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A geomorphological overview of glacial landforms on the Icelandic continental shelf

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Abstract

The availability of a bathymetric database that covers about 80% of the Icelandic shelf has made it possible to produce a geomorphological map of the glacial landforms. The digital elevation model of the bathymetry was analyzed as a series of shaded relief images. Trough edges, bulging trough mouths, moraines, eskers, melt water channels, streamlined bedrock and streamlined drift, mostly hitherto unmapped, distributed all around the island have been identified. Moraines are found on the shelf, within troughs and inside fjords. Streamlined landforms are always confined to the bottom of troughs. Troughs appear to have been cut by ice streams draining an ice sheet that likely covered the entire shelf. At the shelf break, most troughs terminate with contours that bulge in a convex-outwards fashion. This suggests that an ice stream eroded, transported and finally deposited large amounts of sediment at the trough mouth. Overall, the glacial morphology of the shelf highlights a radial pattern that indicates a main ice divide near the centre of Iceland.

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1. Introduction

Iceland (Figure 1) experienced several periods of ice sheet expansion between the Late Pliocene and the Pleistocene (Geirsdóttir and Eiríksson, 1994). During the last glacial period, the ice sheet is thought to have covered most of the island (Norðdahl, 1990) extending across the Icelandic shelf. In particular, recent data and models (Hubbard et al., 2006; Andrews, 2008) seem to confirm earlier theories (Denton and Hughes, 1981; Ingólfsson and Norðdahl, 1994) that the Icelandic Ice Sheet largely extended onto the shelf at the Last Glacial Maximum, and in some cases extended to the shelf break. This is seen through the presence of some moraines (Ólafsdóttir, 1975; Egloff and Johnson, 1979; Syvitski et al., 1999; Andrews et al., 2002; Geirsdóttir et al., 2002; Principato et al., 2006) and a series of glacial troughs (Vogt et al., 1980), some of which have been interpreted as the erosional product of ice streams (Bourgeois et al., 2000).

Within this context, a detailed and continuous geomorphological analysis of glacial landforms on the Icelandic shelf is useful for assessing the ice extent and the style of shelf glaciation and it can be used for planning future coring and dating campaigns. In this paper we present observations made on a recently-released bathymetric digital elevation model that covers most of the Icelandic shelf.

2. Methods

2.1 Data source

The Norwegian Olex database is a bathymetric digital elevation model (DEM) with a cell size of 5 m, positional accuracy generally better than 10 m and a vertical accuracy from 0.1 to 1 m (see Bradwell et al., 2008, for more details). The database is created by interpolating bathymetric data collected by fishing boat echosounders. Specifically, data collected during fishing cruises is interpolated to cover an area that buffers the actual boat track of 10 m (5 m on each side of the track) and integrated with the data already achieved from earlier cruises. The effective horizontal resolution clearly depends on the instruments on board of the ships and, overall, it is probably closer to a few 10s of metres than to 5 m.

The DEM is provided within a custom software package and it can be viewed as a shaded image with exchangeable light sources either from the NW or the NE. The image is projected with a modified Mercator projection, with parallel and equidistant latitude and longitude lines. A smoothing factor can be applied to the image to make its layout

