Coastal erosion and coastal protection near the bridge across Jökulsá river, Breiðamerkursandur, Iceland

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Abstract – During the twentieth century there has been a substantial coastal erosion on Breiðamerkursandur near the bridge across Jökulsá river. From 1904 to 2003 the erosion has been 770 m or about 8 m/year. This erosion threatens the safety of the road (Route One) across Breiðamerkursandur and two powerlines. Since 1990 the Public Roads Administration has initiated various research projects in the area, the aim being to maintain a secure road across Breiðamerkursandur. Herein, this research is described and the main emphasis is on the possibility of securing the road by defending the coast. Sea defences are shown to be a viable solution to the problem of maintaining a secure road across Breiðamerkursandur. The feasibility of sea defences is among other things based on the fact that land at the southeast coast of Iceland is rising due to reduced ice volume of glaciers in the area. Current uplift rates at the edge of Vatnajökull are 15 mm/year and the uplift rate may be as high as 40 mm/year in 2050, with total uplift at the ice edge of 4 m from 2000 to 2100.

Keywords: Coastal erosion, coastal protection.

The retreat of Breiðamerkurjökull and the cause of the coastal erosion

The location of the study area within Iceland is shown in Fig. 1. Price (1982) gives a good overview of the changes of Breiðamerkurjökull, Breiðamerkursandur, Jökulsárlón and Jökulsá from 1890 to 1980. Breiðamerkurjökull reached its maximum extent in historical times about 1890 and has since then been retreating (Fig. 2). The glacier did not retreat evenly and at the outlet of Jökulsá from Jökulsárlón the glacier started to readvance sometimes before 1920. At the outlet the glacier reached furthest south in 1933 when according to Björnsson (1993) it advanced a little across the moraine ridges which are closest to outlet.

From 1890 to 2003 the glacier has retreated about 4,7 km (Fig. 4). In 2003 the area of Jökulsárlón was 17,0 km^2. For comparison it should be noted that in 1975 the area of Jökulsárlón was 7,9 km^2 (Boulton et al.,1982).

Scientists believe that the ice front was much further to the north, than it is now, when the country was colonized in about 900 A.D. After 1200 A.D. to 1400 A.D. glaciers begin to advance. According to Knopf's map from 1735 the glacier was 9 km from the beach in 1732 (Þórarinsson, 1943) and according to the map of Sveinn Pálsson from 1794 and information in his biography it can be expected that the ice front was 2,5 km from the beach in 1793 (Þórarinsson, 1943). Nowhere in written records from past centuries is it mentioned that on

Breiðamerkursandur there existed a lake or a lagoon where Jökulsárlón is now. It is, therefore, concluded that the glacier produced the basin of Jökulsárlón when advancing across Breiðamerkursandur. The fact that such a deep basin can be eroded into the sand is caused by a complicated interaction between the glacier and the river that flows beneath it. Without the river the glacier can not produce such a deep basin because it is the river that carries the sediment to the sea.

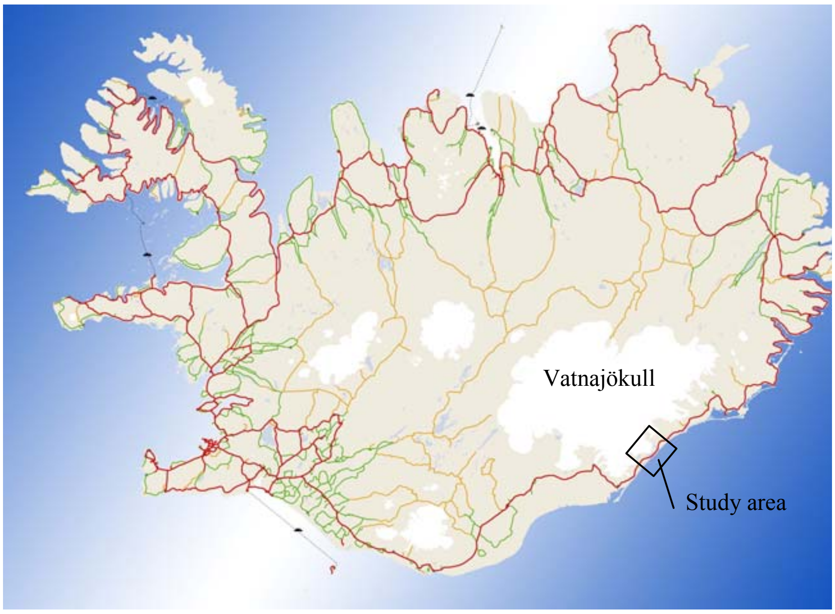

Figure 1. Location of the study area within Iceland. Glaciers are white. The picture also shows the Icelandic road system.

The bathymetry of Jökulsárlón was measured in 1975 (Boulton et al., 1982). The volume of Jökulsárlón in 1975 was estimated to be 500 million m^3. Boulton et al. (1982) concluded that the glacier eroded the basin of Jökulsárlón in a period of maximum 135 to 175 years. Their conclusion is based on the information Þórarinsson (1943) collected on the location of the ice front in past centuries. The sediment load of the river must, therefore, on average have been 3 to 4 million m^3/year.

Radio echo-soundings of Breiðamerkurjökull show that under the glacier (north of Jökulsárlón) there is a 2 to 4 km wide and 20 km long fjord which bottom is as much as 300 m below sea level (Björnsson et al., 1992 and Björnsson, 1994 and 1996). Björnsson (1996) argues that the fjord could have been produced during the advance of the glacier after 1100 A.D. The volume of the fjord is 11500 million m^3 (Jökulsárlón included) and if the whole fjord was produced in 800 years the sediment load of Jökulsá must have been on average 14 million m^3/year (Björnsson, 1996). This estimate of the sediment load of Jökulsá is four times higher than the previous estimate which was only based on the estimated sediment load during the period when the basin of Jökulsárlón was produced.

