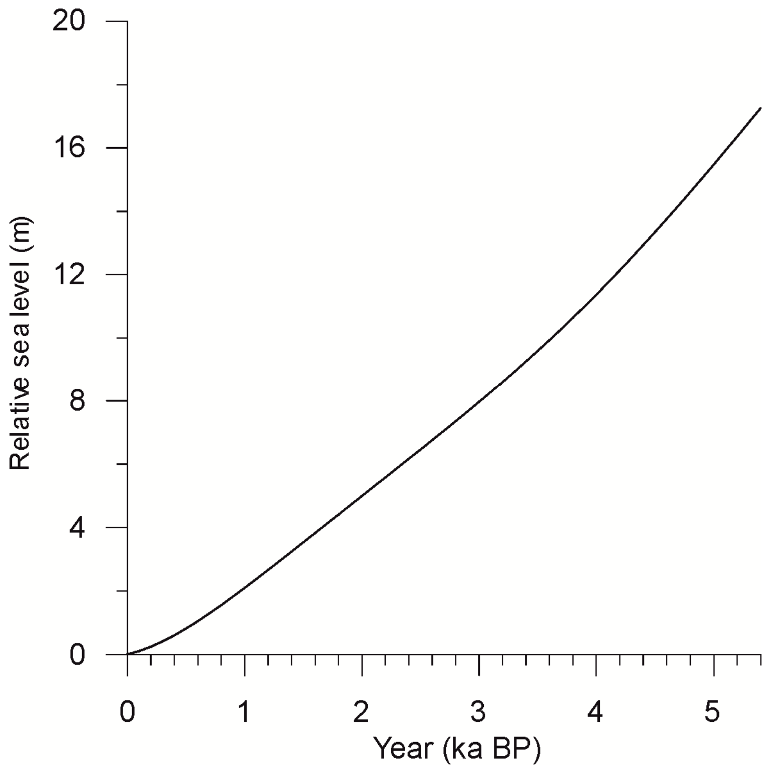

Figure 2 Variation of relative sea level in the study area over the last 5.4 ka based on empirical model by Påsse and Andersson (2005).