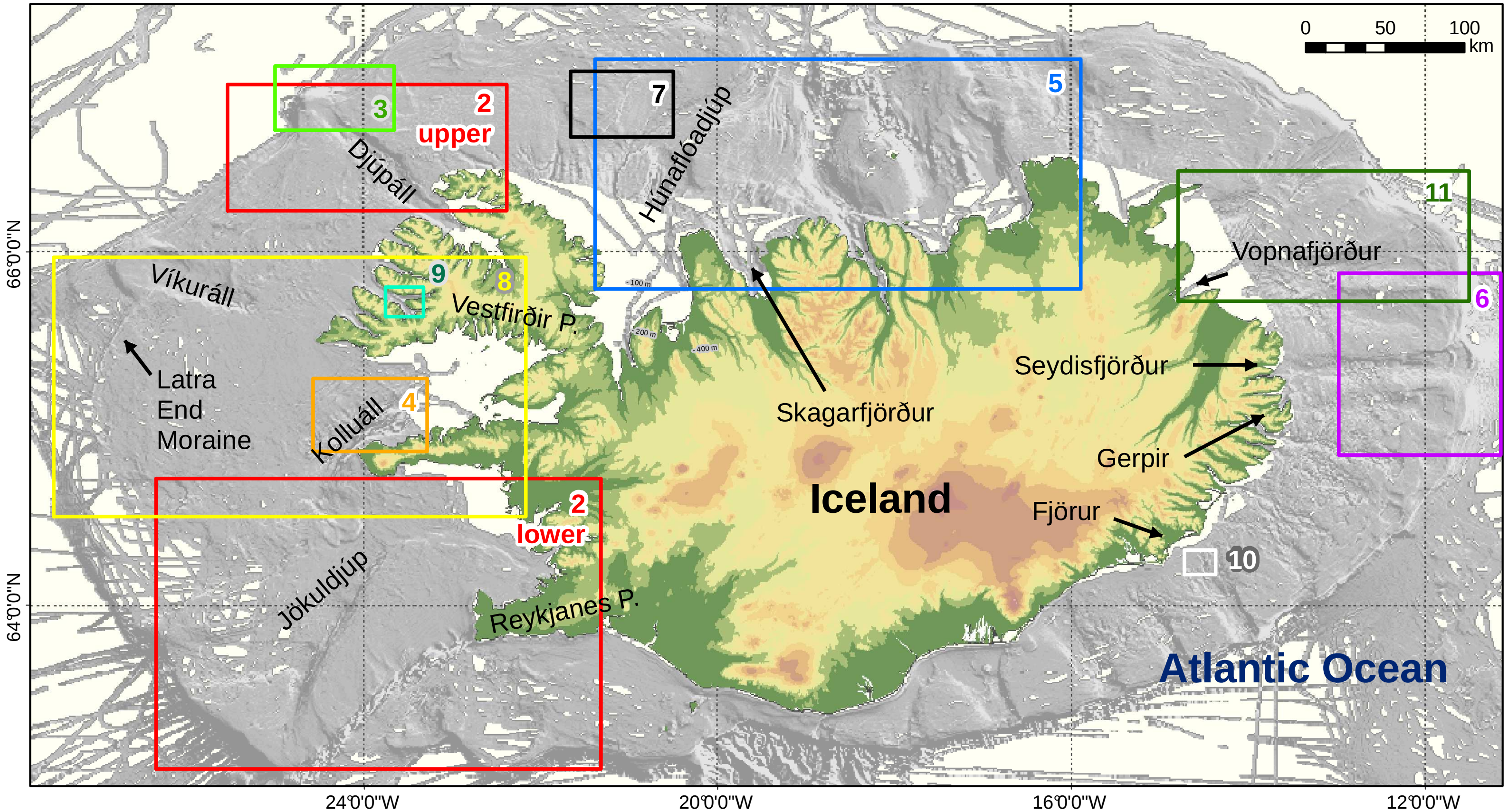

Figure 1. Geographic insets of the figures in this paper (numbers refer to figure numbers) and the main locations cited in the text. The bathymetry is reproduced from the Olex database by permission.

more easily readable. The smoothing tool is particularly useful because the data suffer from several artefacts (e.g. ship tracks) that can confuse the observer's eye. Although the Olex database allows customers to use shaded images, it also provides tools for 3D visualization, measuring distances (in nautical miles), and for drawing bathymetric profiles.

2.2 Mapping technique

The Icelandic continental shelf was analysed at different scales, different levels of smoothness of the images, different visualizations (2- and 3D) and by looking at topographic profiles. All recognized glacial landforms were mapped on screen in a GIS environment. For this purpose, several Olex images were exported as screen snapshots and referenced to a common coordinate system (Equidistant Cylindrical, WGS 84).

2.3 Accuracy and map completeness

The snapshot images that served as a basis for the mapping were geo-referenced using coastal features as control points. This means that the absolute position of a landform mapped on these images near the coast is more accurate than that of a landform mapped further offshore.

The shelf around Iceland is not imaged entirely by Olex database (see "no data" areas in the upper image of the Map). In particular, nearshore and near shelf break data are often missing. Therefore, some landforms are only partially imaged by our mapping and some may appear truncated because of a no data area.

