Geomorphology 206 (2014) 262–270

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Statistical analysis of Brepollen bathymetry as a key to determine average depths on a glacier foreland

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ARTICLE INFO

Article history:
Received 7 March 2013
Received in revised form 26 August 2013
Accepted 8 September 2013
Available online 19 October 2013

Keywords:
Spitsbergen
Glacier valley
Bathymetry
Statistical analysis

ABSTRACT

The study demonstrates the usefulness of statistical analysis to classify valleys because of the influence of the glaciers that formed them, as well as to determine the average depth at their cross-section parallel to the glacier front. Moreover, the usefulness of the analysis of shape of the histogram of depth, the value of skewness and kurtosis, and the relation between the average, median, and mode of depths to classify valleys is shown. The statistical analysis of the normalized shape of the valley cross-sections allowed establishment of the relation between the measured depth, the location of the measurements and the average depth of the valley cross-sections.

1. Introduction

One of the issues considered by glaciologists in the analysis of the mass balance of glaciers and, in particular, in determining the glacier mass loss as a result of glacier calving processes, is to determine the thickness of glaciers flowing into the sea in their front part (Jania et al., 2011). While the size of the surface recession of glaciers is relatively easy to determine, determining the volume by which the glaciers have shrunk is more difficult. Determination of Svalbard glaciers' volume loss, which occurs in the process of glacier calving when glaciers flow into the sea, so far has been based on the adoption of the average thickness of the glaciers in the whole archipelago (Hagen et al., 2003; Błaszczyk et al., 2009; Moholdt et al., 2010). Knowledge of detailed bathymetry is important in determining regional glacier mass balance using digital elevation models (DEMs). Detailed comparison of DEMs from different periods of time allows the mass balance of glaciers and glacier mass loss to be determined over large areas. However, in such calculations glacier mass loss in their underwater parts is often overlooked because of lack of bathymetric data (Moholdt et al., 2010).

Information about the thickness of glaciers (heights of ice cliffs and depths of glacier fronts) for Svalbard glaciers is rare. For the glaciers of Spitsbergen, an average value of 100 ± 10 m has been adopted (Dowdeswell et al., 1984; Błaszczyk et al., 2009). We should note, however, that the differences between thickness for individual glaciers as well as within the same glacier can be very large. For example, according to Grześ et al. (2009) the depth of the sea, from the cliff of the Dahlbreen to 6.2 km from the glacier front, varies in the range of 10 to 110 m. The knowledge of the average depth of a particular valley in front of the glacier cliff flowing into the sea will allow for more precise estimation of the calving rate. In cases when we possess bathymetric data in the form of a cross-section in the valley central part, determining its average depth is possible. However, it is useful to have an understanding of the shape of the transverse cross-section of the valley in the form of mathematical equations that describe the shape of the examined part of the valley or by modeling glacial erosion of the valley bottom (James, 1996; Egholm et al., 2012). In the region of Brepollen, several possible shapes of valleys have been distinguished; so in this study the statistical analysis of transverse cross-sections of valleys occurring there has been used.

2. Study site

The Brepollen region, where the research was carried out, is the inner part of the Hornsund Fjord, which itself is the most southerly fjord in the western part of Spitsbergen (Fig. 1A). The Hornsund Fjord, with a length of about 34 km, is characterized by a highly varied shoreline. Its average depth is 90 m, and the maximum exceeds 260 m. Because the fjord axis orientation is perpendicular to the tectonic structures, deeply indented bays and peninsulas occur in the north–south direction. Because of the numerous glaciers flowing into the fjord, the coast partly takes the form of an ice cliff (Styszyńska, 1996). Brepollen is separated from the main part of the fjord by an isthmus between two peninsulas: Treskelodden from the north and Meranpynten from the south. The surface and shape of Brepollen have been changing dramatically over the last

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http://dx.doi.org/10.1016/j.geomorph.2013.09.029

100 years. At the end of the nineteenth century, Brepollen was completely covered with glaciers (Pälli et al., 2003; Kolondra, 2011). The length of Brepollen is nearly 15 km, and the width varies between 1.5 and 15 km. There are also a number of smaller peninsulas and several islands in the northern and eastern part of Brepollen. The authors' calculations show that the surface area of Brepollen in 2010 was almost 95 km^2. Brepollen receives six tidewater glaciers: Hyrnebreen, Storbreen, Hornbreen, Svalisbreen, Mendelejevbreen, and Chomjakovbreen (Jania, 1988; Jania et al., 2003). Forelands of each glacier form separate bays.

