Earth Surf. Dynam. Discuss., doi:10.5194/esurf-2016-24, 2016
Manuscript under review for journal Earth Surf. Dynam.
Published: 21 April 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 long-term variations in grain-size distribution in sediments from Gåsfjärden, a fjord-like inlet on the south-west Baltic Sea, and explored potential drivers of the recorded changes in sediment grain-size data. Over the last 5.4 thousand years (ka), the relative sea level decreased 17 m in the study region, caused by isostatic land uplift. As a consequence, Gåsfjärden has been transformed from an open coastal setting into a semi-closed inlet surrounded on the east by numerous small islands. To quantitatively estimate the morphological changes in Gåsfjärden over the last 5.4 ka and to further link the changes to our grain-size data, a digital elevation model (DEM)-based openness index was calculated. In the period between 5.4 and 4.4 ka BP, the inlet was characterised by the largest openness index. During this interval, the highest sand contents (~0.4%) and silt/clay ratios (~0.3) in the sediment sequence were recorded, indicating relatively high bottom water energy. After 4.4 ka BP, the average sand content was halved to ~0.2% and the silt/clay ratios showed a significant decreasing trend over the last 4 ka. These changes are found to be associated with the gradual embayment of Gåsfjärden as represented in the openness index. The silt/clay ratios exhibited a delayed and slower change compared with the sand contents, which further suggest that finer particles are less sensitive to changes in hydrodynamic energy. Our DEM-based coastal openness index has proved to be a useful tool for interpreting the sedimentary grain-size record.

1 Introduction

Sedimentary grain-size distribution provides important information on the depositional conditions and has been widely analysed in both modern samples and sediment cores (Tanner, 1992; Yang et al., 2008; Virtasalo et al., 2014). Grain-size distribution is generally governed by hydrodynamic energy conditions, and the higher the energy conditions, the higher proportion of coarse grain (Dearing, 1997; Jönsson et al., 2005). Water depth, wind direction and strength, as well as basin morphometry, and man-made constructions such as dam-building, influence the bottom water hydrodynamics and may lead to different characteristics in grain-size distributions. The Baltic Sea is connected with the North Atlantic with the narrow

Danish Straits. Although tide can strongly influence grain-size distribution in coastal region (Zhang et al., 2002), the amplitude of the tide recorded in the Baltic Sea is only several centimetres (Ekman and Stigebrandt, 1990) and therefore its impact on sediment grain-size is negligible. Wind conditions and coastal morphometry are probably the most important factors that influence 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 Holocene resulted in shoreline displacements in the coastal zones of the Baltic Sea. A maximum 60 m decline in relative sea level (RSL) has been recorded over the last six thousand years (ka) (Påsse and Andersson, 2005), leading to basin isolations and long-term changes in the coastal morphometry (Eronen et al., 2001). The changes in the coastal morphometry variations may potentially be linked with variations in grain-size distributions, 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 perspective, quantitative estimates of the coastal morphometry, including water depth and cross-section areas are needed. Achieving such estimate is difficult and may cause large uncertainty, due to: 1) the lack of high-resolution bathymetry data, 2) difficulties in selecting the cross-section area and 3) unknown sedimentation rates. Alternatively, previous studies by Lindgren (2011) used a geographical information system (GIS)-based wave fetch index, called 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).There are also other GIS-based indexes 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 indexes have been so far restricted in depicting modern coastal morphometry and have not yet employed in the context of paleoenvironmental studies.

In this study, our approach of calculating an openness index using a Digital Elevation Model-based method 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 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

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. The surface area of Gåsfjärden is 22 km^2 and the mean and maximum water depths are 10 m and 51 m respectively. 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).

2.2 Grain-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 covering the last 5.4 ka (Ning et al., 2016). Organic matter, 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 section 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).

2.4 Openness index calculation

The calculation of the openness index 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 lines towards the east (seaward) and the other 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 lines with a 5° interval but with different shifting angles θ (1-4°) were also created (see Fig. 3).
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. The openness index was calculated as the average length of the selected lines.
7) The seaward and landward openness indexes were obtained accordingly (Figs. 4, 5).