After the glacier started to retreat, and Jökulsárlón emerged, the sediment load carried by Jökulsá to the sea changed from being about 14 million m^3/year to be negligible. The reason for this is that all the sediment load carried by the river is now trapped by Jökulsárlón. The shape of the coast in the beginning of this century was influenced by the fact that Jökulsá carried substantial amount of sediment to the sea (Figures 2 and 4). The coast had advanced until littoral currents were able to carry the sediment load of the river to both east and west of the river outlet. After the sediment load of the river was reduced the shape of the shoreline was not in equilibrium with the currents along the coast. The currents are still eroding sediment from the shore but no sediment is added to the coast by the river. Sediment is, therefore, continuously lost from the coast which is eroding (Figures 2 and 4) towards a new equilibrium.

The current rate of the coastal erosion

The shoreline at Breiðamerkursandur is a part of a relatively straight shoreline that extends between two headlands of solid rock, Ingólfshöfði which is 33 km to the west of Jökulsá and Þrándarholt which is 22 km to the east of Jökulsá (Figure 3). In Figures 4 and 5 the shoreline at the Jökulsá river outlet is shown for the years 1904, 1945, 1960, 1982, 1989 and 1997. In Fig. 4 only a section of a map is shown that extends from Ingólfshöfði in the west to Höfn í Hornafirði in the east (Víkingsson, 1991). Erosion at the Jökulsá river outlet is occurring in a 8 km long reach. The Jökulsá river outlet marks the centre of this reach so that erosion extends 4 km to both the west and the east of the outlet. Further to the east and west the changes in the shoreline are much smaller.

In Table 1 the distance between the coastal defence line and the shoreline is shown as measured along section number 9 which is located about 100 m east of Jökulsá river (Fig. 5). According to Table 1 the shoreline erosion has been 765 m in 99 years or 7.7 m/year on average. Assuming that the erosion started in 1930 when Jökulsárlón started to emerge the erosion rate was highest 20.7 m/year for the period 1930-1945 but is 5.5 m/year for the period 1982-2003. It can, therefore, be concluded that the erosion is slowing down.

Table 1. Shoreline changes along section number 9

Year	Distance (m) from shoreline to defence line along section number 9	Period	Erosion rate m/year
1904	900		
1945	590	1930-1945	20.7
1960	390	1945-1960	13.3
1982	250	1960-1982	6.4
1989	205		
1997	195		
2003	135	1982-2003	5.5

The erosion at Breiðamerkursandur has created approximately 2 to 4 m high steep bank which is continuously being undermined by the erosion of the shoreline. When this bank has retreated towards the structures in this area (bridge, road, powerlines) their foundations will be undermined. On October 21st 2004 the shortest distance between the bank and the road 1000 m east of the river was 71 m, the shortest distance between the bank and a powerline was 26.2 m and the shortest distance from the bank to the bridge was 250 m. The erosion of this bank has been monitored since 1991. The results are shown in Fig. 6b together with a picture of the bank (Fig. 6a). The 5-year average erosion rate of the west bank (1200-2000 m west of the river) was high in the beginning and equal to 9 m/yr in 1996 and has since continuously reduced and was 2 m/yr in 2004. The 5-year average erosion rate of the east bank (1000-1800 m east of the river) has been more or less constant and equal to 4.5 m from

1996-2004. These numbers are somewhat lower than the erosion along section 9, the reason being that section 9 is in the center of the erosion area but the measurements of the bank are further to the east and west where the landscape has not been influenced by the river channel.

The impact of future land uplift around Vatnajökull on coastal erosion

The glaciers in Iceland retreated during the twentieth century and it has been estimated that the Vatnajökull ice cap reduced by 182 km^3 from 1890 to 1978 (Pagli et al., 2005). Current uplift rates at the edge of Vatnajökull are about 15 mm/year (Sigmundsson et al., 2005). It has been estimated that the southern part of Vatnajökull ice cap may be reduced by about 500 km^3 from 2000 to 2100 (Jóhannesson et al., 2004) due to a global warming rate of 2.25˚C/100yr. It is therefore not unreasonable to expect that the total reduction of Vatnajökull icecap may be about 1000 km^3 from 2000 to 2100. This reduction of ice volume will influence the uplift rates which may be as high as 40 mm/year in 2050, with total uplift at the ice edge of 4 m from 2000 to 2100 (Sigmundsson et al., 2005).

The Bruun Rule of erosion (Bruun, 1983) states that if sea-level rises by a there will be a coastal erosion s equal to

$$s = la/h \qquad (1)$$

where h is the maximum depth of exchange of material between the nearshore and the offshore and l is the length of profile of exchange. The rule is based on the assumption of a closed material balance system between the (1) beach and nearshore and (2) the offshore bottom profile. It is further assumed that full profile equilibrium exists which means that the combined beach and offshore profile maintains an equilibrium shape and that the shore or section of shore to which the rule is applied is in quantitative material-balance condition.

The impact of land uplift should have the same effect on the coast as lowering the sea-level. Herein, it will be assumed that Eq. 1 can be used to estimated the impact of the land uplift on the coastal erosion rate at Breiðamerkursandur although the Bruun Rule of erosion may not be as applicable for the case of lowering sea-level as for the case of rising sea-level. Substituting a equal to 40 mm/year, l equal to 700 m if h is 10 m and l equal 1200 m if h is 15 m into Eq. 1 the result is s = 2.8 – 3.2 m/year. This means that the future land uplift around Vatnajökull may cause the erosion rate at Breiðamerkursandur to lower by as much as 3 m/year by the year 2050.

