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Morphological characterization of Recherchefjorden (Bellsund, Svalbard) using marine geomorphometry

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Abstract: Geomorphological research based on geomorphological mapping seeks to identify the origins and age of forms as well as to describe the process that created or transformed a particular form. One of the most important aspects of this study is the morphometry and morphology of the landscape. This also applies to the submarine areas, and issues related to marine geomorphometry. Bathymetric data used in this study were obtained from the measurements of the Norwegian Hydrographic Service and measurements conducted by the authors. Its main goal was: to determine the bathymetry of the Recherchefjorden (Bellsund, Svalbard), establish morphometric parameters for the analysis of the morphology of the bottom. The boundaries of zones, related to the specific character of bottom geomorphology linked with geological structure, tectonics and, in particular, the impact of glacial system, was delineated. The sets of landforms (areas) were distinguished based on the morphometric analysis resulting from the determined parameters: slopes, its aspects, curvatures and Bathymetric Position Index. Basically, this areas are concentrated in two zones: the main Recherchefjorden and its surroundings. The delimitation also takes into account the origins and location of theme in relation to the glacial systems. On this basis, moraine areas were distinguished. They are linked with the Holocene advances of two glaciers, Renardbeen and Recherchebreen, mainly during the Little Ice Age. They constitute boundary zones between areas with different morphometric parameters: outer fjord and inner fjord. Moreover, taking into account geology and terrestrial geomorphology it was possible to describe paraglacial processes in this area.

Key words: Arctic, Spitsbergen, marine geomorphometry, submarine landforms, glacial and paraglacial geomorphology, Svalbard.

Introduction

The diversity of a given landscape, including various geomorphological systems, results from the impact of many endo- and exogenic processes (Zwoliński 2004). Geomorphological research based on geomorphological mapping seeks to identify the origins and age of forms as well as to describe the process that create or transformed a particular form. That is why morphometry and morphology are regarded as the key components of geomorphology, leading to the determination of the age and origin of a specific landscape (Smith *et al.* 2011; Bishop *et al.* 2012). Thanks to the dynamic development of information technology, we have access to increasingly better sources of field data as well as tools and methods for their processing (Jasiewicz *et al.* 2015). This also applies to marine geomorphology as a separate discipline (Harris *et al.* 2014; Smoot 2015). Marine geomorphometry is one of its most important elements. A comprehensive review of marine geomorphometry is presented by Lecours *et al.* (2016 and references therein) who describe the main stages, from data collection to the use of specific attributes and functions. Marine geomorphometry also plays a significant role in the study of polar regions, particularly the fjord bottoms and their surroundings, as it becomes a starting point for detailed geomorphological and paleogeographic analysis (*e.g.* Ottesen *et al.* 2005; Ottesen *et al.* 2008; Kristensen *et al.* 2009; Ottesen and Dowdeswell 2009; Moskalik *et al.* 2012, 2013, 2014a,b; Kempf *et al.* 2013; Dowdeswell *et al.* 2016). In this study methodological approach to marine geomorphometry presented by Lecours *et al.* (2016) was applied to determine the bathymetry of the Recherchefjorden (Bellsund, Svalbard) and establish morphometric parameters for analysing the morphology of the bottom. Thanks to the data obtained, the boundaries of zones with distinct landforms on the seafloor were determined.

Study area

The investigation area encompassed the Recherchefjorden (Recherche Fjord) and the area to the north along with the edge of Bellsund (Fig. 1A). Pocockodden (NW) and Reinodden (NE) mark the northern geographic boundary of the Recherchefjorden. The area of the fjord itself is 34 km^2 and 38.5 km^2 when the Recherche Lagoon in front of the Recherchebreen (Recherche Glacier) is included. The Recherchefjorden has three tributary valleys: valley with Renardbreen (Renard Glacier), Chamberlindalen (Chamberlin Valley) and valley with Recherchebreen, filled by glaciers to varying degrees. The Chamberlindalen is fragmentarily filled with glaciers, while the two others valleys are filled almost completely (Zagórski *et al.* 2012).

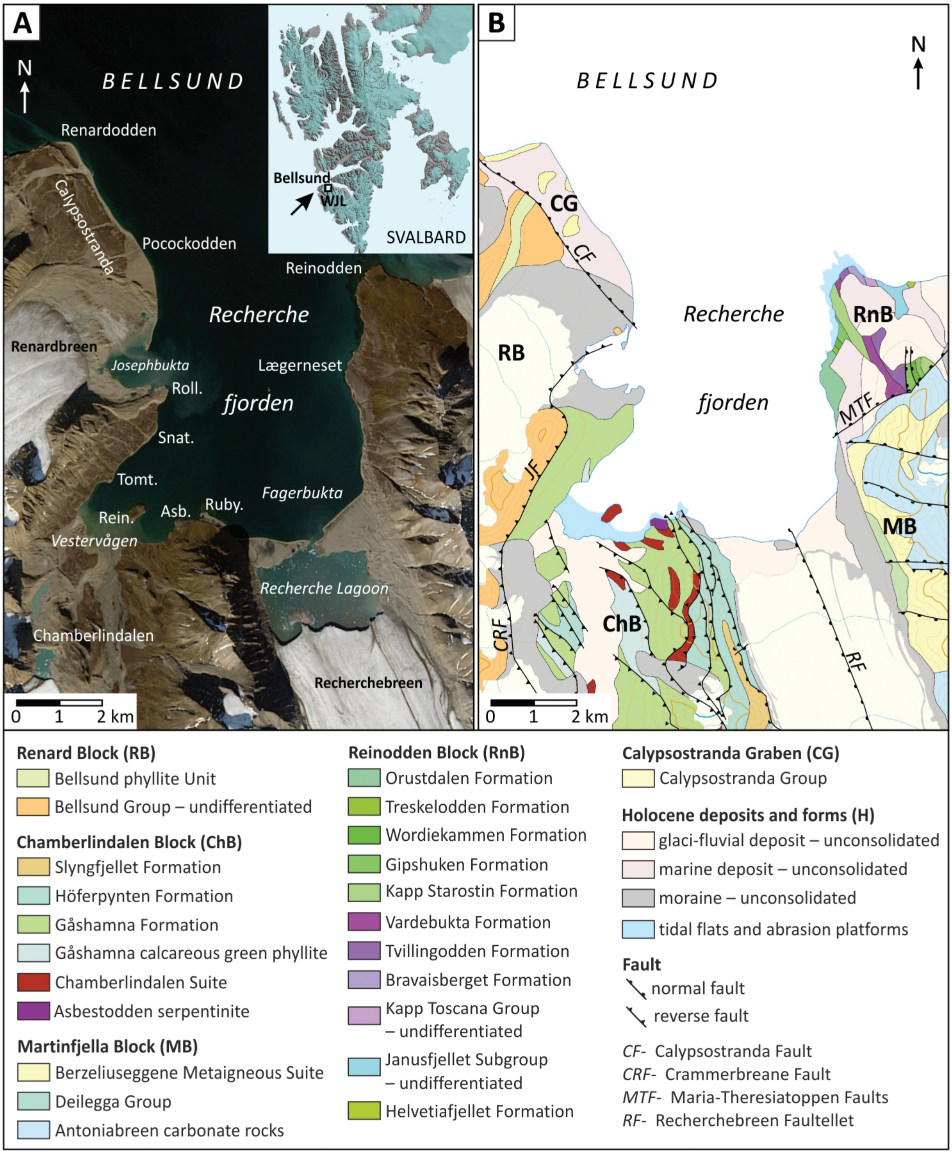

Fig. 1. Recherchefjorden; (**A**) location map of study area: WJL – Wedel Jarlsberg Land, Asb. – Asbestodden, Rein. – Reinholmen, Roll. – Rollestonpynten, Ruby. – Rubypynten, Snat. – Snacherpynten, Tomt. – Tomtodden (source: Landsat-8 image collected on August 23, 2014, courtesy of the U.S. Geological Survey, Department of the Interior); (**B**) geological map (source Svalbardkarte, Norsk Polarinstitutt WebGIS, www.svalbardkartet.npolar.no, NPI 2016).

Josephbukta, a bay located as a continuation of the Renardbreen valley stands out in the north-western part of the Recherchefjorden (Fig. 1A). The lower, currently non-glaciated part of the valley is formed by an extensive inner zone closed by the arch of a push moraine, several dozen metres high, extending from Calypsostranda to Josephbukta and, on the southern side, in the vicinity of Rollestonpynten (Reder 1996; Reder and Zagórski 2007; Zagórski *et al*. 2012). The large areal extent of the inner zone indicates the fast changes linked with the retreat of the Renardbreen. During this process, the glacier has left a significant volume of sediments and a number of geomorphological forms of glacial and fluvio-glacial origin (Zagórski 2007; Rodzik *et al*. 2013). From the end of the 19th century (the end of the Little Ice Age, LIA) until the 1940s, the catchment also contained an area located outside the moraine ridges, shaped by fluvio-glacial waters (extramarginal outwash plains, Pocockodden). From the end of the Little Ace Age up to the present, a continuous retreat of the Renardbreen was recorded, at the rate of approximately 10 $m \cdot a^{-1}$, (Zagórski *et al*. 2008; Rodzik *et al*. 2013). The retreat of Renardbreen was significantly influenced by its contact with the fjord waters in Josephbukta area where the frontal retreat was mainly caused by thermal abrasion. The front of the glacier had contact with the fjord waters up to the 1990s.