3 Results and Discussions

3.1 Estimated openness indexes under different scenarios

We calculated the openness index under different scenarios in order to determine the optimal interval for the application of the openness index. Both the seaward and landward openness indexes, calculated with 15° and 10° intervals, exhibited relatively large deviations as compared with openness indexes calculated using the smaller degree intervals (Fig. 6). Only minor differences were observed between the openness indexes calculated using 1-3° intervals. The larger degree intervals, such as 5°, 10° and 15°, resulted in fewer radical lines; as a consequence, the weight of a few very long or short radical 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 be larger when using radical lines with larger intervals. The high frequency of radical lines 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.

Seaward and landward openness indexes have shown a continuous decline over the last 5.4 ka (Fig. 6), reflecting the embayment process caused by isostatic land uplift. 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

Both the seaward openness index and sand contents had the highest values between 5.4 and 4.4 ka BP (Fig. 8). We have noted a synchronous large decline in seaward openness and sand contents around 4.4 ka BP, which indicates a connection between the depositional environment and coastal openness variations. 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 different hydrodynamic statuses. The relatively higher sand content during 5.4-4.4 ka BP may also be associated with the increased sand transport when Gåsfjärden had a relatively large cross-sectional area. The maximum sand content 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) have estimated that the mean critical depth separating the depositional areas from the erosion and transport areas was located at 19 m. Presently our coring site has a water depth of 31 m. Together with sheltered condition, low sand contents are expected in the sediments. Large variability in the sand contents has been recorded within the last millennium, which may be linked with catchment disturbance from human activities (Karlsson et al., 2015).

Silt/clay ratios 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 contents, particularly during the period when Gåsfjärden was relatively open, between 5.4 and 4.0 ka BP, suggests that different grain-size classes respond differently to changes in hydrodynamic conditions. Although sand contents decreased from 5.4 to 4.4 ka BP, indicating a decline in bottom water energy, the energy was probably high enough to maintain the silt/clay ratios. Different grain-size classes responding differently to hydrodynamic changes were 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 embayment process, seem to follow the silt/clay ratios. 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 coastal openness on the grain-size distributions.

4 Conclusions

Our DEM-based calculations of coastal openness indexes have shown to be a useful tool in the interpretation of long-term sedimentary grain-size data. A relatively high relative sea level is linked with a large coastal openness and high hydrodynamic energy, which is well reflected in the seaward openness index. The high values of both sand contents and the seaward openness index were recorded in the early part of the record, indicating that coastal openness strongly influences grain-size distribution. The different patterns for sand contents and silt/clay ratios imply that finer particles are less sensitive to changes in hydrodynamic energy. The significant decline in silt/clay ratios between 4 and 0.1 ka shows that coastal openness had a long-term influence on grain-size distributions. The DEM-based openness index can be easily applied to other coastal settings that have experienced large sea-level changes over time.

Acknowledgements

W. Zhendong is thanked for the help on data analysis. The project was funded by FORMAS Strong Re-search Environment: Managing Multiple Stressors in the Baltic Sea (217-2010-126). We thank the captain and crew of R/V Ocean Surveyor for help during sampling. We thank Nathalie V. Putten and Åsa Wallin for guidance during grain size analysis. We also acknowledge funding from the Crafoord Founda-tion and the Royal Physiographic Society in Lund. J. Tang was financed by the Villum foundation (VKR022589) and The Danish National Research Foundation (CENPERM DNRF100)