Coastal protection

In 2003 the banks of Jökulsá river were protected following a substantial erosion of the river banks due to a flood in the river in October 2002. In conjunction with this project a defense line for the road across Breiðamerkursandur was defined. The defence line is the line where sea defenses will be built in due time to prevent sea flooding and erosion (Ísaksson, 1994). The defense line is shown in Fig. 5. Fig. 5 also shows the present location of the road and the future road alignment. The location of the defence line is based on the assumption that the road alignment east of the river will be changed. In 2003 60.000 m^3 of armour stone and quarry run were used to for the bank revetment, two rock thresholds across the river channel and a 240 m long section in the defence line east of the river. The total cost was about 1.3 million USD (80 million isl. kr.). For this project a rock quarry was opened 12 km west of

Jökulsá river. The forecasted quarry yield is 54% > 0,2 tn, 44% > 0,5 tn, 37% > 1,0 tn, 20% > 5 tn and 7% > 20 tn.

In order to monitor the changes in the area and to be able to do preliminary estimates of the feasibility of coastal defences in the area the bathymetry of the nearshore area south of Breiðamerkursandur was measured in 1996, 2002 and 2003. The result for 2003 is shown in Fig. 7. In Fig. 8 the bed elevations along sections 9 and 10 are shown. The location of the defence line and the road is also shown in Fig. 8. The bed is characterised by shoals that are at a distance about 400 m offshore at a depth of about 5 m. The bedslope between the 5 and 10 m depth contours is 1:60. There is a relatively flat area between the 10 and 15 m depth contours with a slope of 1:100. Then the slope steepens again towards Breiðamerkurdjúp. In 2003 the distance along section 9 from the defence line to the mean sea level bed contour was 150 m and the distance from the defence line to the 5 m depth contour was 300 m.

The total length of the defence line is 1000 m (350 m west of Jökulsá and 650 m east of Jökulsá). The bank revetment extends 100 m south of the defence line along the west bank and 150 m south of the defence line along the east bank. Characteristic cross-sections of shore protection in the defence line are shown in Fig. 9. Cross-section 1 is built from quarry run or gravel. Cross-section 1 is built to protect the road from sea-water that reaches across the beach crest. Shore protection according to cross-section 1 was built in 2003 for a 240 m long section of the defence line east of the river.

Shore protection according to cross-section 2 will be built in the defence line before the wave crest / steep bank reaches the defence line. Design bed elevation at the toe is equal to the elevation of mean sea level. Shore protection according to cross-section 2 has been partially completed for the southernmost 100 m of the bank revetment of the east river bank. In order to complete the shore protection according to cross-section 2 for the defence line and the river bank south of the defence line 70.000 m^3 of armour stone is needed and the cost is estimated to be 4 million USD (240 million isl. kr.).

Shore protection according to cross-section 3 will be built in the defence line before the bed elevation at the defence line becomes equal to the elevation of mean sea level. Design bed elevation at the toe is equal to 5 m below mean sea level elevation. In order to complete the shore protection according to cross-section 3 for the defence line and the river bank south of the defence line 120.000 m^3 of armour stone is needed and the cost is estimated to be 7 million USD (400 million isl. kr.).

In addition to it is expected that 30.000 m^3 of armour stone and quarry run is needed in the future to maintain the river channel (bank revetment and rock thresholds) at a cost of about 1.7 million USD (100 million isl. kr.).

Conclusions

The total cost of sea defences at Breiðamerkursandur is of the order of 13 million USD (750 million isl. kr.) and it is expected that these defences will be sufficient for the next 50 years or until about 2050. Not included in these numbers is the cost of changing the road alignment east of Jökulsá or building a new double lane bridge to replace the current single lane bridge. The sea defences will be built gradually and it is expected that the above cost will be more or less evenly distributed over the 50 year period. Looking further ahead than 50 years it seams possible that sea defences may be a permanent solution to the problem of maintaining a secure road across Breiðamerkursandur. This conclusion is partly based on the assumption that substantial land uplift will occur in the future due to reduced ice volume of Vatnajökull due to a warming climate.

Sea defences seem to be a viable solution to the problem of maintaining a secure road across Breiðamerkursandur. This is different from the conclusion reached by the first author of this paper 10 years ago (Jóhannesson, 1994 and 1995). There it was concluded that the most promising alternative was to build a new road across the southern part of Jökulsárlón. The feasibility of sea defences is among other things based on the following facts:

- A rock quarry has been found and opened at a distance of 12 km from Jökulsá.
- Sea defences generally cause an accelerated erosion on the downdrift side of the defended area but this is not a concern at Breiðamerkursandur since there are no structures close to the sea east and west of the defended area.
- The erosion at Breiðamerkursandur has been slowing down for the past decades and a further reduction is expected due to land uplift. Current uplift rates at Breiðamerkursandur are about 15 mm/year and are expected to be as high as 40 mm/year in 2050 if the ice volume of Vatnajökull will be reduced due to a warming climate as is expected.

