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Abstract

This study presents the first analysis of ice-free cirques on the Faroe Islands using a Geographical Information System (GIS) and the Automated Cirque Metric Extraction (ACME) tool. The length, width, area, circularity, mean aspect, mean slope, and elevation range, minimum, and maximum were calculated using ACME. Cirque distance to coastline was measured using ArcGIS. A total of 116 cirques were identified. Mean cirque length is 950 m and mean cirque width is 890 m. Average cirque area is 0.8 km2 and mean elevation is 386 m a.s.l. The modal orientation of the aspect of cirques is north-northeast, with a vector mean of 7° and mean resultant length of 0.09. Aspect data have large dispersion, which shows evidence of cloudy ablation seasons in the past. The dispersion in aspect may also be related to the time transgressive nature of glacier occupation in these cirques. Past equilibrium-line altitudes (ELAs) of cirque glaciers reconstructed with the minimum point method resulted in a mean palaeo-ELA of 213 m a.s.l. Positive, linear relationships are observed between palaeo-ELA and cirque distance to coastline. There are at least two possible interpretations of this relationship: (i) that the cirque formation is dependent on pre-existing topography with cirques forming at the head of valleys, which occurs at higher elevations further inland, and (ii) that this relationship demonstrates the importance of access to moisture for glacier survival. A combination of both interpretations is also possible. Positive linear relationships are also observed between longitude and palaeo-ELA indicative of palaeo-precipitation patterns along an east–west gradient. Cirques on the Faroe Islands are smaller in length and width and present at lower elevations compared to cirques located in other regions of the world. The timing of glacial occupation in these cirques is not known, and the landforms likely formed over multiple glaciations.

Keywords

cirque, glacier, Faroe Islands, GIS, paleoclimate

Disciplines

Earth Sciences | Environmental Sciences | Geology | Geomorphology | Glaciology

Quantitative analyses of cirques on the Faroe Islands: Evidence for time transgressive glacier occupation

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This study presents the first analysis of ice-free cirques on the Faroe Islands using a Geographic Information System (GIS) and the Automated Cirque Metric Extraction (ACME) tool. The length, width, area, circularity, mean aspect, mean slope, and elevation range, minimum, and maximum were calculated using ACME. Cirque distance to coastline was measured using ArcGIS. A total of 116 cirques were identified. Mean cirque length is 950 m and mean cirque width is 890 m. Average cirque area is 0.8 km^2 and mean elevation is 386 m. The modal orientation of the aspect of cirques is north-northeast, with a vector mean of 7° and mean resultant length of 0.09. Aspect data have large dispersion, which shows evidence of cloudy ablation seasons in the past. The dispersion in aspect may also be related to the time transgressive nature of glacier occupation in these cirques. Past equilibrium-line altitudes (ELAs) of cirque glaciers reconstructed with the minimum point method resulted in a mean palaeo-ELA of 213 m a.s.l. Positive, linear relationships are observed between palaeo-ELA and cirque distance to coastline. There are at least two possible interpretations of this relationship: (i) that the cirque formation is dependent on pre-existing topography with cirques forming at the head of valleys, which occurs at higher elevations further inland, and (ii) that this relationship demonstrates the importance of access to moisture for glacier survival. A combination of both interpretations is also possible. Positive linear relationships are also observed between longitude and palaeo-ELA indicative of palaeo-precipitation patterns along an east-west gradient. Cirques on the Faroe Islands are smaller in length and width and present at lower elevations compared to cirques located in other regions of the world. The timing of glacial occupation in these cirques is not known, and the landforms likely formed over multiple glaciations.