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Manuscript under review for journal Earth Surf. Dynam.
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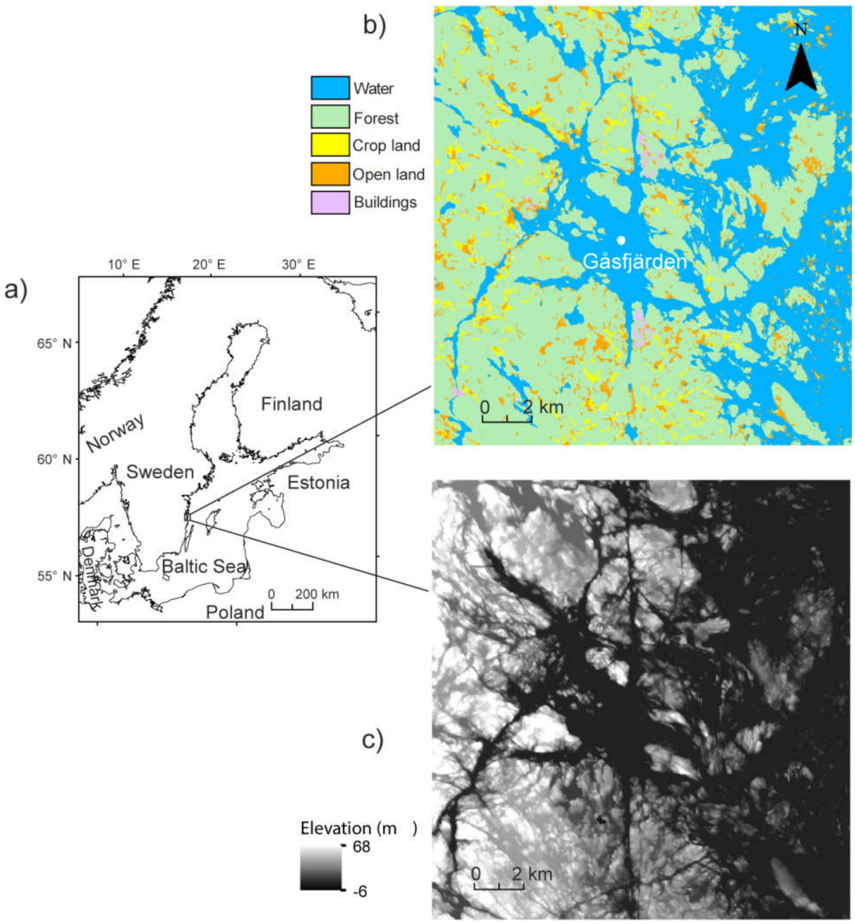
Figures



5 **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.**

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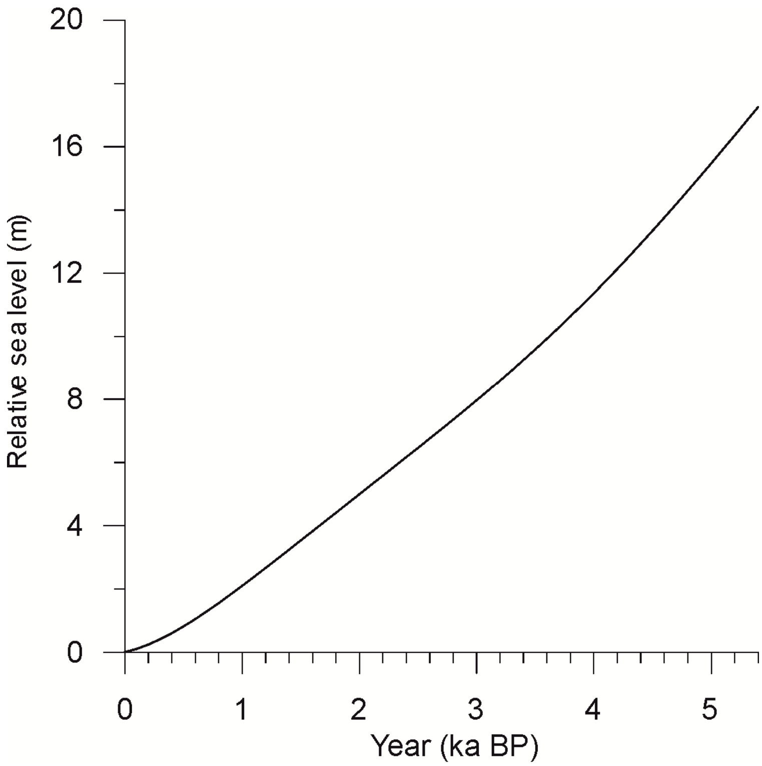

Figure 2 Variation of relative sea level in the study area over the last 5.4 ka based on empirical model by Påsse and Andersson (2005).