The Chamberlindalen connects with the south-western part of the Recherchefjorden. The bottom of the valley transitions into the tidal flat of Vestervågen, along with the Reinholmen (Rein Island) (Fig. 1A). The bottom of the valley constitutes a system of raised marine terraces transformed by gelifluction processes and a vast outwash plain transitioning into an approximately 1 km long and 1.4 km wide tidal flat of Vestervågen (Pękala and Repelewska-Pękalowa 1988; Zagórski *et al*. 2013). The kind of the valley's relief and the lithology of the surface sediments indicate the lack of direct glacial impact in this area throughout the Holocene (Zagórski *et al*. 2012). Towards the end of the Little Ice Age, glaciers in the Chamberlindalen occupied about 17 km^2 (31% of the valley), and their range is now indicated by ice-moraine ridges (Rodzik *et al*. 2013).

Fagerbukta is a bay located in the south-eastern part of the fjord, as an extension of the Recherchebreen Valley (Fig. 1A). In the south, it is delimited by outwash plains at the northern flank of the vast inner lagoon in front of the Recherchebreen ice cliffs. It was one of the most dynamically changing areas in this region during the last two centuries (Reder 1996; Zagórski *et al*. 2012). The front of the glacier has been subject to oscillation caused by several surge episodes. One of them, in 1839 (Liestøl 1969) led to the pushing/deposition of glacial-marine sediments that currently lie along the eastern shores of the Recherchefjorden as far as Lægerneset (about 4.5 km from the present range of the front of the glacier; Fig. 1A) and in the vicinity of Rubypynten, on the western side of Fagerbukta (Reder 1996; Zagórski *et al*. 2012; Rodzik *et al*. 2013). The successive glacier surges that occurred in the first half of the 20th century had a considerably smaller range limited to the southern part of Fagerbukta (unpublished data based on the analysis of archived cartographic and photographic materials; Hamberg 1905; Statens kartverk Sjø 1927; B11 Van Keulenfjorden 1952). The continuity of the moraine series was almost totally disrupted as a result of marine and glacio-fluvial processes. Today, only a few residual moraines dominate above the level of the outwash plain (Zagórski *et al*. 2012).

The last fragment of the coast of the Recherchefjorden, in its north-eastern part, north of Lægerneset, forms a system of raised marine terraces transformed by periglacial and fluvial processes (Repelewska-Pękalowa and Pękala 1991). Their surfaces does not have any trace of Holocene glacial impact (Zagórski *et al*. 2013). The geological structure and tectonics played a dominant role in the development of the part of the Recherchefjorden coastline. Owing to the layout of the rock layers and their resistance, the coast here features cliffs with abrasion platforms at their base (Zagórski 2002).

In geological terms, the investigated area is situated within several rock lithostratigraphic units that vary considerably with regard to age and lithology (Dallmann 1989; Dallmann *et al*. 1990; Birkenmajer 2006; Birkenmajer and Gmur 2010; Majka *et al*. 2015; NPI 2016). The rocks in the study area are cut by zones of thrust faults and faults renewed and remodelled during Tertiary tectonic activity (Dallmann *et al*. 1993; Birkenmajer 2004, 2006, 2010). Palaeogene tectonic movements brought about new tectonic discontinuities or renewed old fault zones. In the north-western part of the Wedel Jarlsberg Land, several main fault systems can be distinguished (Fig. 1B), such as: 1) main Recherchebreen strike-slip fault (RF) discontinuity zone, 2) a group of Crammerbreane (CRF) and Josephbukta (JF) dip-slip faults, 3) Maria-Theresiatoppen strike-slip fault (MTF) 4) NW-SE-trending Calypsostranda dip-slip fault (CF). Based on the above, the following tectonic units can be distinguished (Birkenmajer 2004, 2006): 1) Renardbreen Block (RB); 2) Chamberlindalen Block (ChB); 3) Martinfjella Block (MB); 4) Reinodden Block (RnB); 5) open Calypsostranda Graben (CG). For a detailed description of the main lithostratigraphic and tectonic units, see Figure 1B and a legend provided (NPI 2016).

Datasets and methods

Bathymetric data. — Bathymetric data used in this study were obtained from two sources: the measurements of the Norwegian Hydrographic Service (NHS) and measurements conducted by the authors. NHS measurements in the Recherchefjorden areas were conducted with a Simrad EQ echo-sounder and mini-ranger radar positioning system in the years 1985–1994. Based on bibliographic data for the system above, positions were determined with the accuracy of 5–10 m (Anderson *et al*. 1973). In the case of this study, the accuracy of the horizontal position was determined as less than 20 m and the accuracy of bathymetric measurements as 2 m (according to NHS). The NHS depth values were determined at specific points. The distribution of the measurement points is variable, however the whole study area has been covered (Fig. 2A). The lowest density of measurement points occurs outside the Recherchefjorden, in the south-eastern part of Bellsund. The distance between measurement points in that area ranges from 300 to 500 m. In the Recherchefjorden, the distance

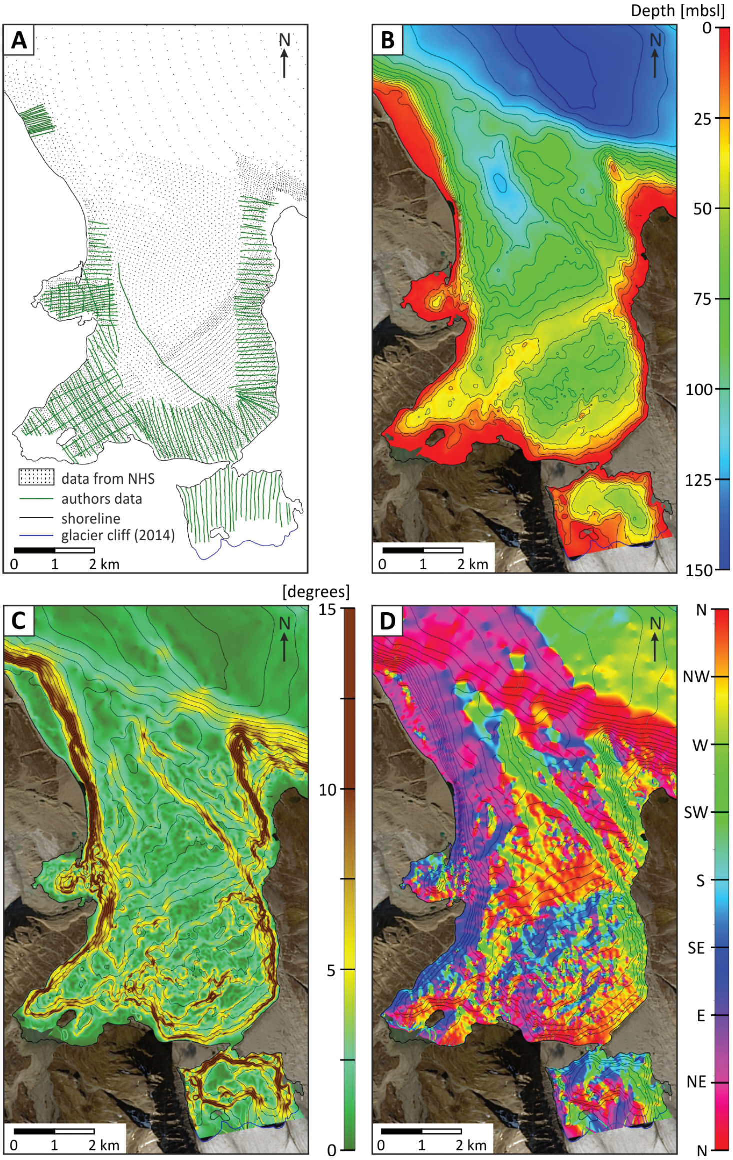

Fig. 2. (**A**) Measurements localisation; (**B**) Interpolated bathymetry; (**C**) slope; (**D**) aspect.

is 100–150 m in its north-western part and 50–100 m in the south-eastern part. The highest density of measurement points occurs in the coastal areas and in the bays: Fagerbukta, Josephbukta, Vestervågen and its extension to the line connecting Snatcherpynten in the north and Rubypynten in the south.