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Recent advancements in automated computing techniques facilitate quantitative analyses of glacial landforms (e.g. Robb *et al.* 2015; Yu *et al*. 2015; Spagnolo *et al*. 2017; Zhao *et al*. 2018). In this study, we use the Automated Cirque Metric Extraction (ACME) tool developed by Spagnolo *et al.* (2017) to quantify properties of cirques on the Faroe Islands (Fig. 1). Small glaciers in mountainous regions commonly create cirques, which are small bowl-shaped depressions carved by glacial erosive processes (Barr & Spagnolo 2015a; Evans 2020). They have been studied for more than 150 years (e.g. Darwin 1842; Tyndall 1862), but a recent resurgence has focused on the formation, morphology, and distribution of cirques (e.g. Hassinen 1998; Jansson *et al.* 1999; Hughes *et al.* 2007; Křížek *et al.* 2012; Mitchell & Humphries 2015). Reconstructing the equilibrium-line altitude (ELA) of former glaciers in cirques provides palaeoclimate information (e.g. Paasche *et al.* 2007; Anders *et al.* 2010; Barr & Spagnolo 2013). Similarly, cirque dimensions are indicative of the intensity of former glacial erosion and periglacial weathering (Evans 2006a; Barr *et al.* 2019). The importance of cirques goes beyond their influence as palaeo-environmental proxies, as they also are evidence of how glaciers and climate limit the growth of mountains at a global scale (e.g. Mitchell & Montgomery 2006). This fact makes cirques important to understanding the interactions between glaciers, climate, and topography (e.g. Anders *et al.* 2010; Mitchell & Humphries 2015).

Morphometric information on cirques is used to examine the nature and extent of cirque development and to make subsequent links to palaeoclimate (e.g. Federici & Spagnolo 2004). Cirque dimensions are evidence of the intensity, duration, and nature of glacial erosion and periglacial weathering (Barr *et al.* 2019). For example, through a morphometric analysis of cirques in the Kamchatka peninsula, Barr & Spagnolo (2013) found evidence of the region’s former aridity. Additionally, variations in cirque morphometry due to aspect have been linked to past deviations in local climate and the extent of former glaciation. Delmas *et al.* (2014, 2015) demonstrated that in the French Pyrenees, NE-facing cirques exhibited the greatest altitudinal range while SE-facing cirques tended to be the shallowest. They connected this discrepancy to the lifespan of former glaciers, arguing that SE-facing glaciers were short-lived in comparison to the long lasting NE-facing glaciers.

Cirques are used for palaeo-ELA reconstruction, because the regional climatic ELA during former periods of glacier initiation tends to coincide with the altitude of the cirque floor (Barr & Spagnolo 2015a). Various techniques are used to reconstruct the ELA of glaciers and ice sheets. The palaeo-ELA of cirque glaciers is commonly calculated using several methods: cirque floor altitude (e.g. Williams 1975; Pelto 1992; Principato & Lee 2014), the altitude-ratio technique (Meierding 1982; Porter 2001), the accumulation-area ratio (AAR) technique (Meier & Post 1962), and the minimum point method (e.g. Barr & Spagnolo 2015b; Ipsen *et al.* 2018).

Cirque aspect is a measure of a feature's geometric orientation in the horizontal plane (Barr & Spagnolo 2015a). Cirques in the northern hemisphere typically face NE (Evans 1977; Evans 2006b), while cirques in the southern hemisphere commonly face southerly directions with a modal SE aspect (Loffler 1972). Cirque aspect provides information about palaeoclimate such as solar radiation, prevailing wind direction, cloudiness during the ablation season, and the extent of former glaciation (Evans 2006b).

Previous studies show that distance to moisture sources and proximity to the ocean influences the elevation of palaeo-ELAs (e.g. Benn & Evans 2010; Principato & Lee 2014; Barr & Spagnolo 2015a, b; Ipsen *et al.* 2018). Principato & Lee (2014) and Ipsen *et al.* (2018) demonstrate that cirques in Iceland have lower palaeo-ELAs when they are close to the coastline and higher palaeo-ELAs when they are located further inland. This finding is indicative of the importance of access to a moisture source for glacier survival (Benn & Evans 2010). However, Oien *et al.* (2020) show that many factors influence the ELA of modern cirque glaciers in Scandinavia, including topography, and the time transgressive occupation of cirques should be taken into account in palaeo-ELA studies.