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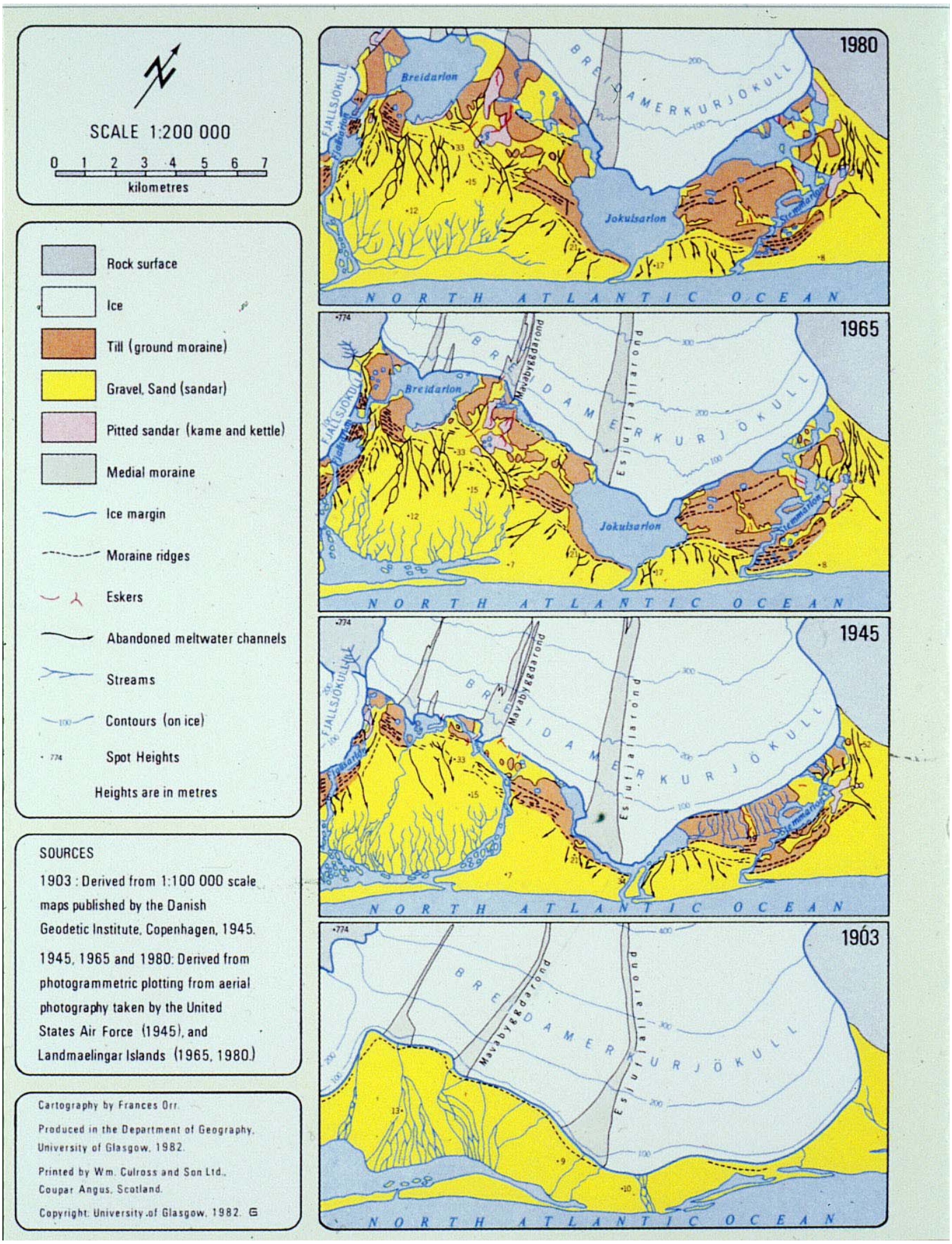

Figure 2. The development of Breiðamerkurjökull, Breiðamerkursandur, Jökulsárlón and Jökulsá river from 1903 to 1980 (Price, 1982).