In our final map we show unambiguous glacial landforms (trough edges, bulged trough mouths, moraines, streamlined bedrock and drift) as well as landforms that resemble some of their onshore counterparts but their shapes are somewhat atypical; these are the "speculative" moraines, eskers and melt water channels illustrated on the legend. Also, we include some landforms of uncertain origin that may or may not be related to the Icelandic Ice Sheet (i.e. prominent breaks-of-slope, enclosed depressions, shelf-break grooves).

The scale choice of the final map (1:3,240,000) was selected to highlight prominent glacial geomorphic features on the shelf and to create a final map that could be printed in an A3 format. As a consequence of this mapping scale, some very small landforms, like the within-fjord moraines to the NW, are not readily visible.

Figure 2. Two examples of troughs characterized by a classic U-shaped (upper) and asymmetric (lower) cross profiles: the Djúpáll trough (off Isafjardardjúp on the NW Icelandic shelf) in the upper image and the Jökuldjúp trough (W shelf) in the lower image. See Figure 1 for image location. Onshore terrain is in yellow while the seabed is represented by a shaded image with blue colours varying from light blue (shallow) to dark blue (deep). Insets on top of the pictures are bathymetric profiles normal to trough axes, from SW to NE in the upper image and from SE to NW in the lower image. The bathymetric profiles shown in the insets above each image are marked on the images by a red line. The ice flow direction is marked by a green arrow. These images and all images in Figure 3 to 11 are reproduced from the Olex database, by permission.

3. Results

3.1 Troughs

Troughs (Figure 2) are the most prominent glacial landforms of the shelf. We identified almost 40 troughs: they are generally short, narrow and straight on the eastern and southern area of the continental shelf, large and long on the western shelf, and deep, long, sinuous and distributive on the northern shelf. In several cases, troughs show an asymmetric bathymetric profile from side to side (Figure 2, lower image), with one side of the trough much steeper than the other. Although trough axes can generally be followed and mapped, the exact lateral boundary of a trough, i.e. the trough edge, is not always marked by an evident break of slope. In this case, the trough edge appears as a discontinuous line on the map. Some troughs overlap at different depths, suggesting a multi-phase glacial evolution of the shelf morphology with different ice flow directions. Although many troughs are clearly the offshore geomorphic extensions of onshore valleys and fjords, others appear to have no geomorphic relationship to the near-coast and onshore topography, e.g. the Víkuráll trough on the NW shelf (Figure 8). Most troughs show a bulged mouth, likely built by successive depositions of glacial sediments (Figure 3). We specifically avoided the term "trough mouth fan" because this is commonly used to indicate the fan that begins at the shelf break and ends further offshore, while the Olex bathymetric data only cover the mouth of the troughs at the shelf break. Still, these bulged mouths are important landforms because they highlight how glacial processes can contribute to the enlargement of a continental platform.

3.2 Structurally-controlled and tectonic landforms

In most places, because of the effective resolution of the images, only streamlined landforms of the order of several hundred metres are evident. When recognizable, streamlined bedrock landforms (Figure 4) are up to 15 km long with a relief from just a few metres to up to 30 m. Streamlined drift includes crag-and-tails, drumlins and Mega Scale Glacial Lineations (MSGL Clark, 1993). MSGL (Figure 5) are the most abundant landforms of the three and they are as long as 56 km, as wide as 600 m and with a relief of up to 50 m.

Figure 3. A typical bulged trough mouth at the distal end of the Djúpáll trough, off Isafjardardjúp on the NW Icelandic shelf. See Figure 1 for image location. The seabed is represented by a gray shaded image. The bathymetric profile (upper inset, red line on the image) is drawn parallel to the ice flow direction from upflow (SE) to downflow (NW), and it terminates at the shelf break. The ice flow direction is marked by a green arrow.

Figure 4. Streamlined bedrock in the Kolluáll trough, western shelf. See Figure 1 for image location. The bathymetric profile (upper inset, red line on the image) is drawn across the trough from SE to NW. The ice flow direction is marked by a green arrow.

Figure 5. Streamlined drift (MSGL) in the Skagar trough, recording ice flow northwards from Skagarfjörður. See Figure 1 for image location. The yellow oval outline shows the MSGL location on the seabed. The yellow arrows indicate the position of the median moraine at the confluence between the Húnaflóadjúp and the Skagar troughs. Also note the presence of several ship tracks going from SE to NW as an example of artefacts in the Olex database. The ice flow direction is marked by a green arrow.