Although previous cirque studies include thousands of cirques globally (e.g. Mitchell & Humphries 2015; Barr & Spagnolo 2015a), we provide the first spatial analyses of cirques on the Faroe Islands. The goal of this study is to examine ice-free cirques on the Faroe Islands through morphometric analyses and palaeo-ELA reconstructions. Cirque aspect and distance to coastline are also investigated. We aim to compare the morphology of cirques on the Faroe Islands with the morphology of cirques in other regions of the world to place them within a global context.

Study area

The Faroe Islands are located between Iceland, Scotland, and Norway in the North Atlantic Ocean (Fig. 1). The land area is made up of 18 individual islands with a total area of 1397 km^2. The bedrock is Tertiary plateau basalts with a total thickness of at least 5200 m and maximum elevation above sea level of 880 m (Rasmussen & Noe-Nygaard 1970; Berthelsen *et al.* 1984; Passey & Bell 2007). Both simple and compound lava flows are present on the Faroe Islands with structures providing evidence for a six-stage tectonic evolution (Passey & Bell 2007; Walker 2010). The landscape is composed of basalt plateau with typical glacial imprints such as cirques, U-shaped valleys and fjords (Humlum *et al.* 1996). Previous studies from sediment cores provide information about the palaeoclimate of the Faroe Islands using sedimentology and tephrochronology (e.g. Andersen *et al.* 2000; Nielsen *et al.* 2007; Wastegard *et al.* 2018).

The location of the Faroe Islands in the northern North Atlantic Ocean makes the islands sensitive to climate change because of its proximity to the boundary between sub-arctic and Atlantic water masses, and the islands form part of the Iceland-Scotland Ridge that separates the Nordic seas from the North Atlantic Ocean (Nielsen *et al.* 2007; Justwan *et al.* 2008; Rasmussen *et al.* 2011; Seidov *et al.* 2015). In warm periods, when generally strong circulation occurs in the atmosphere and ocean, the islands lie in the main arm of the North Atlantic Drift, or the Gulf Stream; in colder periods, when the North Atlantic Drift weakens or its main branch drifts southerly, polar water from the East Icelandic branch of the East Greenland Current approaches from the north (Humlum & Christiansen 1998; Justwan *et al.* 2008; Rasmussen *et al*. 2011; Seidov *et al.* 2015). The location of the islands is sensitive to these shifts in water currents that fluctuate with the overall climate in the northern hemisphere (Ruddiman & McIntyre 1981; Bard *et al.* 1987; Justwan *et al.* 2008; Seidov *et al.* 2015). During the Younger Dryas and Pre-Boreal, the East Iceland Current was stronger than it is today, which supported cold conditions on the Faroe shelf with evidence based on the distribution of planktic and benthic foraminifera, oxygen and carbon isotopes, and the deposition of ice-rafted debris (Rasmussen *et al.* 2011). The strength of the current gradually reduced during the Pre-Boreal, and there was a transition from Arctic waters dominating the area to Atlantic waters increasing influence over the area (Justwan *et al.* 2008; Rasmussen *et al.* 2011). Atlantic waters weakened between 4.7 and 2.2 cal. ka BP, but since 2.2 cal. ka BP through present there has been an increased influence of Atlantic waters (Justwan *et al.* 2008).

Through the study of moraine systems in the Faroe Islands, Humlum *et al.* (1996) identified at least two glacial advances during the Younger Dryas and suggested that the islands were covered with a local ice cap during the Last Glacial Maximum. Jørgenson & Rasmussen