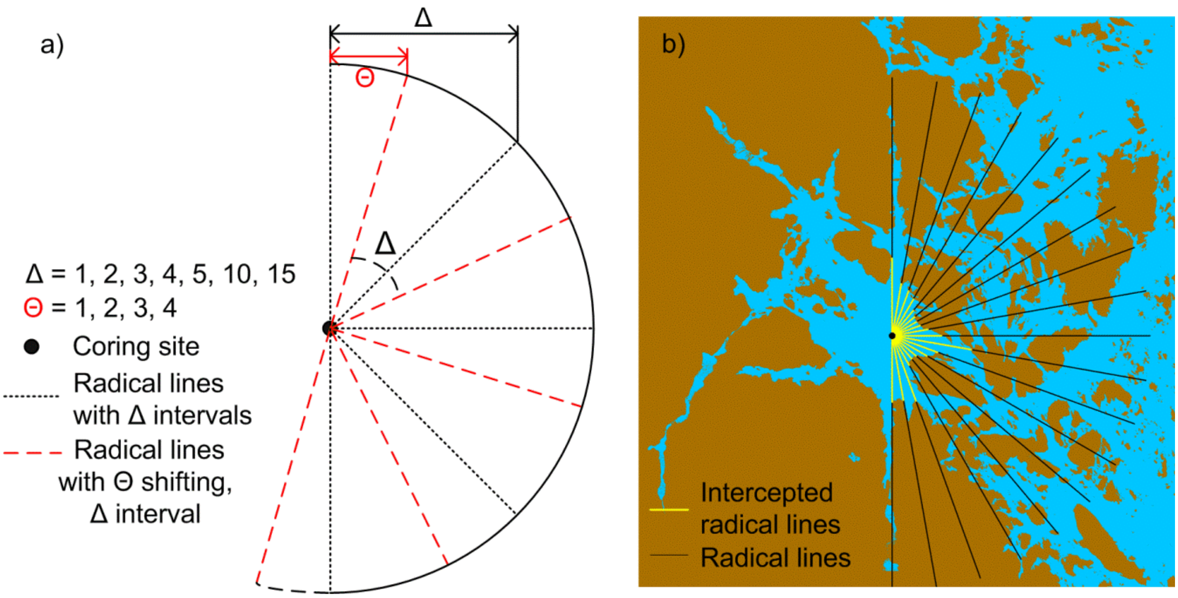

Figure 3 (a) Illustration of the 180 degree radiating lines, the intervals (Δ), and the shifting angles (Θ); (b) black and yellow lines representing the 8 km-long radical lines and the intercepted lines for openness index calculation.