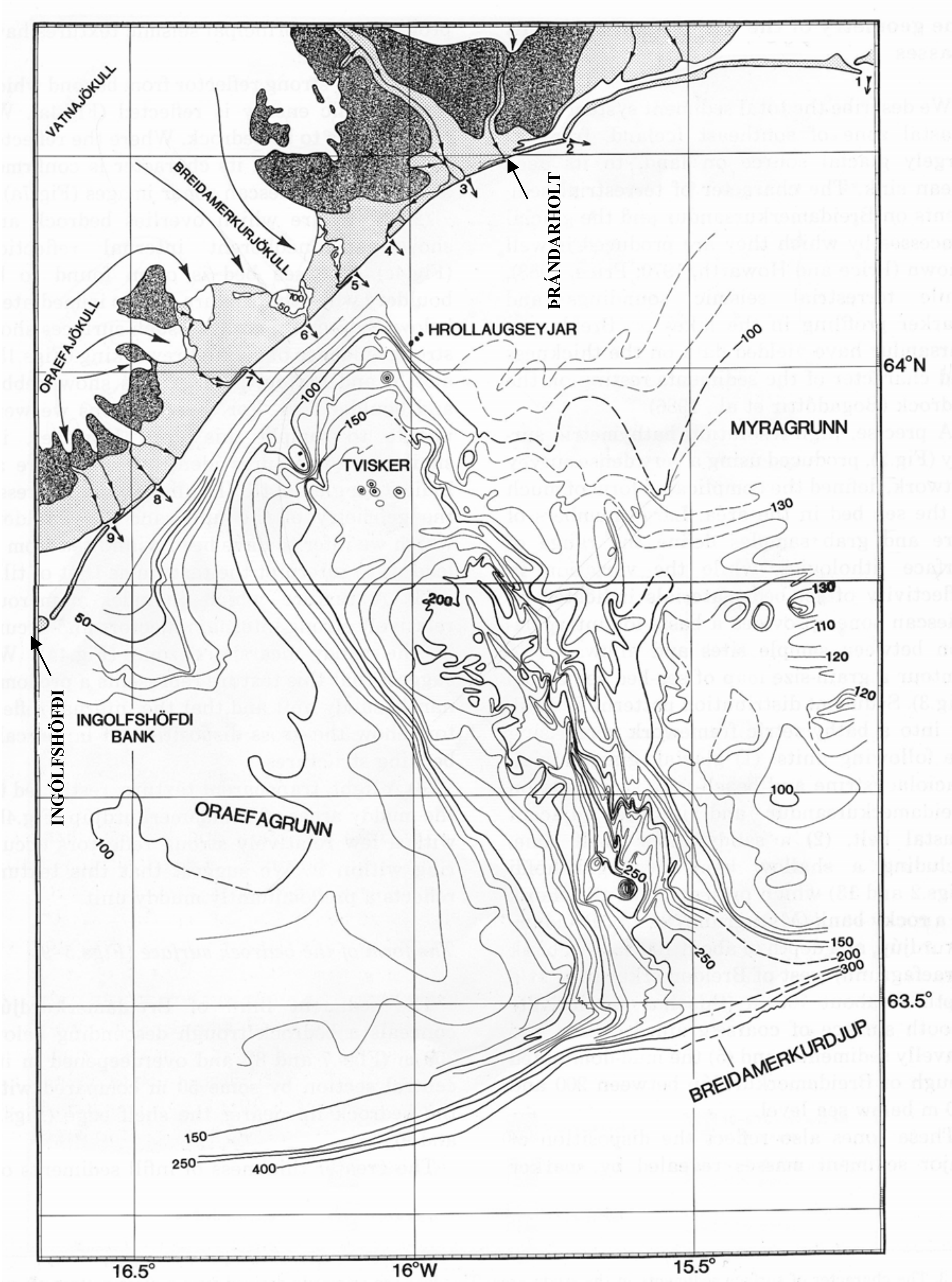

Figure 3. The bathymetry south of Breiðamerkursandur (Boulton et. al., 1988). Also shown are headlands of solid rock on the coastline closest to Jökulsárlón, which are Ingólfshöfði (33 km to the west of Jökulsárlón) and Þrándarholt (22 km to the east of Jökulsárlón).

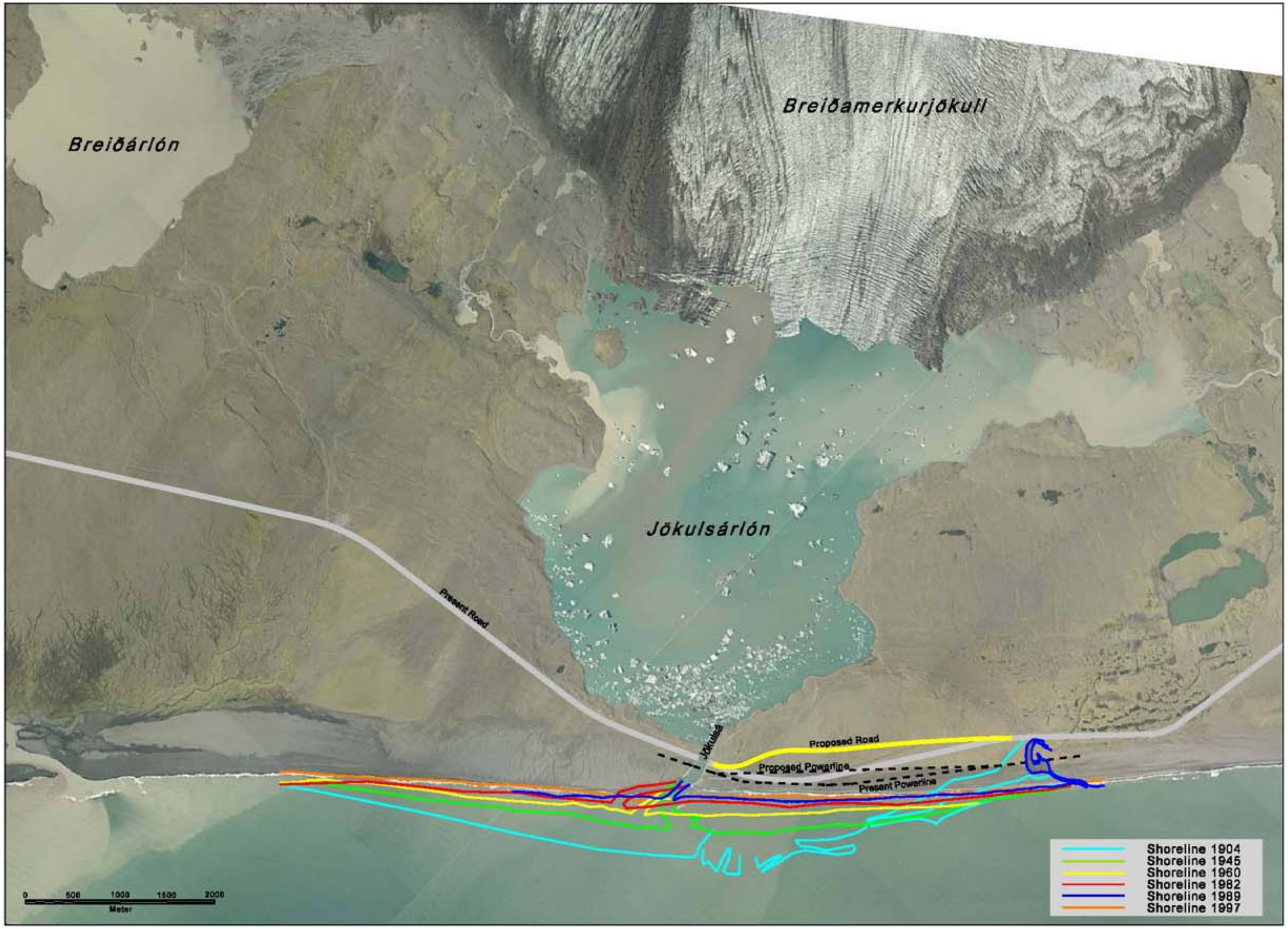

Figure 4. Shoreline changes at Breiðamerkursandur. Also shown is the present road / powerline and a proposed new road / powerline alignment east of Jökulsá. The aerial photograph in the background is from 2003.