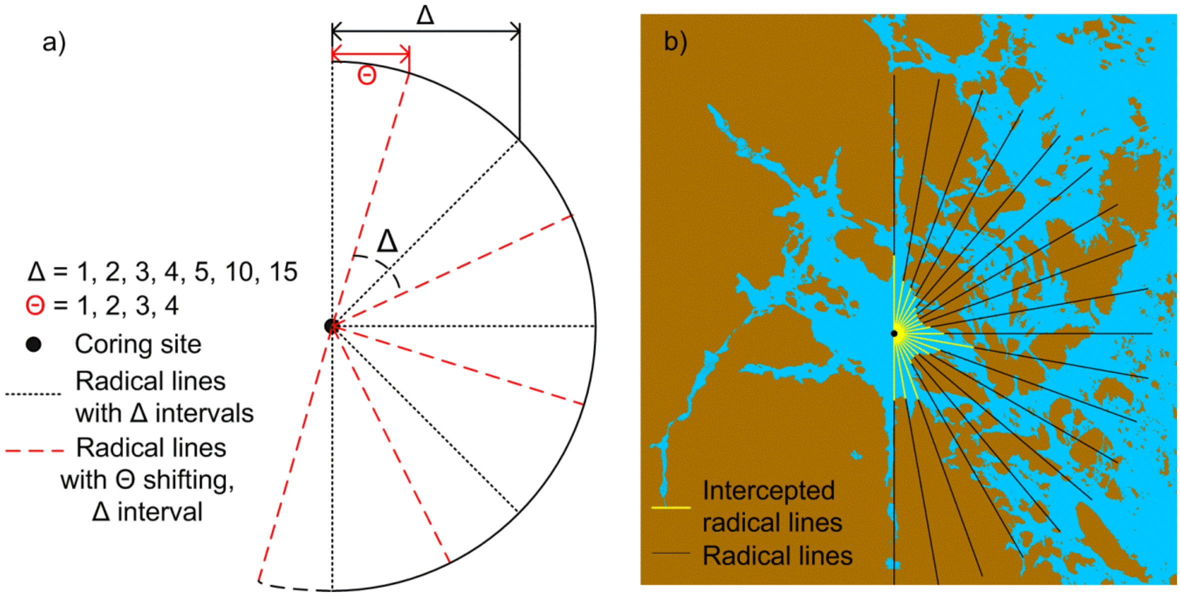

Figure 3 (a) Illustration of the 180 degree radiating lines, the intervals (Δ), and the shifting angles (Θ); (b) black and yellow lines representing the 8 km-long ~~radical~~radial lines and the intercepted lines for openness index calculation.

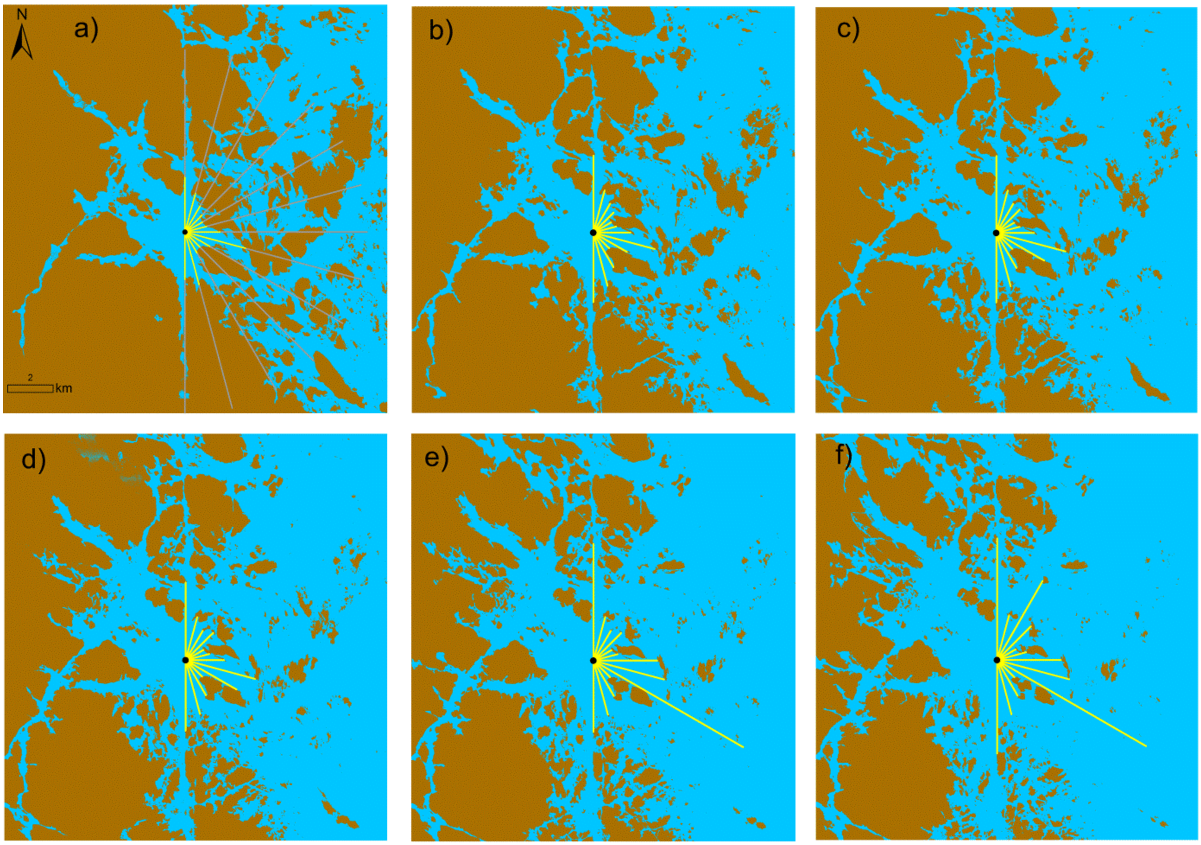

Figure 4 Illustrations showing the variations of seaward ~~radical~~radial lines intercepted with land over the last 5.4 ka years. (a) 0.1 ka BP (b) 2.5 ka BP (c) 3.5 ka BP (d) 4 ka BP (e) 4.5 ka BP (f) 5.4 ka BP.