The measurements were conducted by the authors in 2011 and 2012, using an analogue echo-sounder of the Multi-Frequency Bathy-500 MF type and the DGPS (GPS) Leica System 500 (SR530 recivers). The bathymetric profiling of the fjord was preceded by the calibration of the echo-sounder oscillator to factor in the variation of salinity and temperature in the depth profile. In contrast with the bathymetric data from the NHS, the authors' measurements were carried out in bathymetric profiles at a distance between them about 100 m (Fig. 2A). In total, 216 profiles have been prepared and preserved an analogue paper rolls with time and GPS coordinates provided. The location of measurements were carried out at the beginning and end of the profile and during the profiling in the form of checkpoints at a specific, constant time intervals. The measurements had an accuracy of 2 cm (DGPS) and took into account the tide value.

Data pre-processing. — The preparation and processing of data related to the interpolation, the designation of morphometric parameters and analysis of morphological and geomorphological parameters are described in detail below

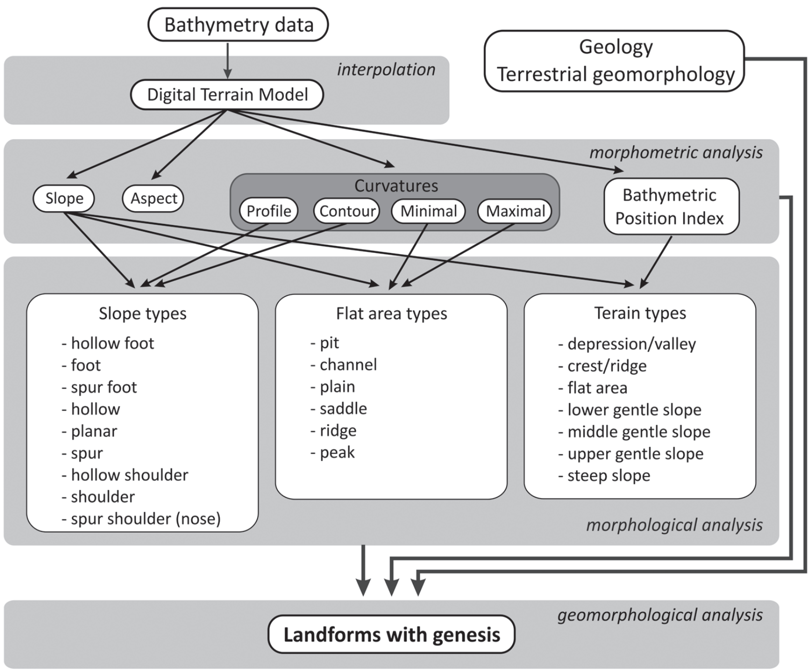

Fig. 3. Diagram of the steps of data processing and measurement results.

(Fig. 3). Converting the 2011–2012 data from analogue into digital format as well as verification and distance correction were important elements of the research. Post-processing was carried out using ArcGIS 10.1 software. All bathymetric images were scanned and converted to vectors in shapefile format. Using the *Spatial Adjustment* module, all layers were adjusted to the actual length of the profiles according to the precise geodesic GPS measurements. Bathymetric measurements were read in each profile every 5 m. The bathymetric profiles prepared were juxtaposed with NHS data. The Recherchefjorden Digital Terrain Model (DTM) is a result of interpolating all the bathymetric data on a regular 5-metre grid. Ordinary Kriging method, described and compared with another popular interpolation method by Moskalik *et al*. (2013), was used for interpolation. Up to 300 nearest depth points, located no further than 1000 m apart, were used for interpolation for every points on the grid. To eliminate significant interpolation errors, additional two-dimensional median filter has been applied on the DTM.

First and second DTM derivatives. — DTM can be used to analyse terrain characteristics at the local and global scale (Wilson *et al*. 2007). Typical morphometric parameters describing terrain are its first derivatives: (i) slope (*slope*) and (ii) aspect of slope (*aspect*). Other morphometric parameters describing terrain are its second-order derivatives, namely curvatures. The following parameters were used for morphometric analyses: (iii) profile ($prof_c$) (also named vertical), (iv) contour ($cont_c$) (also named plane), (v) minimal (min_c), and (vi) maximal (max_c) curvature.

If $f(x,y)$ is a DTM function, we have an analytical formula for these parameters:

(i) $$slope = \arctan\left(\sqrt{f_x^2 + f_y^2}\right) \qquad (1),$$

(ii) *aspect* is a direction of the vector $\begin{pmatrix} f_x \\ f_y \end{pmatrix}$ (2),

(iii) $$prof_c = -\frac{f_{xx} f_x^2 + 2 f_{xy} f_x f_y + f_{yy} f_y^2}{\left(f_x^2 + f_y^2\right)\left(1 + f_x^2 + f_y^2\right)^{1.5}} \qquad (3)$$

(iv) $$cont_c = -\frac{f_{xx} f_y^2 - 2 f_{xy} f_x f_y + f_{yy} f_x^2}{\left(f_x^2 + f_y^2\right)^{1.5}} \qquad (4)$$

(v) $$min_c = -\frac{\left(1 + f_y^2\right) f_{xx} - 2 \mathrm{f}_{xy} f_x f_y + \left(1 + f_x^2\right) f_{yy}}{2\left(1 + f_x^2 + f_y^2\right)^{1.5}} - r_c \qquad (5)$$

(vi) $$max_c = -\frac{\left(1 + f_y^2\right) f_{xx} - 2 \mathrm{f}_{xy} f_x f_y + \left(1 + f_x^2\right) f_{yy}}{2\left(1 + f_x^2 + f_y^2\right)^{1.5}} + r_c \qquad (6)$$

where

$$r_c = \frac{0.5}{\left(1+f_x^2+f_y^2\right)^{1.5}}\left\{\frac{\left(f_{xx}F^{0.5}-f_{yy}F^{-0.5}\right)^2}{1+f_x^2+f_y^2}+\left(\left(f_x f_y f_{xx}-2f_{xy}\right)F^{0.5}+f_x f_y f_{yy}F^{-0.5}\right)^2\right\}^{0.5} \tag{7}$$

and

$$F = \frac{1+f_y^2}{1+f_x^2} \tag{8}$$

For $prof_c$ and $cont_c$ formulas proposed by Schmidt *et al*. (2003) and Shary *et al*. (2002) based on Evans (1972) were used. For min_c and max_c formulas proposed by Shary *et al*. (2002) based on Shary (1995) were used. In equations 1–8, the partial derivative of $f(x,y)$ with respect to the variable x is denoted as f_x and analogously for other partial derivatives.

Slope is an important factor in determining the direction of redeposited sediment transport and its accumulation (Moskalik *et al*. 2012). Such processes are important in marine glacial geomorphology interpretation, especially from the perspective of sediment type on the bottom. Based on *slope* and *aspect*, it is possible to define separate regions that could represent different geomorphological forms. In particular, it could be used to find geomorphological forms perpendicular or parallel to glacier cliffs. Most submarine landforms produced by glaciers perpendicular to the glacier front, such as valley slopes, streamlined glacial lineation's and lateral ice-stream moraine, are associated with glacier movements. Parallel landforms, such as terminal, recessional, and annual retreat moraines, are associated with the accumulation of sediments in front of glacier cliffs during glacier retreat (*e.g*. Ottesen and Dowdeswell 2006, 2009; Ottesen *et al*. 2008; Dowdeswell *et al*. 2016).

Curvatures are used to describe the convex, concave or straight character of planes and slopes. There are different types of curvatures depending on the direction taken to derive them. $Prof_c$ and $cont_c$ were chosen from among other curvatures because they describe curves determined along the steepest downslope direction ($prof_c$) and the direction parallel to isohypses ($cont_c$). Using $prof_c$ and $cont_c$ it is possible to distinguish five morphological types of slopes: shoulder slope (convex $prof_c$), spur (convex $cont_c$), hollow (concave $cont_c$), foot slope (concave $prof_c$) and planar slope (straight $cont_c$ and $prof_c$) as well as their four combinations: spur shoulder (nose; convex $cont_c$ and convex $prof_c$), hollow shoulder (concave $cont_c$ and convex $prof_c$), spur foot (convex $cont_c$ and concave $prof_c$), hollow foot (concave $cont_c$ and concave $prof_c$). Such a classification was used by Schmidt and Hewitt (2004) who preferred to use tangential curvature rather than $cont_c$.

It is problematic to use the curvatures described above on a flat area where $f_x^2+f_y^2$ is close to 0 and $cont_c$ and $prof_c$ are undetermined (eq. 3 and 4). In such a situation, Schmidt and Hewitt (2004) used max_c and min_c to determine six morphological forms: peak (both are convex), pit (both are concave), plain (both are straight), saddle (min_c is concave and max_c is convex), ridge (max_c is convex and min_c is straight) and channel (min_c is concave and max_c is straight).