(1986) mapped striae and roches moutonnées, and they interpreted a radial ice sheet covering the northern islands during an early phase of glaciation ensued by ice following topography. They also suggested that the ice sheet extended onto the shelf beyond the present coastline (Jørgenson & Rasmussen 1986). Evidence from marine cores and seismic data examined by Nielsen *et al*. (2007) shows that glacial ice advanced onto the shelf during the Quaternary, but suggests that the outer shelf was probably ice-free during the Weichselian glaciation. The age of submarine morainal ridges are unknown (Nielsen *et al.* 2007). The chronology of these glacial events and exact ice extent offshore remains unknown, and previous studies have not found evidence for any Holocene glaciations (Humlum *et al.* 1996; Andresen *et al.* 2006; Bennike *et al.* 2018). Mortensen *et al.* (2008) suggest that only thin ice covered the Faroe Islands, and that fjords were likely above sea level with the Quaternary coastlines unknown. No raised beaches have been found on the Faroe Islands (Humlum *et al*. 1996). The Faroe Islands do not contain modern, active glaciers. Landslide deposits dominate the surface sediments of the Faroe Islands, likely covering or removing glacial sediments (Dahl *et al.* 2010; Dahl *et al.* 2012). One exception is the outcrop of glacial and penultimate glacial deposits near Klaksvik (Bennike *et al.* 2018).

Modern temperature and precipitation data have been collected from weather stations in Tórshavn, Streymoy, since 1873 by the Danish Meteorological Institute (Cappelen 2019; https://www.dmi.dk/). A second weather station in Strond Kraftstation, Borðoy, approximately 30 km to the northeast of Tórshavn, records precipitation (Fig. 1, Table 1). Modern precipitation patterns are also influenced by topography with lowest values of precipitation near the coastline rising to above 3000 mm in central regions of the Faroe Islands (Cappelen 2019).

Methods

Cirque identification

Cirques were identified using satellite imagery from Google Earth Pro where the characteristic bowl shape was visible. Slope profiles of cirques were used to locate the headwall, toewall and cirque floor using the methods of Principato & Lee (2014) (Fig. 2). The location of each cirque was pinned in Google Earth Pro and then imported into ArcGIS. Additional cirques were identified using five-meter contour lines and a slope raster derived from the ArcticDEM of the Faroe Islands (DEM created from DigitalGlobe, Inc. imagery; Porter *et al.* 2018). The area of pinned cirques was digitized by freehand on ArcGIS.

Cirque metrics, morphometry, and distance to coastline

Cirque metrics and morphology were determined using the GIS tool for Automated Cirque Metric Extraction (ACME) created by Spagnolo *et al.* (2017). ACME required an input of cirque polygons, a DEM, and a cirque threshold point file. The cirque threshold point was manually identified as the midpoint along the toewall. The 5 m Arctic DEM was used as the topographic base layer (DEM created from DigitalGlobe, Inc. imagery; Porter *et al.* 2018). The morphometric measurements included: length, width, perimeter, area, circularity, altitudinal range**,** slope mean, and aspect. The hypsometric maximum and integral of each cirque was automatically calculated by ACME.

For each cirque, the distance from coastline was calculated using ArcGIS. First, cirque centroids were created by extracting the X and Y coordinate data in ArcGIS. Then, the distance to coastline, defined as the minimum distance from cirque centroid to the nearest body of water, was measured using the “Near” tool.

Palaeo-ELA measurements

Three methods were used to calculate palaeo-ELAs for cirques. The first method used the minimum point (MP) calculated by ACME. Many of the cirques had poorly defined headwalls or toewalls or existed as compound landforms, and a more detailed calculation was not possible. The elevation of the minimum point within each cirque polygon was interpreted as the cirque's palaeo-ELA. This method has shown to have similar palaeo-ELA results to the cirque floor method in previous studies by Barr & Spagnolo (2015b) and Ipsen *et al.* (2018).

A second method for measuring palaeo-ELAs used the elevation of the cirque floor. Cirque floors (CF) commonly serve as a proxy for ELAs during former periods of glaciation (e.g. Williams 1975; Pelto 1992). Lines were drawn along each cirque using the methods of Principato & Lee (2014). Using a slope raster of the Faroe Islands and the ArcticDEM, slope and elevation points were extracted every 10 m along these lines that extended over the length of the cirque. Slope profiles were derived from these points, and the headwall, toewall, and cirque floor of each cirque was identified (Fig. 2). In analyzing the slope profiles, only cirques with defined headwalls, toewalls, and cirque floors were used in this method. The traditional bowl-like shapes were sought in each cirque's slope profile, and cirques lacking this shape were not used in this methodology.