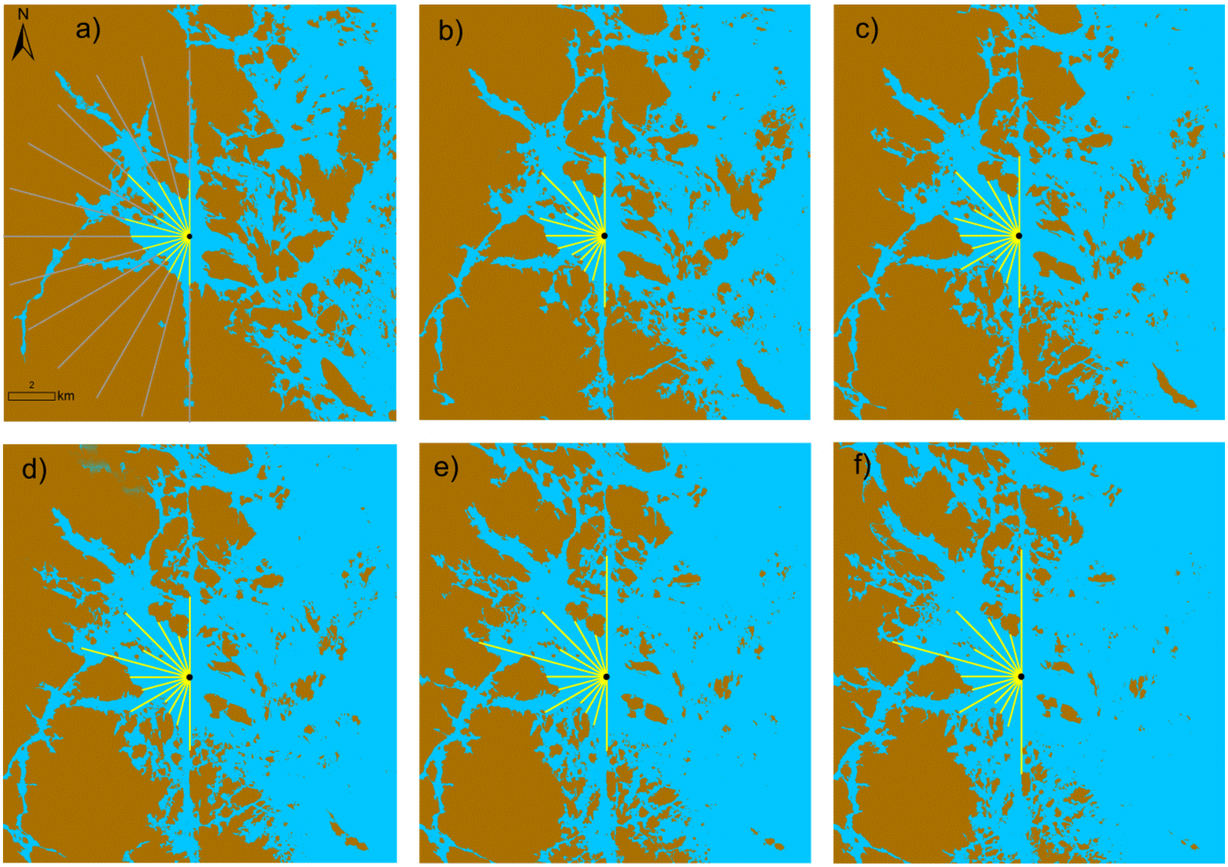

Figure 5 Illustrations showing the variations of landward ~~radical~~radial lines intercepted with land over the last 5.4 ka.

(a) 0.1 ka BP (b) 2.5 ka BP (c) 3.5 ka BP (d) 4 ka BP (e) 4.5 ka BP (f) 5.4 ka BP.