Other curvatures often used in morphometric analysis include: tangential (similar to $cont_c$ but obtained on direction normal to gradient), longitudinal and cross-sectional (similar to the $prof_c$ and $cont_c$), mean (half sum of max_c and min_c) (Schmidt *et al*. 2003; Schmidt and Hewitt 2004; Shary *et al*. 2002; Wilson *et al*. 2007; Blaga 2012).

The described parameters can be determined when DTM is approximated by the quadratic function:

$$f(x,y) = a \cdot x^2 + b \cdot y^2 + c \cdot x \cdot y + d \cdot x + e \cdot y + f_0 \tag{9}$$

If coordinate system is chosen so as the point where parameters are determined is in centre of coordinate system (0, 0) equations 1–6 are described as:

$$aspect = \arctan\left(\sqrt{d^2 + e^2}\right) \tag{10}$$

$$slope = \left\{ \begin{matrix} 270 - \arctan\left(\frac{e}{d}\right) \Leftarrow (d > 0) \\ 90 - \arctan\left(\frac{e}{d}\right) \Leftarrow (d < 0) \\ 0 \Leftarrow (d = 0 \cup e < 0) \\ 180 \Leftarrow (d = 0 \cup e > 0) \\ notexist \Leftarrow (d = 0 \cup e = 0) \end{matrix} \right\} \tag{11}$$

$$prof_c = -2 \frac{a \cdot d^2 + b \cdot e^2 + c \cdot d \cdot e}{(e^2 + d^2) \cdot (1 + e^2 + d^2)^{1.5}} \tag{12}$$

$$cont_c = -2 \frac{b \cdot d^2 + a \cdot e^2 - c \cdot d \cdot e}{(e^2 + d^2)^{1.5}} \tag{13}$$

$$max_c = -a - b + \sqrt{(a-b)^2 + c^2} \tag{14}$$

$$min_c = -a - b - \sqrt{(a-b)^2 + c^2} \tag{15}$$

Such a method was used by Wilson *et al*. (2007) according to the formula provided by Evans (1980).

Bathymetric Position Index (BPI). — BPI is a morphometric parameter defining differences in local depth. This is a modification of Topographic Position Index (TPI) defined by Weiss (2001), used by Lanier *et al*. (2007) and Lundblad *et al*. (2006) for benthic terrain classification and seafloor habitat mapping. BPI can be described as:

$$BPI(x,y) = f(x,y) - mean(f(x,y), r_{min}, r_{max}) \qquad (16)$$

where $mean(f(x,y), r_{min}, r_{max})$ is mean depth in annulus with inner radius r_{min} and outer radius r_{max}. Positive or negative BPI values represent local depth higher or lower than the surrounding area, respectively. BPI close to zero can represent either a flat area or a slope. Comparing BPI with the standard deviation of depth used to calculate BPI, it is possible to find morphological forms like crests/ridges, depressions/valleys, flat areas and slopes (Weiss 2001; Lundblad *et al*. 2006). It is possible to identify more morphological forms calculating BPI in two different sizes of annulus (Weiss 2001; Lundblad *et al*. 2006; Lanier *et al*. 2007). Based on Weiss (2001), morphological forms in this study were defined as follows:

$$\left\{ \begin{array}{c} crests/ridges \Leftarrow \left(\frac{BPI}{std} > 1 \right) \\ depressions/valleys \Leftarrow \left(\frac{BPI}{std} < -1 \right) \\ flatareas \Leftarrow \left(-1 \ \frac{BPI}{std} \ 1 \cup slope < slope_{min} \right) \\ steepslopes \Leftarrow \left(-1 \ \frac{BPI}{std} \ 1 \cup slope > slope_{max} \right) \\ lowergentleslopes \Leftarrow \left(-1 \ \frac{BPI}{std} \ -0.5 \cup slope_{min} \ \ slope \ \ slope_{max} \right) \\ middlegentleslopes \Leftarrow \left(-0.5 \ \frac{BPI}{std} \ 0.5 \cup slope_{min} \ \ slope \ \ slope_{max} \right) \\ uppergentleslopes \Leftarrow \left(0.5 \ \frac{BPI}{std} \ 1 \cup slope_{min} \ \ slope \ \ slope_{max} \right) \end{array} \right\} \qquad (17)$$

where: *std* is a standard deviation of all of the BPI values, $slope_{min}$ and $slope_{max}$ is a minimal and maximal slope defining gentle slopes.

Results

The results of the calculations are presented both on maps (Figs. 2B–D and 4) and in statistical distributions (Fig. 5).

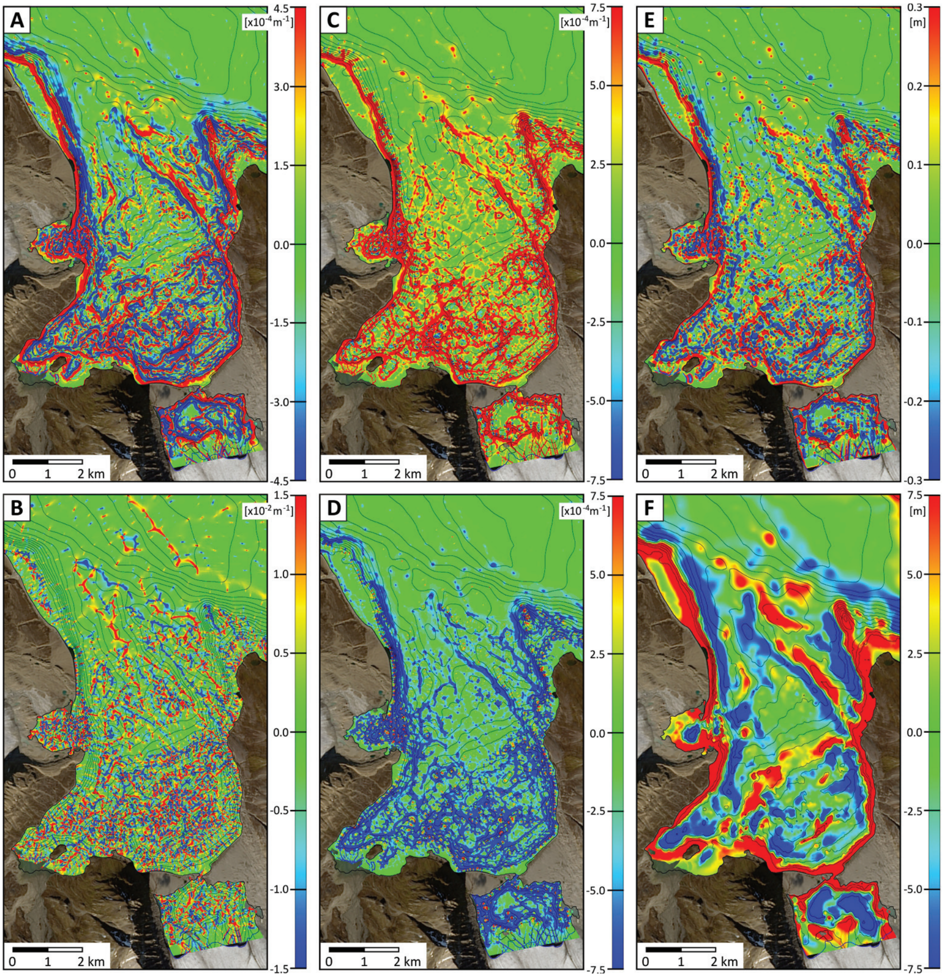

Fig. 4. Morphometric parameters: (**A**) profile curvature (*prof*$_c$); (**B**) contour curvature (*cont*$_c$); (**C**) maximal curvature (*max*$_c$); (**D**) minimal curvature (*min*$_c$); bathymetric position index (BPI) for (**E**) r_{min}=20 m, r_{max}=50 m, and (**F**) r_{min}=200 m, r_{max}=500 m.

Bathymetry, slope and its aspect. — Within the area analysed, the greatest depths occur in the vicinity of Bellsund. In the Recherchefjorden itself, the deepest area is its north-western part with a distinct basin which depth exceeds 120 m (Fig. 2B). The mean depth of the area under study is approximately 70 m. Apart from the shallow zone down to the depth of about 10 m, the distribution of depths shows local minor variations but no value stands out, *i.e*. no dominant depth occurs in the study area (Fig. 5A).