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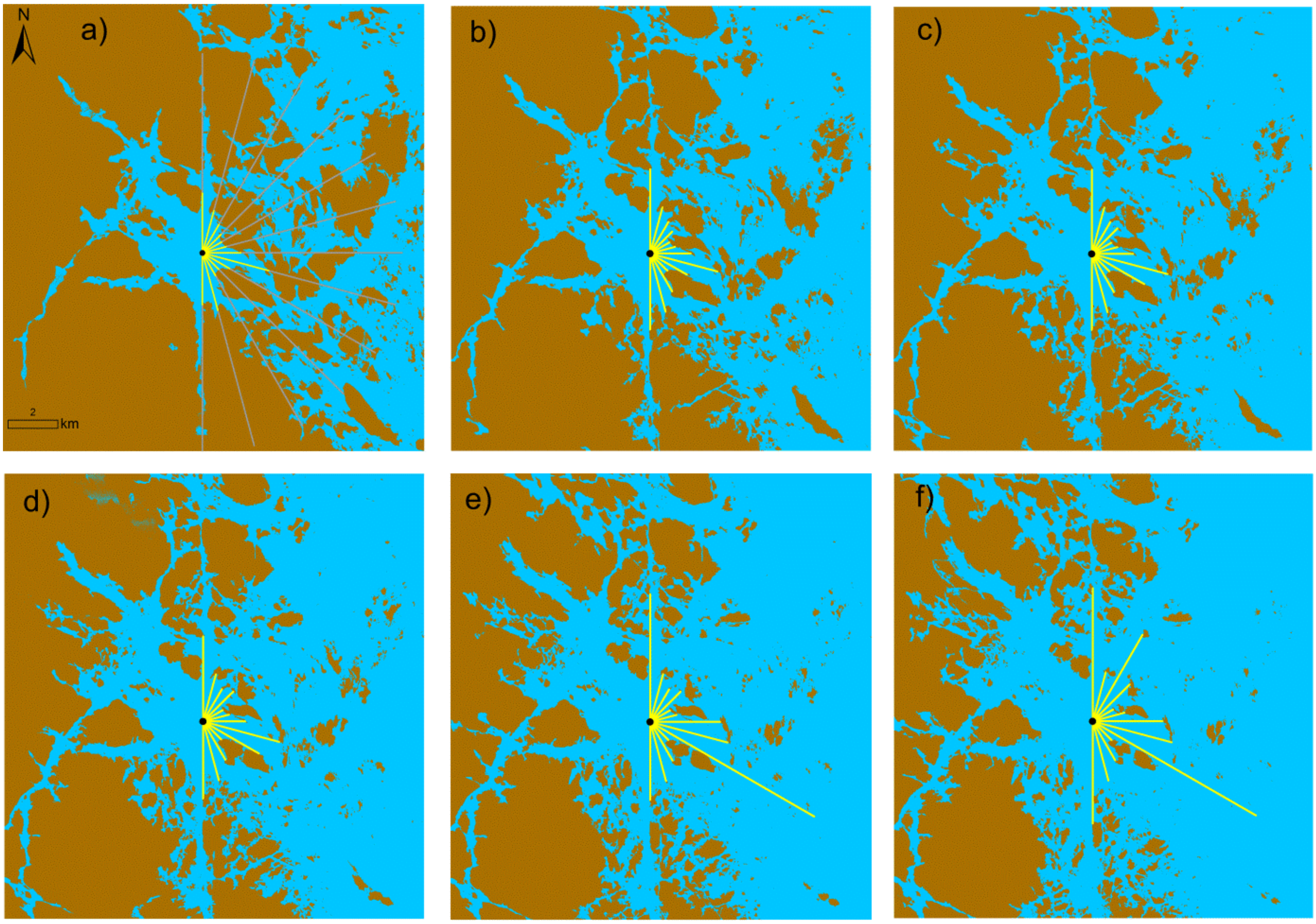

Figure 4 Illustrations showing the variations of seaward radical lines intercepted with land over the last 5.4 ka years. (a) 0.1 ka BP (b) 2.5 ka BP (c) 3.5 ka BP (d) 4 ka BP (e) 4.5 ka BP (f) 5.4 ka BP.