3.3 Moraines

Numerous moraines have been identified on the shelf. They can be grouped into three main categories: trough moraines, shelf moraines outside the troughs and within-fjord moraines.

Trough moraines A medial moraine (Figure 5) is found on the northern continental shelf, at the confluence between the Húnaflóadjúp trough and the nearby trough coming off Skagarfjörður. More abundant are the within-trough frontal moraines such as those on the eastern continental shelf. Among them, there are two cases where there are two concentric frontal moraines not far from each other within the same trough. In one case they are found in the trough off Seydisfjörður (Figure 6) and they are as high as 40 m and as wide as 2.5 km. The innermost one is 14 km long while the outermost is as long as 20 km and they are about 9 km apart. In the other case (65°06′N; 11°53′W) they are found in the trough off Gerpir where they are as high as 35 m, the outer one is 10 km wide and 20 km long while the inner one is 6 km wide and 15 km long.

On the SW shelf, off the Reykjanes Peninsula, a small trough terminates with a frontal moraine 24 km long, 4 km wide and 40 m high (63°37′N; 22°10′W). Of the three known frontal moraines within the Djúpáll trough, off Isafjardardjúp on the northwestern shelf (Andrews et al., 2002), the innermost and outermost ones are clearly visible on Olex database. The innermost one (66°18′N; 23°27′W) is found outside the fjord and it shows a relief of up to 45 m, a maximum width of 3 km and a length of 12 km. The outermost moraine (66°41′N; 24°16′W) is about 25 km upflow from the shelf break and has a relief of up to 30 m, a width up to 2 km and a length of 8 km.

Shelf moraines Moraines are found on the shelf outside troughs and are elongated parallel to the trough direction. They are interpreted as "overspill" lateral moraines. These are found on the north shelf, where a complex of at least three ridges is visible on the northwestern edge of the Húnaflóadjúp trough (Figure 7). The longest and easternmost ridge is as high as 40 m, as wide as 2 km and as long as 35 km. The Latra End Moraine (Figure 8) (Ólafsdóttir, 1975; Syvitski et al., 1999) is on the western shelf and is the longest moraine ($>$ 70 km) on the Icelandic continental shelf. It is the best preserved frontal moraine found outside a trough and is up to 50 m in height and 2 km in width.

Within-fjord moraines Several within-fjord moraines have been recognized in the Vestfirðir peninsula (NW) fjords (Figure 9). They are usually much smaller than the other described moraines, although they can reach a height up to 30 m and a width up to 500 m.

Figure 6. The two concentric frontal moraines (yellow arrows) in the trough off Seydisfjörður. See Figure 1 for image location. The upflow moraine is 14 km long while the outermost is as long as 20 km and they are about 9 km apart. The bathymetric profile (upper inset, red line on the image) is drawn parallel to the ice flow direction, from upflow (W) to downflow (E). In this image the seabed is represented by a gray shaded image. The ice flow direction is marked by a green arrow.

Figure 7. The lateral moraine complex (yellow arrows), as long as 35 km, on the shelf outside the Húnaflóadjúp trough. See Figure 1 for image location. The trough left (NW) edge is not expressed by an evident break of slope, but it's bottom is clearly demarked by some bending streamlines. The bathymetric profile (upper inset, red line on the image) across one of the moraines is drawn from SE to NW. In this image the seabed is represented by a gray shaded image. The ice flow direction is marked by a green arrow.

Figure 8. The Latra End Moraine (yellow arrows) on the west shelf. See Figure 1 for image location. This is the longest (> 70 km) shelf moraine on the Icelandic shelf, right at the break of the western shelf. The bathymetric profile (upper inset, red line on the image) is drawn parallel to the ice flow direction, from upflow (SE) to downflow (NW). In the image are also visible (pink arrows) the Víkuráll trough (NE from the Latra End Moraine) and the Kolluáll trough (to the SE). The ice flow direction is marked by a green arrow.