Bathymetric research in the area of Brepollen has been conducted so far only in the form of preliminary surveys of bathymetry and bottom sediments for the entire Hornsund Fjord in the late 1970s and the 1980s. Based on the data collected, Brepollen was characterized as an undulating area with height differences reaching a few to several meters and being of glacial origin (Rudowski and Marsz, 1996; Styszyńska, 1996). The first comprehensive bathymetric study of the Brepollen region was created by interpolation of bathymetric data from profiles taken in the years 2007 and 2008 (Fig. 1B). Results enabled to determine eight subbasins that underwent deglaciation during the twentieth century, as a result of glacier recession (Moskalik et al., 2013) and showed significant differences in bottom relief of each of them (Moskalik et al., 2014).

Triassic to Paleogene formations with metamorphic and sedimentary rocks dominate the geologic structures in the Brepollen area (Birkenmajer, 1990; Harland, 1997). The main axes of the glaciated valleys in the Hornsund region conform to the major tectonic lineaments (Jania, 1988). Mountain ridges and large glacier valleys have general N–S orientations of their axes and lie parallel to the edge of the continental shelf. Nevertheless the easternmost glaciers in Brepollen, Hornbreen, and Svalisbreen have a NE–SW and NW–SE direction, respectively.

Although the direction of major valleys reflects the underlying geological structure, the present shape of valleys and fjords is also a result of the glaciation history of the Svalbard–Barents Ice Sea continental margin. Svendensen et al. (2004) reconstructed the maximum limits of the Eurasian ice sheets during four large glaciations: the late Saalian (>140 ka), the early Weichselian (100–80 ka), the middle Weichselian (60–50 ka), and the late Weichselian (25–15 ka). According to Siegert et al. (2001) the age of particular glaciations was different. Nevertheless, there has been a general agreement that all glacial advances reached the continental shelf west of the Svalbard Archipelago and thick land ice occupied valleys and fjords (Siegert and Dowdeswell, 1995; Elverhøi et al., 1998; Siegert et al., 2001; Svendensen et al., 2004). According to Siegert et al. (2001), during the Last Glacial Maximum, the largest ice sheet existed over Scandinavia (2–2.75 km thick, depending on the model) and over the Barents Sea (0.75–1.75 km thick). Maximal modeled ice-sheet thickness for southern Spitsbergen amounted to 0.25–1 km, depending on the model.

Kowalewski et al. (1991) distinguished at least four glacial episodes within the Hornsund Fjord. The oldest one was connected with the glacier that filled the entire fjord and extended to the open shelf. In the authors' opinion this glacial episode was most probably contemporaneous with the maximum extent of the last glaciation (late Weichselian). All these glaciation episodes had to have an influence on valleys and fjords, especially if Spitsbergen fjords acted as pathways for fast-flowing ice streams draining the late Weichselian Svalbard–Barents Sea ice sheet (e.g., Landvik et al., 1998, 2005; Ottesen et al., 2005).