In terms of slope inclination, most of the area described is rather flat even though the steepest slope exceeds 35°. Less than 5% of the slopes have an inclination of more than 10° and nearly half of the area has an inclination of less

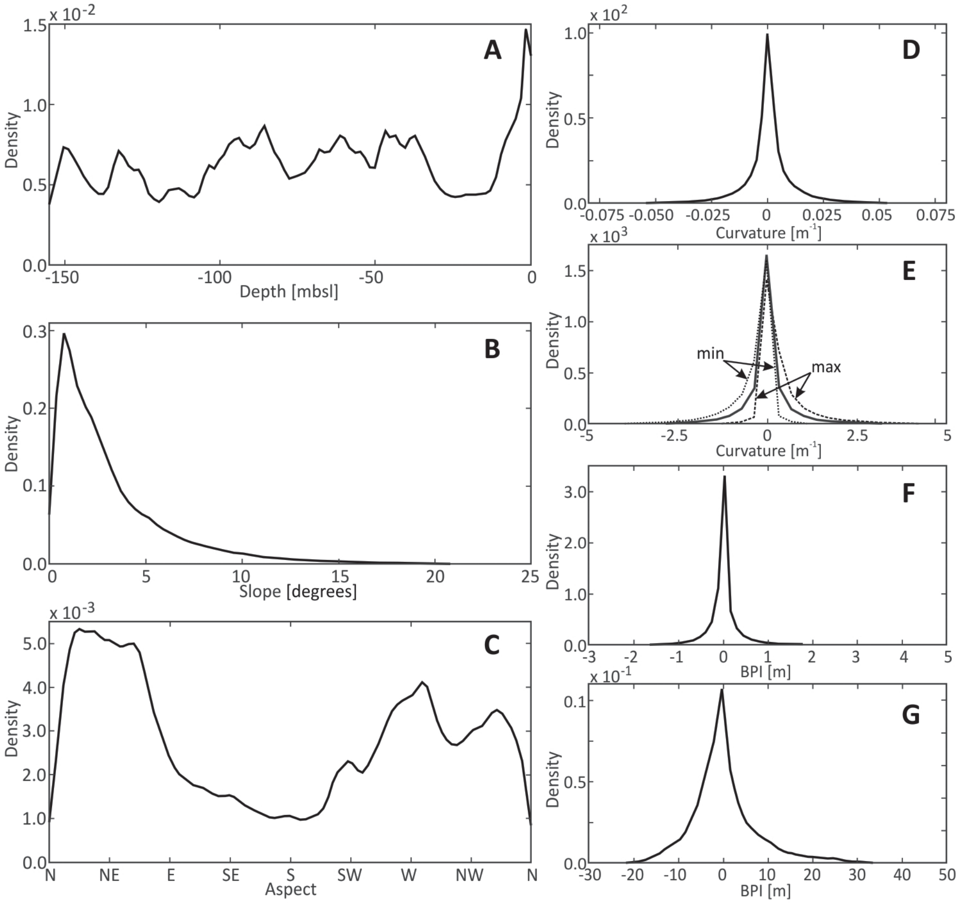

Fig. 5. Density distributions of (**A**) depth; (**B**) slope; (**C**) aspect; (**D**) contour curvature; (**E**) profile (black line), maximal (max) and minimal (min) curvatures; bathymetric position index (BPI) for (**F**) r_{min}=20 m, r_{max}=50 m and (**G**) r_{min}=200 m, r_{max}=500 m.

than 2° (Fig. 5B). The steepest slopes occur in the coastal zone, at the flanks of the bays, at the transition from the Recherchefjorden to Bellsund, irregularly in the southern part of the Recherchefjorden, and in the form a distinct line in the middle part of its northern fragment (Fig. 2C). Slopes inclined towards the NE, W and NW predominate in the study area (Fig. 2C and 5D). Analysing the slope values in the morphometric analysis using BPI, $slope_{min}$=2° and $slope_{max}$=10° were assumed as the boundary values for gentle slopes. Such an assumption will allow the identification of the steepest places in the study area.

Curvatures. — A nearly symmetric distribution of values was obtained for the determined curvatures, with the dominant value close to zero (Fig. 5D and E).

The greatest deviation from the symmetric distribution is shown by max_c and min_c. The distribution is nearly identical but it differs with regard to the sign of the determined value. The zero value of the curvature indicates its straight character.

Analysing the values obtained for $cont_c$, the authors adopted 0.01 m^{-1} as the boundary value between the straight and convex or concave character of the slope. This value corresponds to the curvature with a radius of 100 m. Furthermore, with the value thus adopted, over 80% of the study area has a value indicating the lack of slope curvature along an isobaths. This also means that morphological forms of the spur and hollow type can be found in less than 20% of the analysed area. These forms occur mainly on slopes and their dimensions should not be expected to exceed the assumed value of the curvature radius.

Analysing the values for $prof_c$, min_c, and max_c, it should be noted that they are almost a 100 times lower than $cont_c$. They describe the shape of the slope, in accordance with its direction, or flat areas, and they should be expected to have greater dimensions than forms perpendicular to the slope. In this case, 0.0005 m^{-1} was adopted as the boundary value between *straight* and *convex* or *concave*, and it corresponds to the curvature of a circle with a radius of 2000 m. Such a limitation enabled the separation of fragments of slopes of the *foot* and *shoulder* type from the *planar slope* type. The areas thus distinguished account for less than 20% of the study area. An analogous limitation was adopted for min_c and max_c, which allowed distinguishing concave and convex forms in flat areas.

Taking into account the fact that the classification based on $cont_c$ and $prof_c$ applies to slopes while min_c, and max_c to flat areas, the authors introduced a limitation resulting from the slope inclination. The first analysis concerns areas with a slope value of more than 1° while the second one concerns areas with a slope value of less than 4°. In this case, each morphological classification enabled the analysis of about 75% of the study area. The results of the morphological form types obtained are presented on the map (Fig. 6).

BPI. — In the case of the BPI parameter, a distribution with the predominance of positive values was obtained, which is more visible for BPI values determined for r_{min}=200 m and r_{max}=500 m (Fig. 5F and G). The map of values obtained for BPI with the adopted r_{min}=20 m and r_{max}=50 m contains many artefacts not occurring in the second case (Fig. 4E and F). This effect results from the distance between points in data sets, higher than 100 m. Adopting the previously slope analysis and the adopted values $slope_{min}$=2° and $slope_{max}$=10°, maps of terrain form classification were prepared independently for each of the BPI determined (Fig. 7). The BPI was found to be a positive in coastal areas, and as effect this part was interpreted as crest/ridges, especially for r_{min}=200 m and r_{max}=500 m (Fig. 7B). However, the coastal part of land is higher than coastal part of seafloor. This is because the BPI algorithm considered the land as no

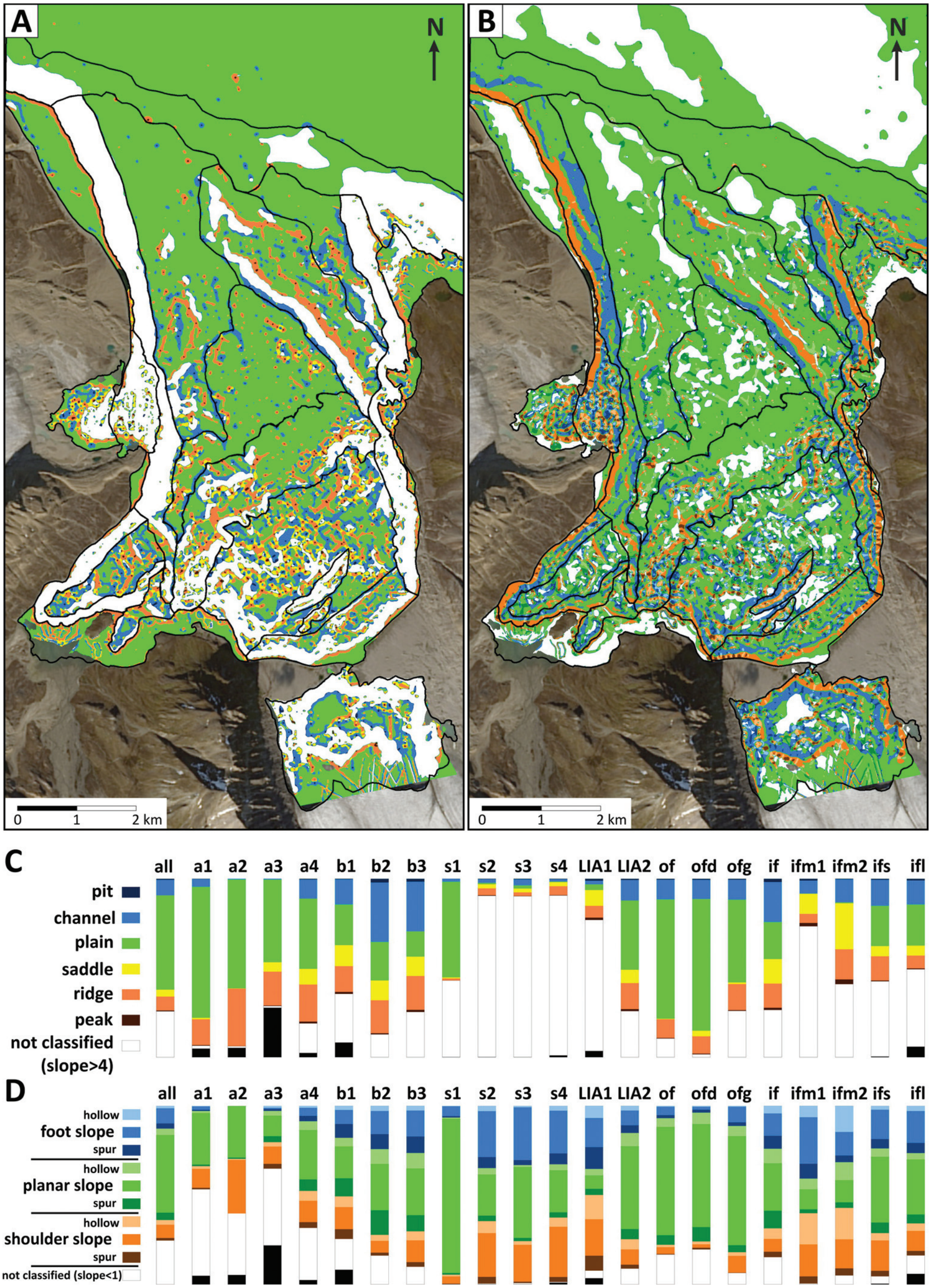

Fig. 6. Morphological parameters in study area (**A**, **B**) and their contribution in sets of landforms (**C**, **D**) base on maximal and minimal curvature – flat area elements (**A**, **C**), and contour and profile curvature – sloping elements (**B**, **D**). Sets of landforms described on Fig. 8.