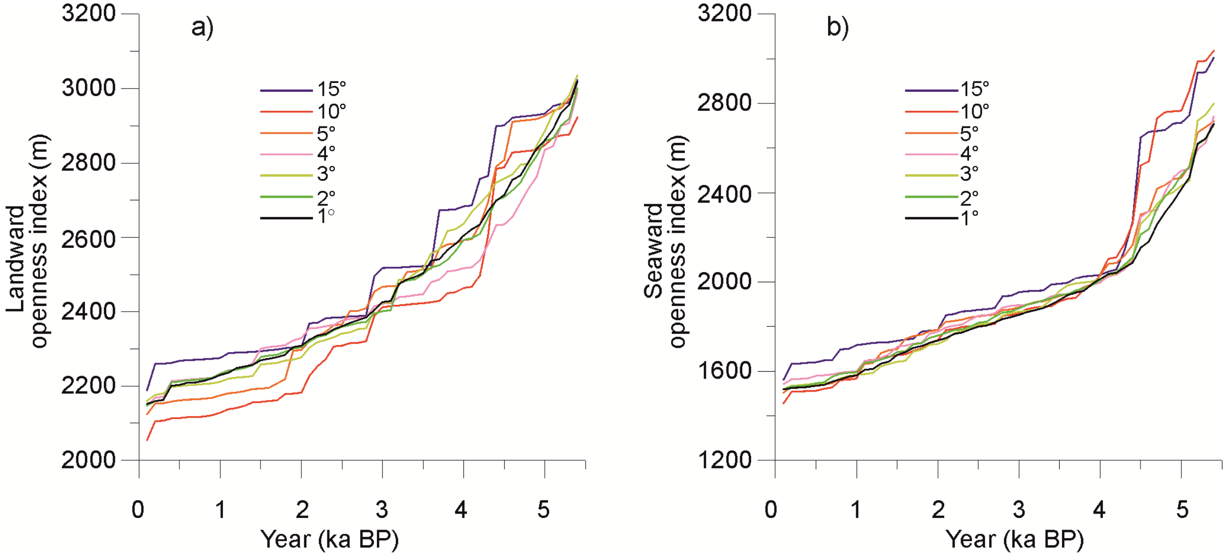

Figure 6 Calculated landward (a) and seaward (b) openness ~~indexes~~indices of Gåsfjärden over the last 5.4 ka using 1-5, 10 and 15° intervals.

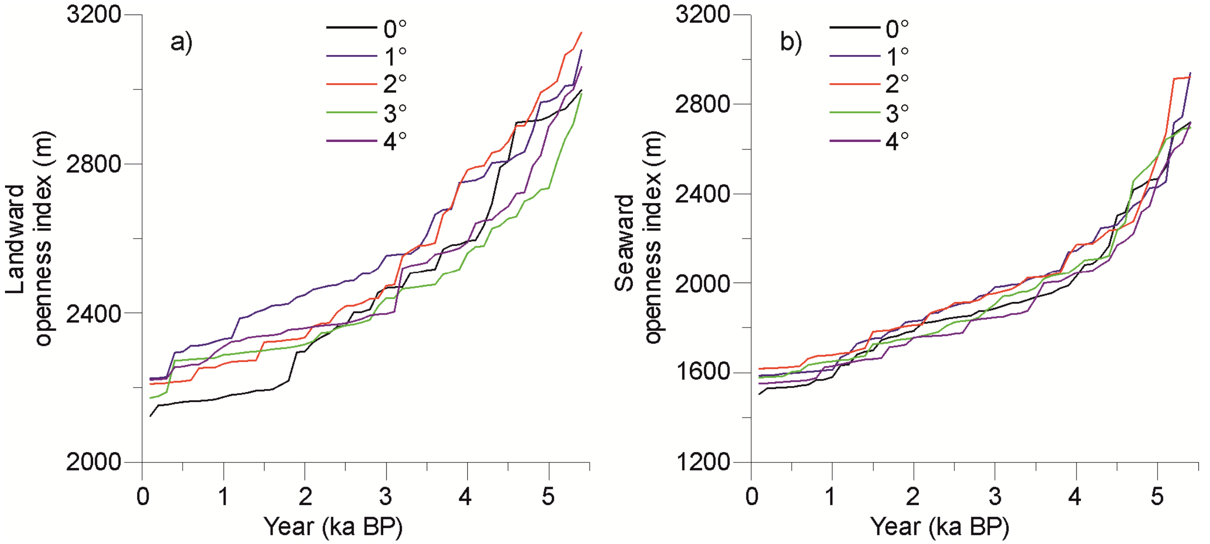

Figure 7 Calculated landward (a) and seaward (b) openness ~~indexes~~indices with 5° interval and 1-4° shift starting angles.