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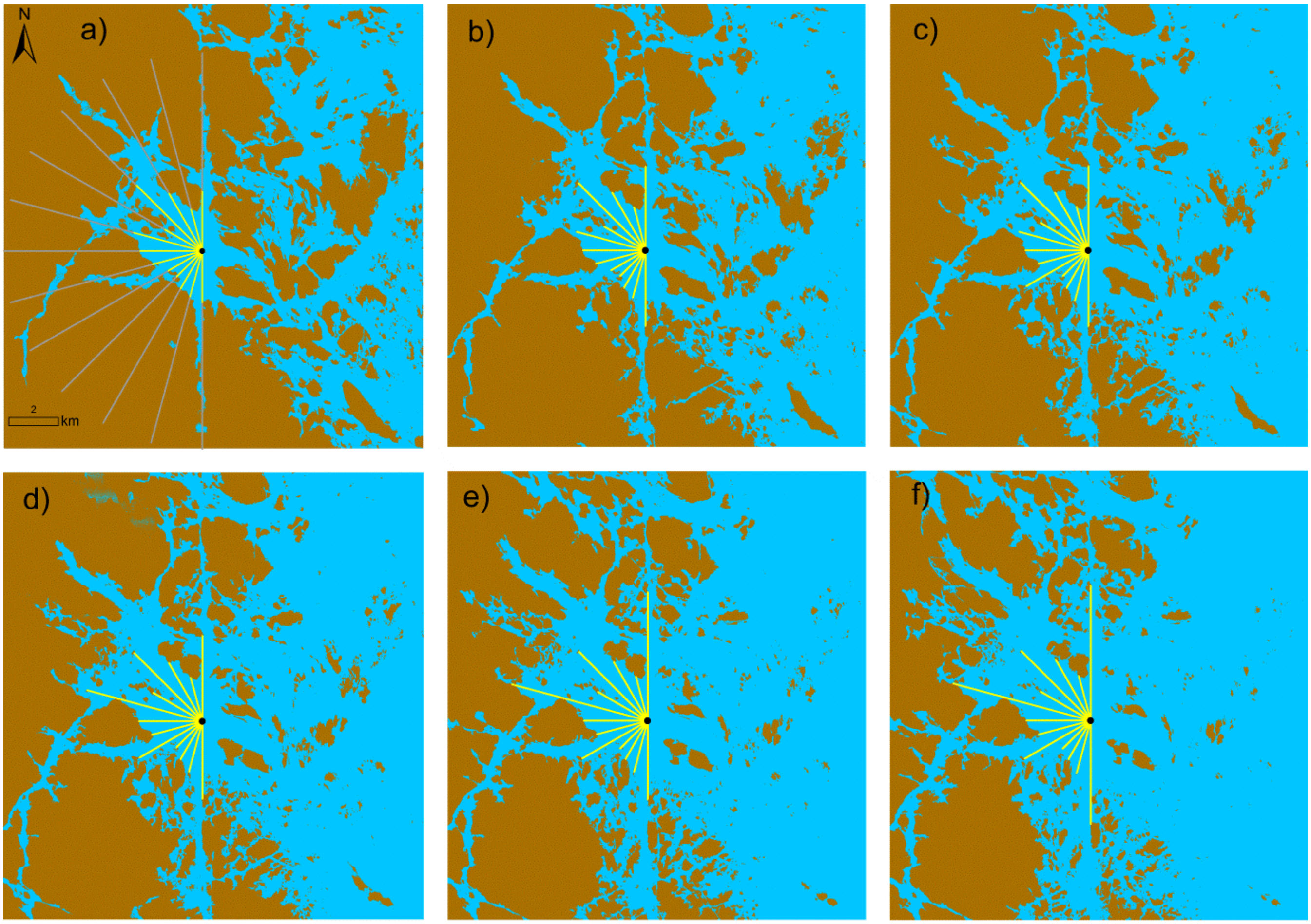

Figure 5 Illustrations showing the variations of landward radical lines intercepted with land over the last 5.4 ka. (a) 0.1 ka BP (b) 2.5 ka BP (c) 3.5 ka BP (d) 4 ka BP (e) 4.5 ka BP (f) 5.4 ka BP.