The third method for calculating palaeo-ELAs uses altitude-ratio method (Meierding 1982; Porter 2001). The firn limit on temperate glaciers at the end of the ablation season has been observed to fall in a position approximately midway between the head of a glacier and its lower limit; because of this positionality, the altitude-ratio method is a useful way to evaluate palaeo-ELAs (Meierding 1982; Porter 2001). Toe-to-head ratio (THAR) values between 0.35-0.4 yielded the best results for glaciers in the mid to high latitudes (Meierding 1982). Similar to the cirque-floor method, cirques with poorly defined headwalls, toewalls, and cirque floors were not analyzed using this method. The majority of cirques in the Faroe Islands lack end or lateral moraine deposits making other palaeo-ELA methods, such as the accumulation-area ratio (AAR) technique by Meier & Post (1962) difficult to use, but previous work by Principato & Lee (2014) show that the commonly used AAR method had statistically similar palaeo-ELA results to the THAR method.

Comparison with modern meteorology data

Seasonal variations in precipitation were calculated using 1st October to 30th April for winter precipitation following the methods of Dahl & Nesje (1996), Bakke *et al.* (2005) and Paasche *et al.* (2007) (Table 1). Mean annual temperature and summer temperature from 1st May to 30th September were calculated for Tórshavn, but monthly temperature data were not available from the Strond Kraftstation. Both mean annual precipitation and winter precipitation are higher in Strond Kraftstation than in Tórshavn (Table 1).

Statistical analyses and fieldwork

Microsoft Excel and VassarStats (http://vassarstats.net/) were used to complete statistical analyses. Linear regression analyses determine relationships between cirque length, width, altitudinal range, their ratios, palaeo-ELAs, distance to ocean and coast, aspect, and latitude, using the correlation and regression tools. T-tests and ANOVAs were conducted to determine which morphometric characteristics had significant relationships with palaeo-ELAs. Statistical analyses of aspect were calculated in Microsoft Excel and using the methods of Davis (1986) and Platt (2014).

Fieldwork was conducted to ground-truth GIS results and confirm cirque identification. Some cirques were accessible by foot (Fig. 3). Cirque floor and toewall elevations were recorded using handheld GPS devices.

Results

Location

A total of 116 cirques were identified on the Faroe Islands (Fig. 4). Other cirques are also present, but were not included in this study due to their morphometric irregularities. Cirques are carved into both the Enni and Malinstindur Formations (Passey & Bell 2007) (Fig. 4). For the landforms included in this analysis, the latitude ranges from 62.0°N to 62.4°N with the largest number of cirques located around 62.3°N (Table S1). Latitude is not correlated with cirque area, length, or width. The latitude of cirques is inversely related to distance to coastline ($r = -0.29$; $p < 0.01$) (Table 2). Longitude of cirques ranges from 7.4°W to 6.4°W, and most cirques are located around 6.7°W. Longitude is significantly related to distance to coastline ($r = 0.48$; $p < 0.01$) and the ELA from all three palaeo-ELA calculation methods (Tables 2, 3).