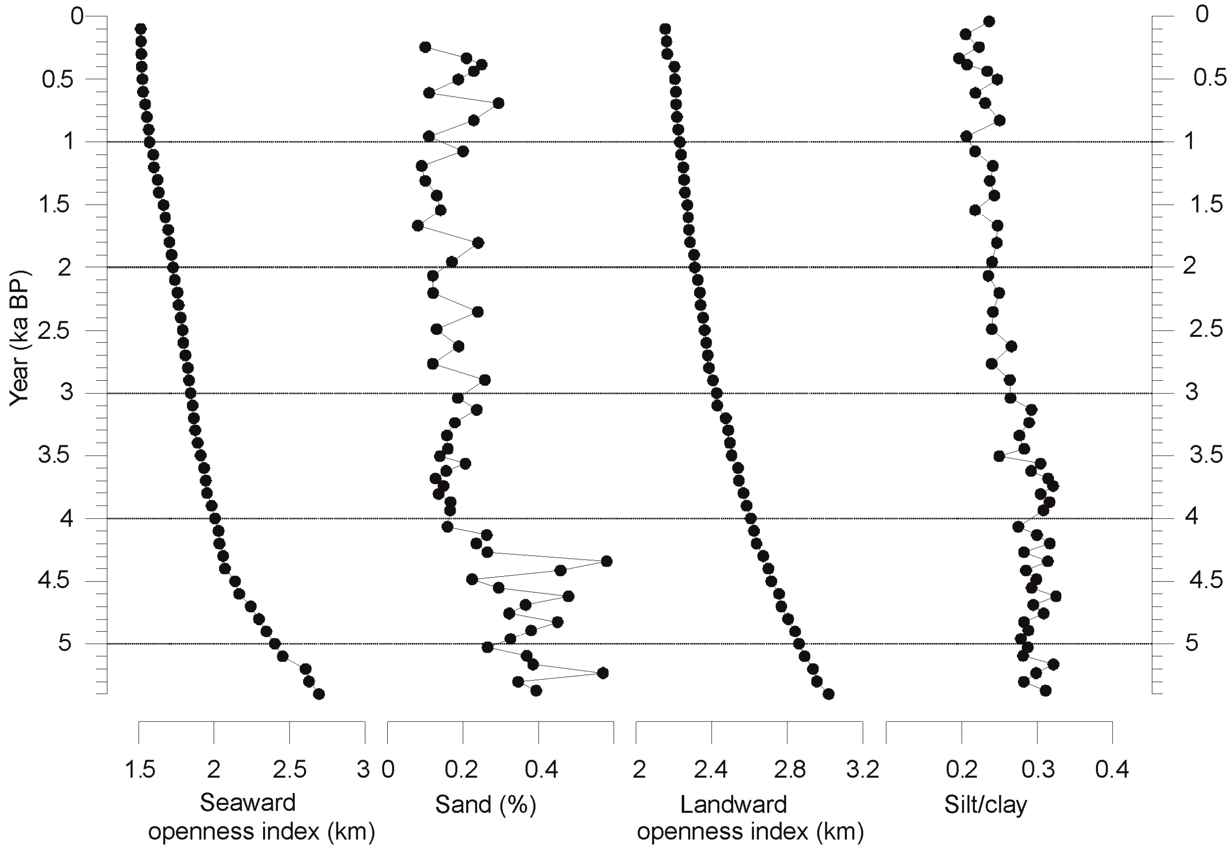

Figure 8 Comparison of the calculated openness ~~indexes~~indices (with 1° interval and 0° shifting) with the measured grain size from the sediment ~~data~~.