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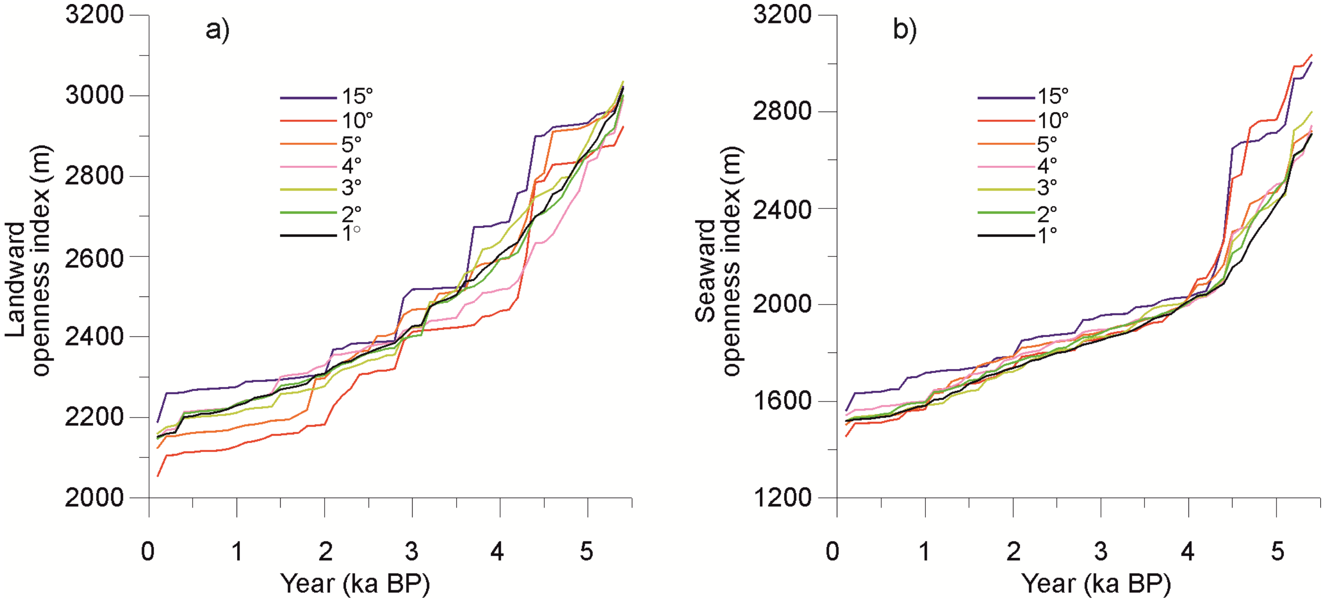

Figure 6 Calculated landward (a) and seaward (b) openness indexes of Gåsfjärden over the last 5.4 ka using 1-5, 10 and 15° intervals.

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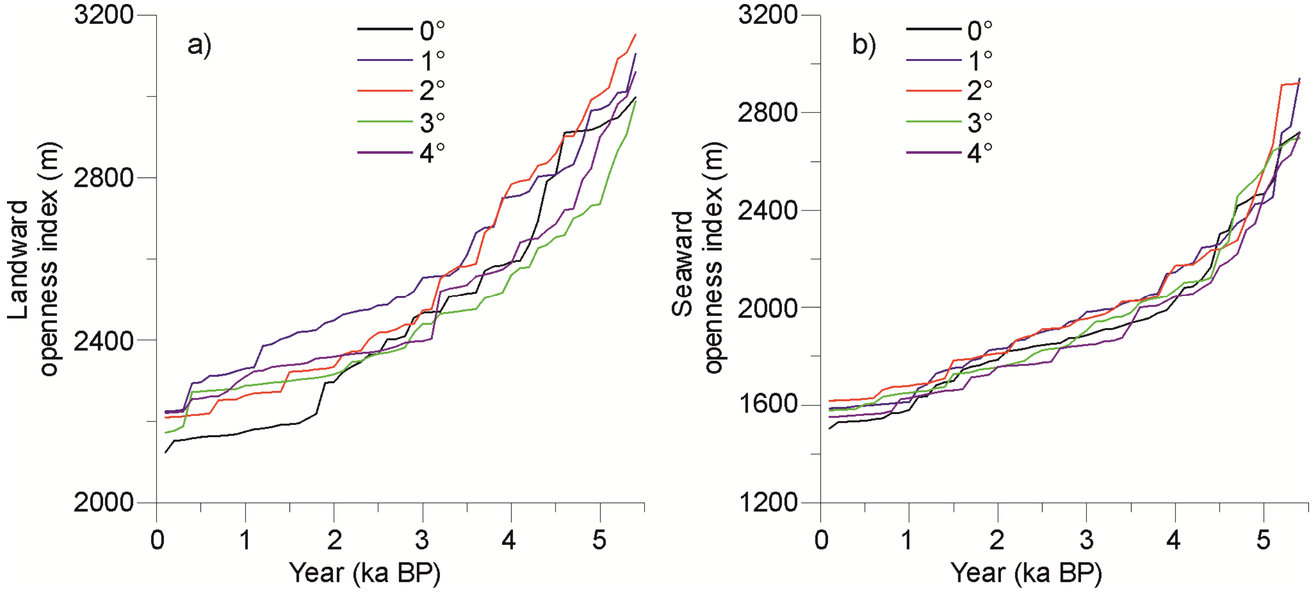

Figure 7 Calculated landward (a) and seaward (b) openness indexes with 5° interval and 1-4° shift starting angles.