3.4 Speculative glacial landforms

Some of the landforms recognized offshore appear to be glacial in origin, but with either an unusual shape, size or relief. Ridges found offshore the Vestfirðir Peninsula are classified as speculative moraines because they are composed of crests alternating with unclear depressions, or with an unusually large and flat crest top. Sinuous ridges, classified as speculative eskers for their limited length of a few kilometres, are found on the shelf east of the Djúpáll trough (northern shelf) (Figure 10). Slightly sinuous depressions, up to 50 m deep, are classified as speculative meltwater channels. They are found northeast of the Vestfirðir Peninsula and on the eastern shelf. Overall, eskers and melt water channels appear to be very rare on the Icelandic shelf.

3.5 Other landforms

Other prominent breaks-of-slope, enclosed depressions and shelf-break grooves are landforms for which we were unable to identify the likely process responsible for their formation. In many cases they are probably related to ice flow, but a gravitational (landslide) or a geologic (tectonics, volcanism) origin cannot be excluded without further investigation.

“Uncertain” breaks-of-slope are found within a few troughs perpendicular to the ice flow direction, as in the Vkuráll trough, while others occur on the shelf outside the troughs and usually near the shelf break, as in between the Víkuráll and the Jökuldjúp trough.

Enclosed depressions are generally found on the shelf not far from the shelf break. In at least one case, i.e. in the Víkuráll area, they mark the beginning of an offshore trough. They are up to 70 m deeper than the surrounding shelf.

Shelf-break grooves are a series of depressions, arcuate in shape, that run for several kilometres (up to 40 km) parallel to the shelf break. They are as deep as 60 m and as wide as 1 km. The largest shelf-break grooves are found on the NE shelf, near the shelf break (Figure 11).

Figure 9. The frontal moraine (yellow arrow) in the Arnarfjörður deposited by the NW-flowing glacier when the west-flowing glacier had already retreated further inland. See Figure 1 for image location. Note also the two other frontal moraines (pink arrows) deposited by the west-flowing glacier further inland. The profile (upper inset, red line on the image), drawn from E to W, intercepts the same frontal moraine in two points. In this image the seabed is represented by a gray shaded image. The ice flow direction is marked by a green arrow.

Figure 10. A sinuous ridge (yellow arrows) interpreted as an esker found on the shelf off Fjörur, on the eastern Icelandic shelf. See Figure 1 for image location. The bathymetric profile (upper inset, red line on the image) is drawn across the ridge, from SW to NE. Note the very large scale. The ice flow direction is marked by a green arrow.

4. Conclusion

The map we present portrays a synthesis of Icelandic shelf glaciation style and extent. Given the good coverage (80% of shelf) of the bathymetric data we propose that many of the main landforms expressed on the seafloor have now been been identified. However, we note that newer versions of the Olex database may fill the "no data" gaps, improve resolution and reduce noise such that some new landforms and their relationship may become apparent. We have identified some three hundred glacial landforms, mostly hitherto unmapped, distributed all around the island.

Overall, the pattern of landforms is radial, indicating that the maximum state ice sheet had its main ice divide in the centre of Iceland, although a subsidiary divide at the northwest (Reykjanes Peninsula) is required to explain the orientation of local troughs. Today's ice masses are preferentially located to the south of the island's central axis in response to this being the zone of higher atmospheric moisture. It thus appears that during growth and decay of the Icelandic Ice Sheet the ice divide migrated from a more maritime to internal position and back.

The presence of glacial troughs extending to the shelf break and, in most cases, being characterized by a bulging mouth indicates that outlet glaciers or ice streams existed and eroded and transported considerable volumes of material. The presence of meltwater channels, eskers and moraines on the shelf, and outside the troughs, demonstrates that the entire shelf was ice-covered, suggesting that the troughs were cut by ice streams rather than piedmont-style outlet glaciers.

For most of the mapped moraines the age of ice margins is unknown, especially on the southern and eastern shelf. We hope that our map will motivate research to conduct targeted seismic and core investigations such that the timing of retreat can be ascertained.

Software

The map was created using ESRI ArcMap 9.2.

Figure 11. Shelf-break grooves (yellow arrows) off Vopnafjörður, NE Icelandic shelf. See Figure 1 for image location. The grooves are up to 40 km long, 60 m deep and 1 km wide and they are found both at the trough mouth and on the shelf between adjacent troughs. The bathymetric profile (upper inset, red line on the image) is drawn across two of these grooves from SW to NE. Note how these features tend to run parallel to the shelf break.

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