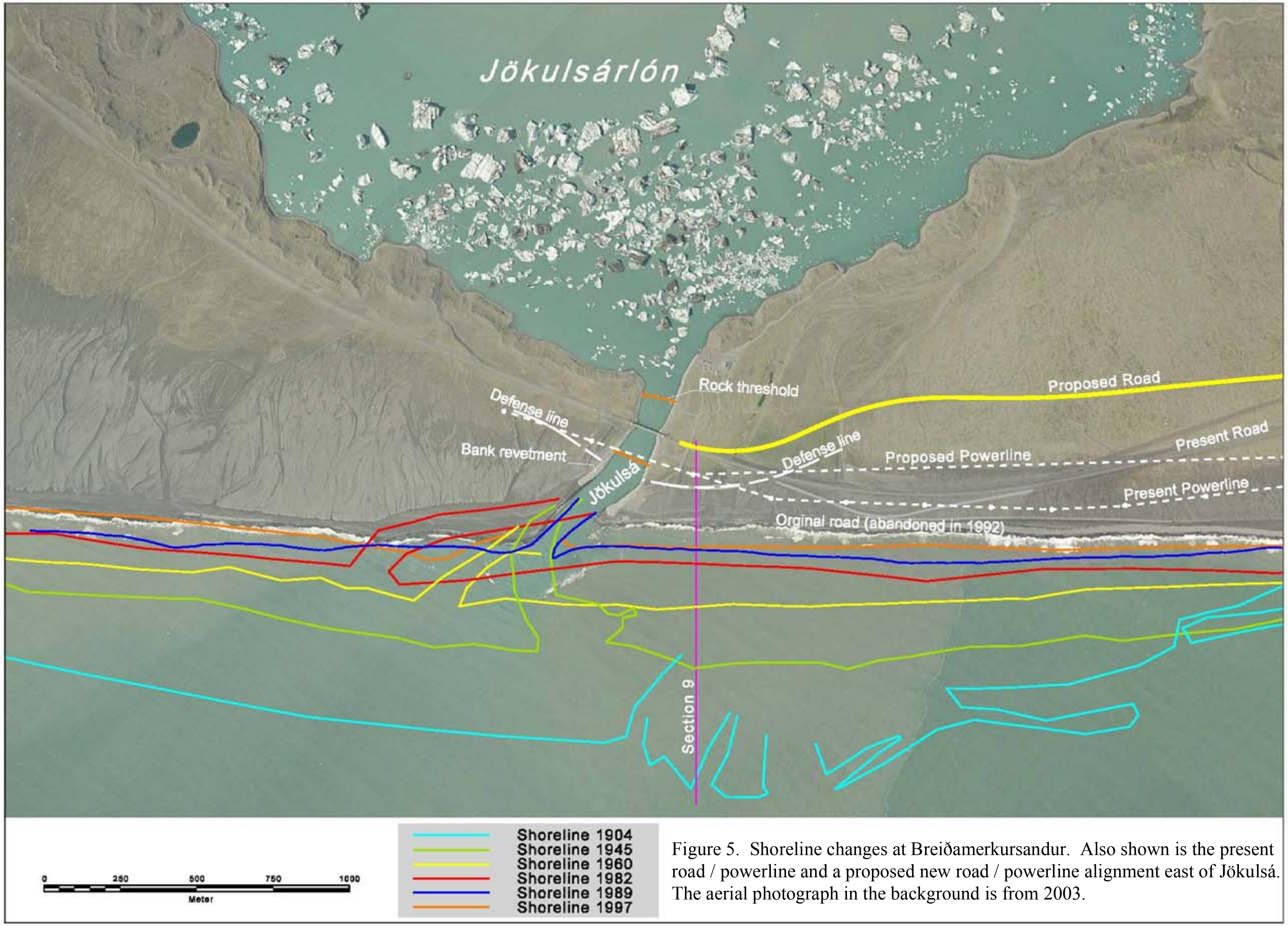

Figure 5. Shoreline changes at Breiðamerkursandur. Also shown is the present road / powerline and a proposed new road / powerline alignment east of Jökulsá. The aerial photograph in the background is from 2003.

Figure 6a. The erosion at Breiðamerkursandur has created a 2 to 4 m high steep bank. The figure shows the bank 1000 m east of Jökulsá river

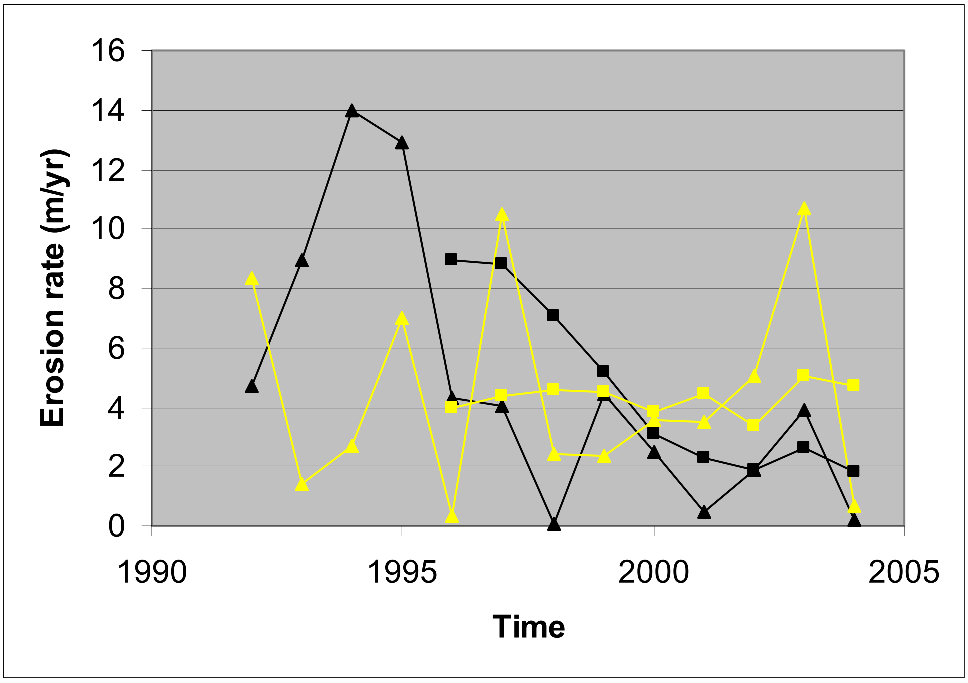

Figure 6b. Erosion rate of the steep bank 1200-2000 m west (black) and 1000-1800 m east (yellow) of Jökulsá. The triangles are yearly measurements and the squares are 5-year averages.