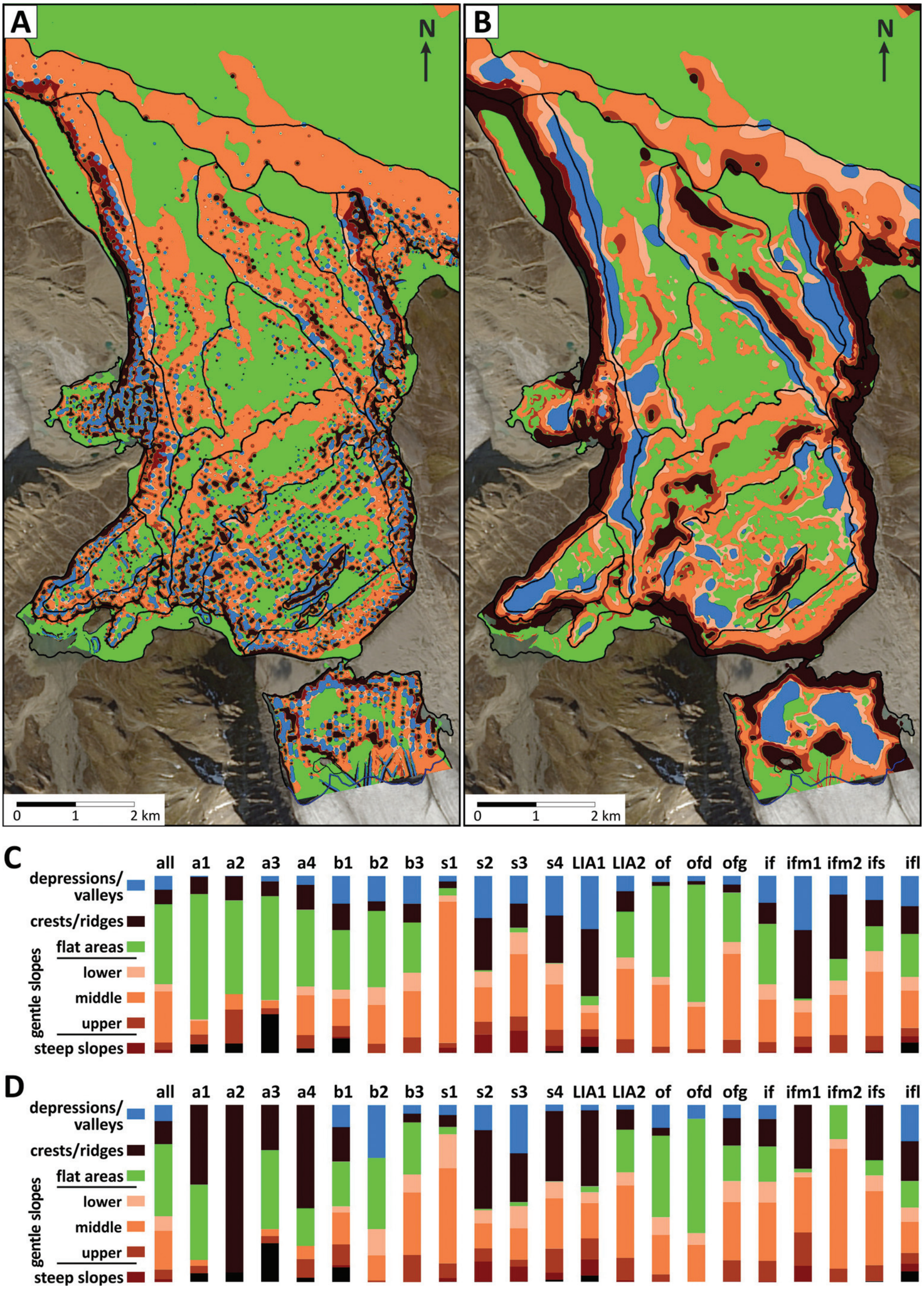

Fig. 7. Morphological parameters in study area (**A**, **B**) and their contribution in sets of landforms (**C**, **D**) base on bathymetric position index for r_{min}=20 m, r_{max}=50 m (**A**, **C**) and r_{min}=200 m, r_{max}=500 m (**B**, **D**). Sets of landforms described on Fig. 8.

data, and it is a limitation of the method. In this situation it could have same interpretation like for smaller scale BPI, r_{min}=20 m and r_{max}=50 m, when such effects is limited to first 50 m coastal part of seafloor.

Discussion

Analysis of depth distribution normalized to maximum value, conducted by Moskalik *et al*. (2013) in the inner part of the Hornsund indicate that U-shaped fjord basins formed by and considerably modified by glaciers are characterised by the occurrence of a dominant depth value greater than the mean depth value in a given basin. Glacier impact is not significant in basins where the dominant depth value is lower than the mean depth, or where the distribution of depths is irregular. The distribution of depths in the Recherchefjorden would indicate the latter (Fig. 5A). On the other hand, analysing the bathymetric map and the slope inclinations (Fig. 2B and C), one can notice distinct slopes and a broad bottom whose shape resembles U-shaped valleys. Thus, in the Recherchefjorden area one should expect a diverse geomorphology of the bottom that results both from geology and the glacial history of the area. Such a varied bottom geomorphology is visible in the determined morphometric and morphological parameters and made it possible to distinguish separate sets of landforms. The sets of landforms (areas) presented in Fig. 8 were distinguished based on the morphological analysis (Figs. 6 and 7) based on the determined morphometric parameters: slope curvatures (Fig. 4A–D) and BPI (Fig. 4E and F). The sets of landforms are concentrated in two zones: the main Recherchefjorden and its surroundings. The delimitation also takes into account the origins and location of these landforms in relation to the glacial systems. Two main moraine areas were distinguished (terminal moraines). They are linked with the Holocene advances of the Renardbreen (LIA1 on Fig. 8) and Recherchebreen (LIA2 on Fig. 8), mainly during the Little Ice Age (Zagórski *et al*. 2008, 2012). These morraines constitute boundary zones between areas with different morphometric parameters.

The first one, Little Ice Age moraine (LIA1 on Fig. 8), is a subaqueous extension of marginal moraines of the Renardbreen occurring on land. They are located at the eastern flank of Josephbukta (b1 on Fig. 8) and partially cover the area of slope (s2 on Fig. 8) to which the front of the glacier extended during the maximum of the Little Ice Age. The morphometric and morphological parameters indicate high variation resulting from the numerous moraine ridges occurring here (their orientation approximates the north to south axis) and depressions between them (Figs. 2C, 4, 6 and 7; prof. J1, J2 on Fig. 9).