The chronology of the Holocene glacial activity in Spitsbergen fjords remains debatable (Forwick and Vorren, 2009). By the beginning of the Holocene, the decay of the large ice sheet over Svalbard and the Barents Sea region was complete, and glacier ice was approaching its present distribution (Siegert and Dowdeswell, 1995). According to Harland (1997), through most of the last 10 ky the extent of glaciers and ice caps over the archipelago has been no greater than that observed today, with the exception of minor readvances in the relatively cold Little Ice Age, which terminated at the beginning of the twentieth century. In a number of areas of Svalbard, the moraine system marking the end of the Little Ice Age cool period represent the most extensive ice advance during the Holocene (Werner, 1993; Wójcik and Ziaja, 1993) that started with a pronounced ice advance in the thirteenth or fourteenth century (Svendsen and Mangerud, 1997). According to Hald et al. (2004), central Spitsbergen was never completely deglaciated during the Holocene but Forwick and Vorren (2009) proved that during the most favorable Holocene climatic and oceanographic conditions (c. 11.2 and 9 ka) ice masses remained only on east Spitsbergen.

Today, ice masses of Svalbard cover an area of c. 36,600 km^2, i.e., 60% of land, and are among the largest glacierized areas in the Arctic (Dowdeswell and Hagen, 2004). The contemporary history of Hornsund deglaciation from the end of the Little Ice Age was analyzed by Błaszczyk et al. (unpublished). Over 67% of the Hornsund drainage basin is covered by glaciers. Tidewater glaciers constitute 97% of the glacierized area, while land-based glaciers only c. 3%. Areas of tidewater glaciers are growing toward the east and are the largest in Brepollen. The total area of glacier cover in Hornsund Fjord diminished between 1899 and 2010 amounting to ca. 172 km^2 with an average aerial retreat rate of 1.6 $km^2\,y^{-1}$. Recession rates increased from ca. 1 $km^2\,y^{-1}$ in the first part of the twentieth century up to ca. 3 $km^2\,y^{-1}$ in the first decade of the twenty-first century. The largest deglaciation (ca. 95 km^2) was noted in the Brepollen region, which was completely covered by glaciers at the beginning of twentieth century. Large glaciers with low slopes of longitudinal profile, such as the Hornbreen system in Brepollen, made the major contribution to such spectacular shrinkage of glaciers. Six tidewater glaciers lost about 17% of their areas up to 2010.

Modeling the evolution of glacial valleys made by Egholm et al. (2012) shows that the formation of a U-shaped valley of about 100 m deep and 1 km wide requires 20–25 ky. The size of the modeled valley is similar to the central part of Brepollen analyzed in this work. Present-day valleys filled by modern glaciers were formed by glaciers present on Spitsbergen in the Pleistocene and their shape is a reminder of those times. Modern glaciers, through forms of sedimentation produced at their foreland, modify mainly longitudinal profiles of the valleys in which they are located. Analysis of these forms was made for an area northwest of Spitsbergen and some selected glacier forelands located in: Isfjord, Van Keulenfjord, and Van Mijenfjord (Ottesen and Dowdeswell, 2006; Ottesen et al., 2008; Ottesen and Dowdeswell, 2009; Dowdeswell et al., 2010).

3. Data and methods

As input data for the analysis map of Brepollen bathymetry was used (Fig. 1B). The map was prepared using ordinary kriging interpolation on regular 25-m grid based on 120 single beam bathymetric profiles of more than 380 km in length (Moskalik et al., 2013). For the area of Brepollen, defining of eight geographical units based on bathymetric interpolation, slope, and aspect grids was possible (Moskalik et al., 2013). For all subbasins, average, median, and mode of depths, standard deviation, skewness, and kurtosis of its distributions (Fig. 2) were calculated (Table 1). Based on the maps transverse cross-section profiles in the Brepollen area were set (Figs. 1B, 3).

Before analyzing normalized transverse cross-section profiles for the whole of Brepollen, the following conditions were set up:

- The valleys are assumed to be symmetrical.
- Transverse cross-sections should be laid evenly over the length of the valley, which means that in a longer valley should be more profiles than in a shorter one.

In order to take into account symmetry of the valleys while carrying out statistical analysis, each of the cross-sections was considered twice: once as if it was laid from the right bank and the other from the left bank. To obtain uniform distribution of transverse cross-sections for each of the subbasins, a weights parameter determined the spacing