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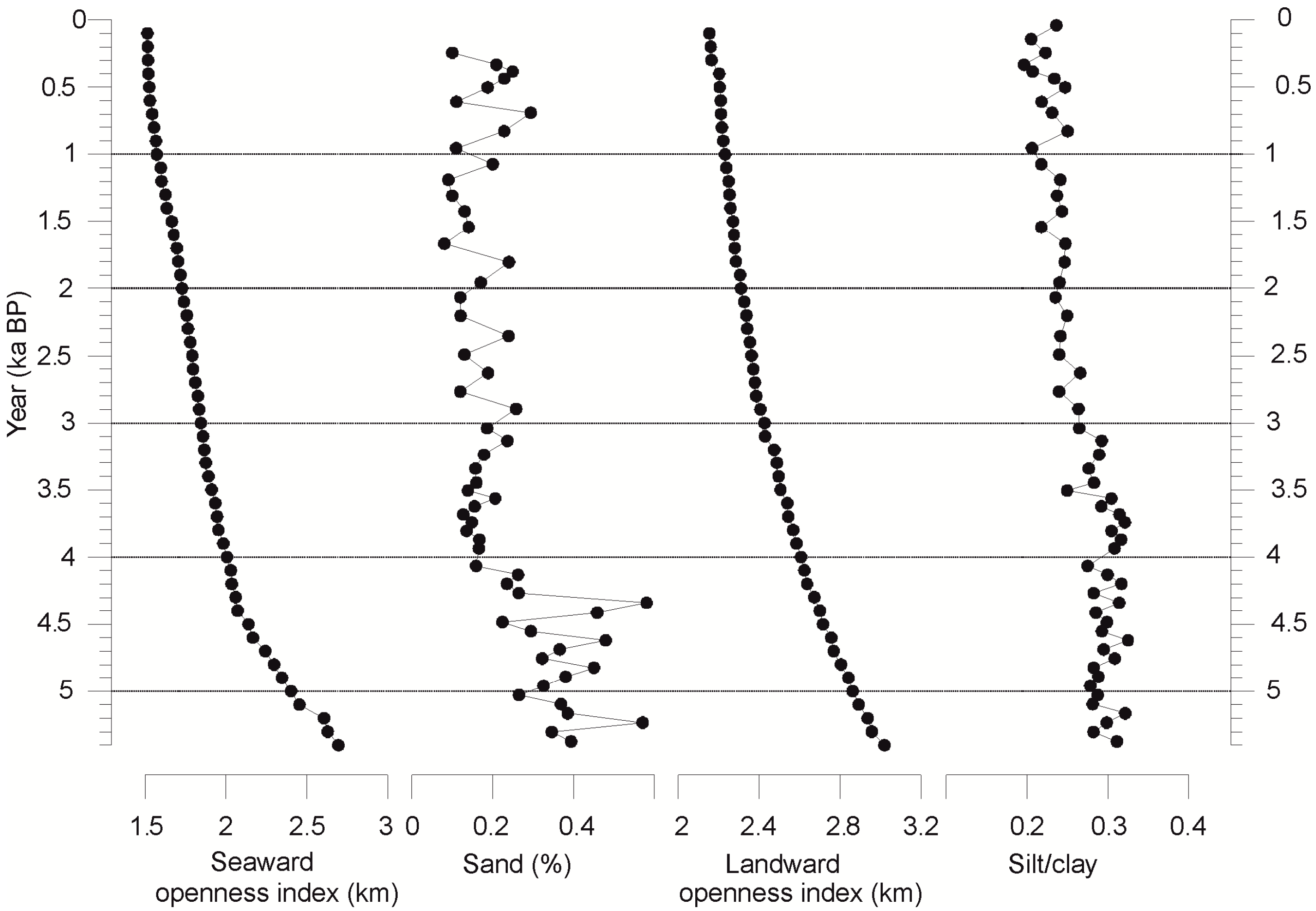

Figure 8 Comparison of the calculated openness indexes with grain size data.