The second area – Little Ice Age moraine (LIA2 on Fig. 8), forms a vast, arched moraine ridge extending between Lægerneset and Rubypynten, 4.2 km

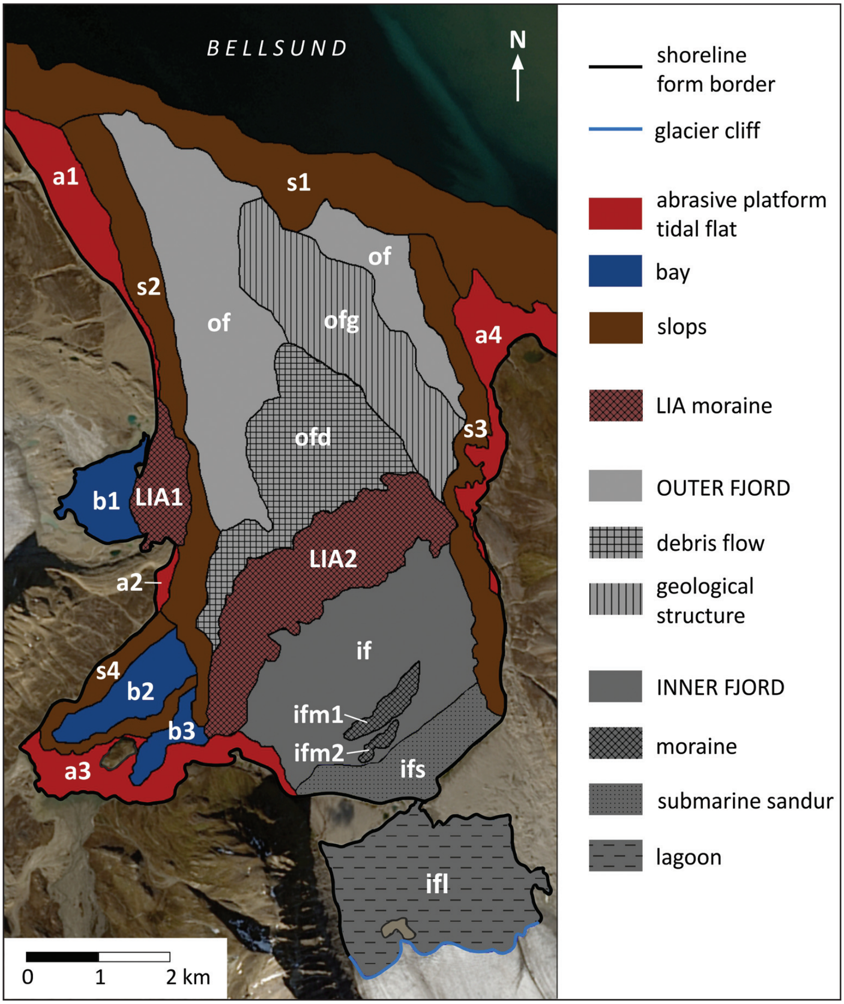

Fig. 8. Sets of landforms obtained through morphometric study.

long and up to 1.3 km wide. The ridge reaches a relative height of more than 40 m and features both flat areas and steep ridges (Figs. 6, 7 and 9; prof. R3 on Fig. 9). This Little Ice Age moraine is continued on land, in the form of moraine ridges, both on the eastern side of Fagerbukta and the western side, in the Rubypynten area (Zagórski *et al*. 2013). This preserved glacial relief is typical for the surge-type moraines and determines the maximum reach of the Recherchebreen front during the Little Ice Age. Bibliographic archive materials date back to the occurrence of the surge for the first half of the nineteenth century, approx. to 1838 (Gaimard 1852; Le Nepvou de Carfort 1894). Taking it into account this allows a significant shift within the glacier front position

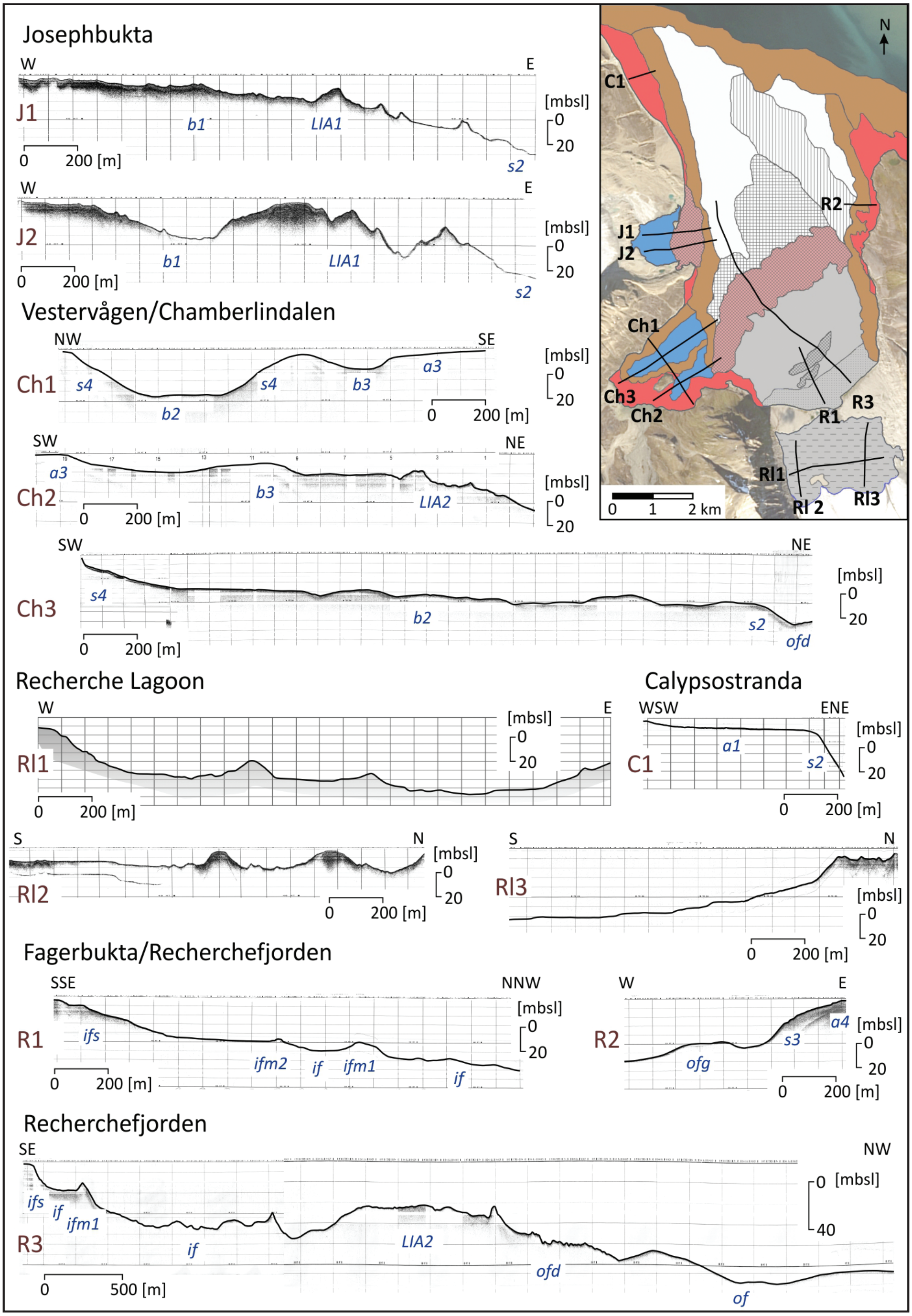

Fig. 9. Example of bathymetric profiles used in this study.

and relative to its position in the 1930s - considered in some studies to be the maximum during the Little Ice Age (Martín-Moreno *et al*. 2017).

The area surrounding the main fjord zone includes, among others, abrasive platforms and tidal flats (a1, a2, a3, a4 on Fig. 8). These are flat areas occurring in the shore zone, genetically different but considered jointly here due to the lack of variation of the morphometric and morphological parameters. Abrasive platforms occur in the nearshore and offshore zone, and result from the abrasive activity of marine processes. Many of these platforms feature skerries (Zagórski *et al*. 2013). A tidal flat is linked with the delivery and deposition of material in the lower reaches of valleys in the tidal zone, at the interface of fluvial and marine processes.

Four areas of this kind were distinguished in the study area (Fig. 8):

- a1 – abrasive platform in the Calypsostranda area, from Renardodden to Pocockodden. It developed within the poorly resistant rocks of the Calypsostranda Group (Eocene/Oligocene) (NPI 2016) (Fig. 1B), and it adjoins a typical accumulative shore. Its surface is even and slightly inclined towards the ENE (Fig. 2C and D; prof. C1 on Fig. 9).
- a2 – abrasive platform to the north of Snatcherpynten; developed within the Neoproterozoic rocks of the Gåshamna Formation (NPI 2016) (Fig. 1B). During the Little Ice Age, its northern part was covered by the moraine deposits of the Renardbreen.
- a3 – tidal flat at the estuary of the Chamberlindalen into Vestervågen, linked with the delivery of material by proglacial rivers. Towards the east, it transitions into an abrasive platform that developed within the rocks of the Chamberlindalen Block (NPI 2016) (Fig. 1B) and is linked with the abrasion of marginal moraines (LIA2 on Fig. 8) of the Recherchebreen in the vicinity of Rubypynten (Fig. 8; prof. Ch1, Ch2 on Fig. 9). It was not possible to distinguish tidal flats and abrasive platforms based on morphometric and morphological properties; hence they are regarded as one area.
- a4 – abrasive platform located in the NE part of the Recherchefjorden, to the north of Lægerneset and continuing further in the Reinodden area (Fig. 8; prof. R2 on Fig. 9). It developed within the resistant silstones of the Reinodden Block (NPI 2016) (Fig. 1B). The peculiar layout of resistant rock layers, their position nearly vertical and their SE-NW orientation, coupled with the long-lasting impact of marine processes (the entire Holocene), influenced the lateral extent of this area in the vicinity of Reinodden; in its axial part the abrasive platform it is more than 1 km long.