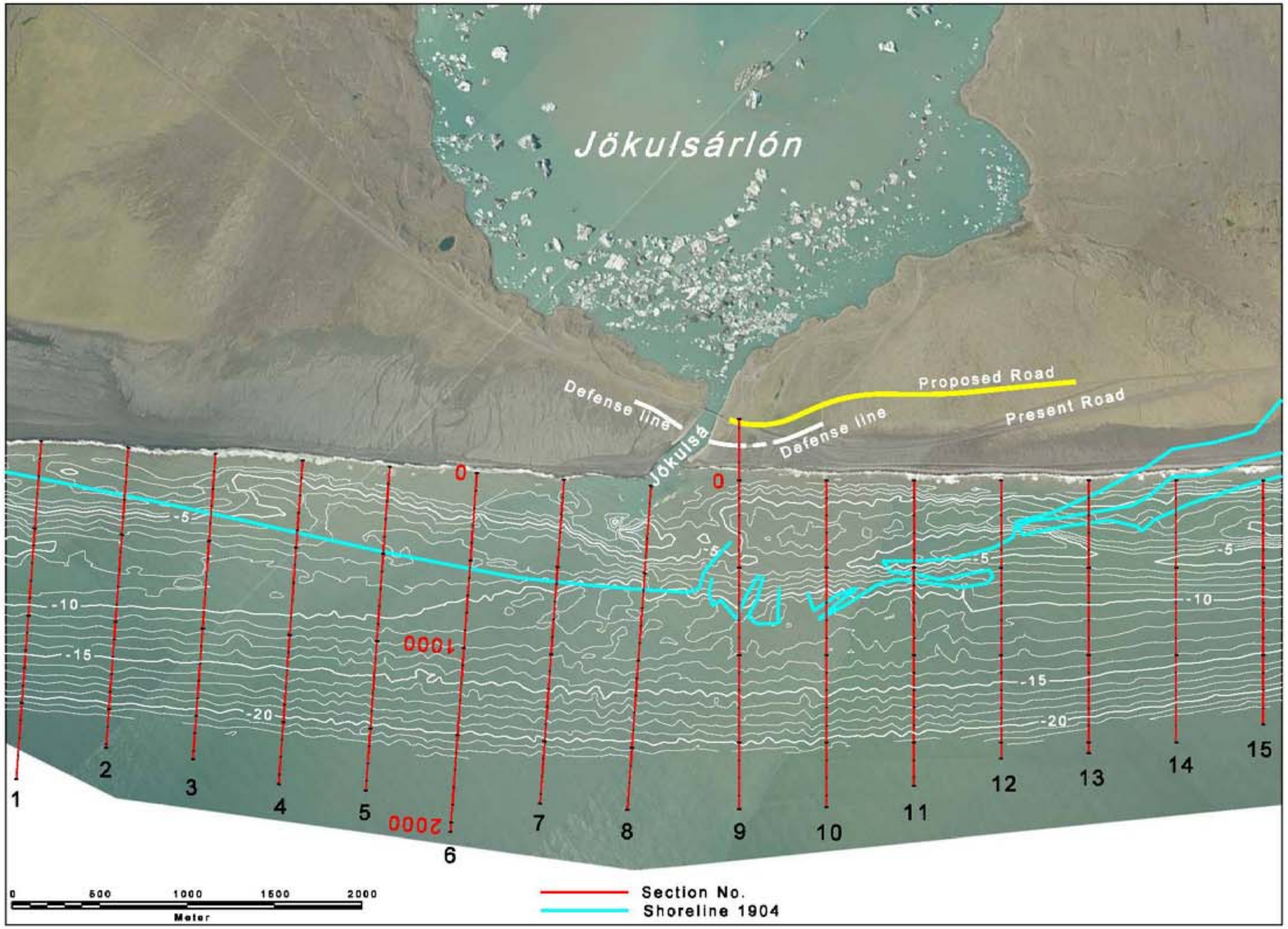

Figure 7. The bathymetry south of Breiðamerkursandur as measured in 2003. The aerial photograph in the background is from 2003.