The surroundings of the main fjord also include the bays (b1, b2, b3 on Fig. 8). They are located on the western and south-western side of the Recherchefjorden. These are all bays connected with the main fjord but different with regard to the degree of the impact of glacial systems.

- b1 – Josephbukta – occurs in the zone under the direct impact of the Renardbreen whose cliff discharged into the bay until the 1990s (Zagórski *et al*. 2008; Rodzik *et al*. 2013). The bottom features are lateral moraine ridges linked with the particular stages of glacier retreat from the end of the Little Ice Age, which is visible in the variation of the morphometric parameter values (Fig. 4) and morphological forms (Figs. 6 and 7). This moraine ridges are visible on the bathymetric profiles from this area (prof. J1, J2 on Fig. 9).

- b2 – area of the fjord to the north of Reinholmen. The bottom of this bay is undulating, with slightly marked ridges and depressions. Such relief results from an absence of glacial impact during the Holocene. This is reflected in the small variation of morphometric and morphological parameters (Figs. 4, 6 and 7), as well as the immediate bathymetric profiles (prof. Ch1, Ch3 on Fig. 9).
- b3 – located east of the Reinholmen, this bay, similarly to the neighbouring bay (b2 on Fig. 8), is characterised by a flat and smooth bottom with depths ranging from 15 to 20 m and a shallower zone in the vicinity of Asbestodden (Fig. 8; prof. Ch2 on Fig. 9) – determined by the geological structure (NPI 2016) (Fig. 1B).

The main zone of the Recherchefjorden bottom and its vicinity is divided by areas referred to as slopes (s1, s2, s3, s4 on Fig. 8) – they are basically steep slopes of the fjord or bays. Four areas were distinguished:

- s1 – a fragment of the southern slope of Bellsund; its course results from the exaration effect of ice streams flowing from the east from the Van Keulenfjorden in Last Glacial Maximum (Ottesen *et al*. 2007; Ingólfsson and Landvik 2013). It rather does not correspond to the geological structure. It is located at the northern flank of the Recherchefjorden which, as a result, has the character of a suspended valley. (Figs. 2B–D and 8).
- s2 – the western slope of the Recherchefjorden, oriented almost exactly along the north–south axis and extending from Renardodden in the north as far as Asbestodden in the south. It is 8.7 km long. Along some stretches, the slope may have tectonic origin, especially between Pocockodden and Asbestodden. Chamberlindalen that, as a result, has the character of a suspended valley (Fig. 2B–D and 8; prof. J1, J2, Ch3 on Fig. 9).
- s3 – the eastern slope of the Recherchefjorden, 6.8 km long. It is also oriented almost exactly along the north-south axis but it is not straight due to the lithological and structural characteristics of the geological structure. Along some stretches, it corresponds to the resistant rocks of Orustdalen Formation (sandstone, shale) and Kapp Starostin Formation (chert, siliceous shale, sandstone, limestone) (Figs. 1B, 2B–D and 8; prof. R2 on Fig. 9).
- s4 – slopes of the trough at the extension of Vestervågen/Chamberlindalen. They constitute the surroundings of bay bottom (b2 on Fig. 8), and their course does not correspond to the geological structure (Fig. 1B and 8; prof. Ch1, Ch3 on Fig. 9).

Analysing the morphometry and the genetic characteristics of the main part of the Recherchefjorden bottom, two macro-areas can be distinguished, i.e. the outer fjord and inner fjord, divided by the moraine zone (LIA2 on Fig. 8) between Rubypynten and Lægerneset (Figs. 2B and 8; prof. R3 on Fig. 9). The outer fjord (of on Fig. 8) encompasses the area located to the north of the moraine ridges (LIA2 on Fig. 8) and constitutes a typical fjord bottom developed during Pleistocene glaciations. Its depth exceeding 100 m. In general, it surface is flat and shows little variety (Fig. 4). Its shape resembles typical U-shaped valleys. Based on morphometric and geological characteristics, two areas were distinguished within the outer fjord: geological structures and debris flow. The area of geological structures (ofg on Fig. 8) is linked with the outcrops of resistant bedrock, extending in a linear manner from Lægerneset towards the north-west, 4.8 km long and 0.8–1.4 km wide. This is built of resistant Lower Carboniferous to Lower Cretaceous rocks of the Reinodden Block, comprising the Orustdalen, Treskelodden and Wordiekammen Formations (Dallmann *et al*. 1990; Birkenmajer 2004) (Figs. 1B and 8; prof. R2 on Fig. 9). The other area distinguished is the area of debris flows (ofd on Fig. 8) (Fig. 8; prof. R3 on Fig. 9). These forms developed as a result of the surface of the outer fjord (of on Fig. 8) being overlain with sediments genetically linked with the activity of the Recherchebreen at its front and movement of the released sediment mass at the distal side of the moraine ridge (LIA2 on Fig. 8) (*e.g*. Ottesen *et al*. 2005, 2008; Kempf *et al*. 2013; Dowdeswell *et al*. 2016). The inner fjord (if on Fig. 8), on the other hand, has the character of a basin reaching the depth of more than 70 m and flanked by the moraine ridge in the north (LIA2 on Fig. 8). Due to the proximal location in relation to the glacial system (Recherchebreen), its surface shows high morphometric and morphological diversity linked with the occurrence of numerous submarine glacial landforms such as moraine ridges and hummocky moraines, De Geer moraines types, and crevasse-squeeze ridges (Lindén and Möller 2005; Ottesen *et al*. 2005, 2008; Kempf *et al*. 2013; Flink *et al*. 2015; Streuf *et al*. 2015; Dowdeswell *el al*. 2016) (Figs. 2B–D; 4, 6 and 7; prof. R1, R3 on Fig. 9). Going towards the south from the moraine ridge (LIA2), the bottom morphology features two distinct moraine ridges (ifm1, ifm2 on Fig. 8) perpendicular to the fjord axis (Fig. 8; prof. R1, R3 on Fig. 9). They are probably related to the surge-like advances of the Recherchebreen front that occurred in the first half of the 20th century (Hamberg 1905; Statens kartverk Sjø 1927; B11 Van Keulenfjorden 1952). Moreover, such surge-like advances probably took place only in western part of Recherchebreen because in this part such forms are observed. The inner lagoon (ifl on Fig. 8), quickly expanding in recent years at the front of the Recherchebreen, is also considered as part of the inner fjord. Two basins were distinguished within it, *i.e*. the western one – shallower (Fig. 2B; prof. Rl1, Rl2 on Fig. 9) and the eastern one – deeper (up to 60 m), rather smooth, gently descending towards the front of the glacier (Fig. 2B; prof. Rl1, Rl3 on Fig. 9). The boundary between them has a clear tectonic origin and is linked with the occurrence of the Recherchebreen Fault (RF) (Dallmann *et al*. 1990, 1993; Birkenmajer 2004; NPI 2016) (Fig. 1B). In the north, the land part of the lagoon is flanked by outwash plains whose formation was linked with the outflow of the Recherchebreen's proglacial waters, particularly during the last five decades (Reder 1996; Zagórski *et al*. 2012). The deposition of material also took place in the subaqueous zone on the southern slope of Fagerbukta, thus forming the submarine sandur (ifs on Fig. 8; prof. R1, R3 on Fig. 9). The deposition of these sediments and development of relatively smooth surfaces was significantly influenced by moraine ridges (ifm1, ifm2 on Fig. 8) that became a natural barrier to the transported sediment.

Summary and Conclusions

This study of morphometric and morphological character of Recherchefjorden bathymetry allowed to determine geomorphological forms such as: abrasive platforms and tidal flats, bays, slopes, outer and inner part of fjord and forms on them like moraines, geological structures, debris flow, submarine sandurs and lagoon. Moreover, taking into account known geology and terrestrial geomorphology it was possible to suggest their origin and describing paraglacial processes in this area. The main results are as follows:

- assignation of maximal glaciers position during Little Ice Age observed as moraines (LIA1 and LIA2 on Fig. 8);
- observation of differences on Josephbukta and Vestervågen as bays with glacier and no-glacier influences during Holocene;
- determination of areas with dominance of geological structures;
- confirmation of surges of Recherchebreen and they uneven character;
- documentation of underwater sandur coverage in southern part of Recherchefjorden;
- determining pioneer mapping of Recherche Lagoon bathymetry and its asymmetric character.

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M.M and Z.P. designed the study and wrote this manuscript, M.M. performed all mathematical calculations and its interpretation, Z.P. prepare geomorphological interpretation, Z.P. and L.L. cooperated during field measurements, Z.P., C.J., and D.P. digitalized data from 2011 and 2012 single beam echosounder profiles.

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