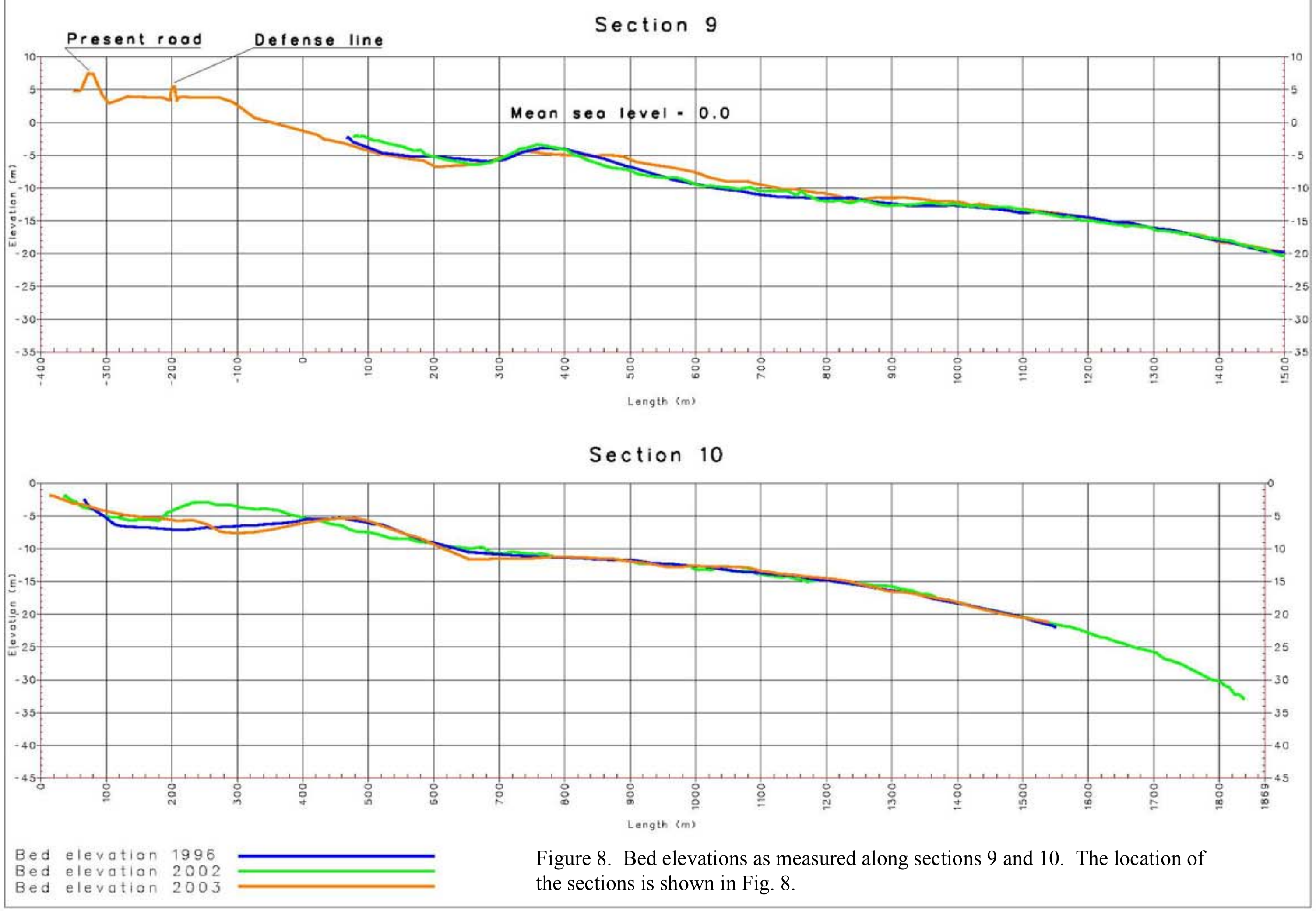

Figure 8. Bed elevations as measured along sections 9 and 10. The location of the sections is shown in Fig. 8.

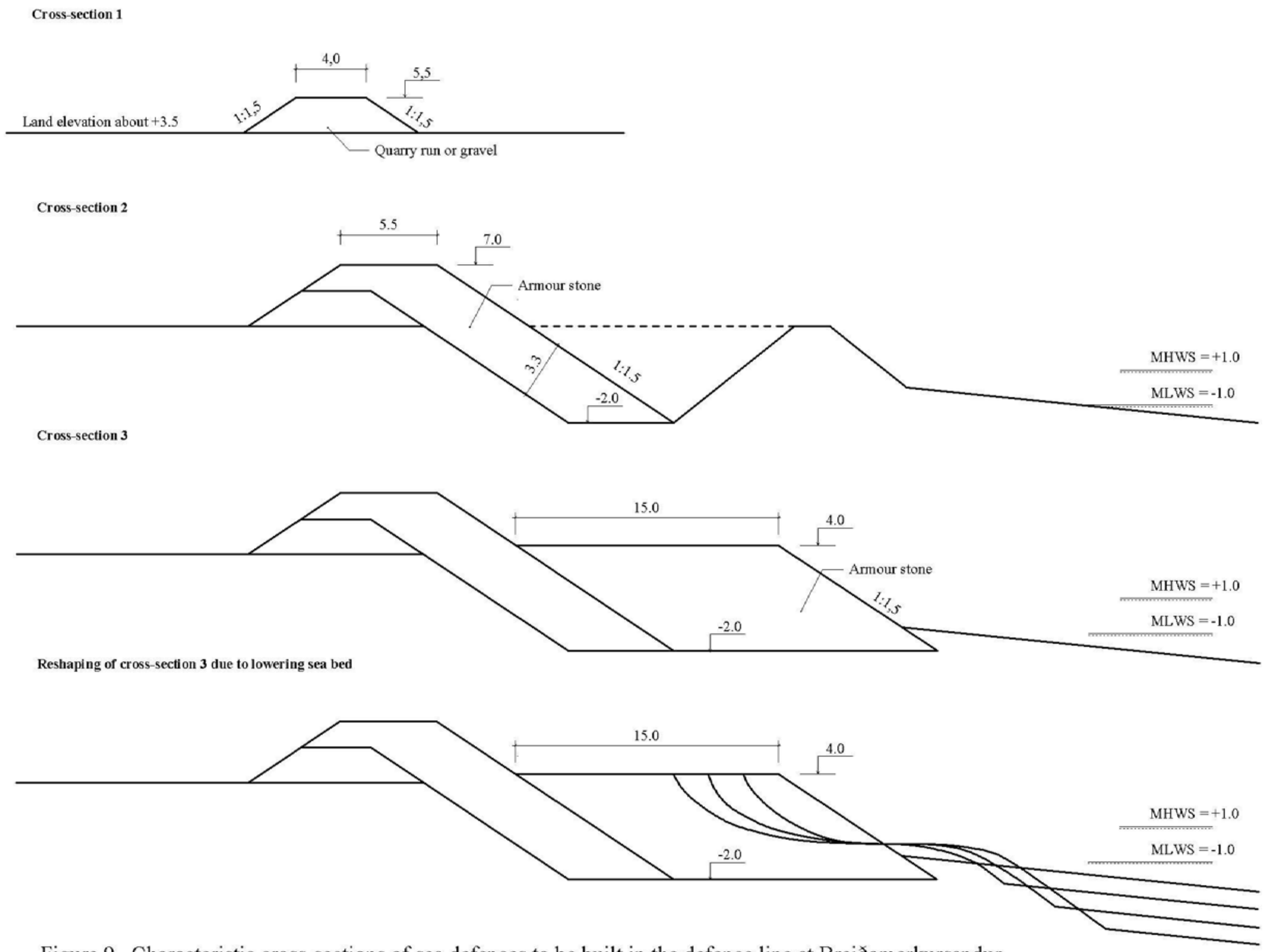

Figure 9. Characteristic cross-sections of sea defences to be built in the defence line at Breiðamerkursandur.