Morphometric analyses

At least 39 statistically significant relationships are observed for each morphometric parameter measured in the overall dataset (Table 2). Cirque length (L) ranges from 261 m to 2301 m with a mean of 950 m (Table 4). Cirque width (W) ranges from 285 m to 2085 m with a mean of 890 m (Table 4). Average cirque perimeter is 3.2 km, and perimeter is most strongly correlated with length ($r = 0.92$, $p < 0.01$), width ($r = 0.89$, $p < 0.05$), altitudinal range ($r = 0.45$, $p < 0.01$), and area ($r = 0.98$, $p < 0.01$) (Tables 2, 4). Circularity ranges from 1.0 to 1.2 with a mean of 1.1 and a median of 1.1 demonstrating that cirques on the Faroe Islands are nearly circular and not elongate (Table 4). The two-dimensional area ranges from 0.1 to 2.3 km^2 with an average of 0.8 km^2, and area is not correlated with latitude (Table 4). Average slope ranges from 12° to 44° with a mean of 27°. Mean slope is correlated with length (r = 0.98; p < 0.01), width (r = 0.37; p < 0.01), altitudinal range (r = 0.48, p < 0.01), and perimeter (r = 0.38; p < 0.01) (Table 2). Distance to coast varies from 0.21 to 3.03 km with a mean value of 1.04 km. Distance to coastline is significantly correlated to several morphometric parameters, including perimeter (r = 0.34, p < 0.01), area (r = 0.36, p < 0.01), and slope (r = 0.39, p < 0.05) (Table 2).

Palaeo-ELAs

The mean palaeo-ELA for the entire dataset calculated using the MP method is 213 m with a minimum of 48 m and maximum of 505 m (Table 5). Twenty-six cirques had well defined headwalls, toewalls, and cirque floors, and they were used to calculate palaeo-ELAs using the CF and THAR methods in addition to the MP method. For this subset, the MP method produced the lowest palaeo-ELA results with an average of 210 m, minimum of 47 m and maximum of 504 m (Table 5). The CF method produced an average palaeo-ELA of 324 m, minimum of 131 m, and maximum of 600 m. Results from the cirque floor and minimum point methods were not statistically significantly different (t = 1.93; p = 0.06). The THAR technique produced the highest palaeo-ELA results with an average of 375 m, minimum of 183 m, and maximum of 671 m. The THAR 0.4 method and cirque floor method produced results that were not statistically significantly different (t = -1.44; p = 0.16), but the THAR 0.4 method and minimum point method are significantly different (t = 3.37; p < 0.002).

An east-west gradient is observed in palaeo-ELA values across the Faroe Islands (Fig. 5). The islands on the eastern side of the Faroe Islands have cirques with lower palaeo-ELAs than the islands on the western side (Fig. 5), and this pattern is present using all three methods for calculating palaeo-ELAs. The islands with larger land mass including Streymoy, Eysturoy and Vagar have cirques with higher palaeo-ELAs than cirques on the smaller islands. The island of Eysturoy has the highest peak on the Faroe Islands with an elevation of 880 m. The highest peaks on the eastern islands of Viðoy and Kunoy are approximately 30 – 40 m lower than the highest peak on Eysturoy, but the peaks on these two eastern islands are at least 40 m higher than the highest peak on Streymoy (Porter *et al.* 2018). The average cirque distance from the coastline was approximately 1 km (Table 4). Palaeo-ELA is significantly correlated with distance to coastline using all three palaeo-ELA reconstruction methods (Table 3). The altitude-ratio method with a THAR value of 0.4 had the strongest positive relationship between cirque palaeo-ELA and distance to coastline ($r = 0.72$; $p < 0.01$) (Fig. 6). A palaeo-ELAs calculated using the THAR method also had a significant correlation with longitude ($r = 0.47$; $p < 0.01$) (Fig. 6).

Cirque aspect

The modal aspect of cirques is north with a mean direction of 7° (Fig. 7). The low value (0.09) of mean resultant length of aspect shows that there is a large amount of dispersion (Davis 1986). At least 50 % of the cirques face south, west, or east (Table 6). Cirques facing south have the largest area and highest elevation (Z_{mean}) compared to cirques with other directions of aspect (Table 6). Cirques facing south also have the highest average palaeo-ELA, and cirques with an eastern aspect have the lowest average palaeo-ELA. Distance to coastline is also greater for cirques facing south and west compared to cirques facing north and east (Table 6).

Discussion

Palaeo-ELA, distance to coastline, and longitude correlations

The strong, positive linear relationship between palaeo-ELA and distance to coastline support the hypothesis that cirques with lower palaeo-ELAs are closer to the coastline than cirques with higher palaeo-ELAs. Cirques with lower altitudes are present along the coast while cirques further inland are present at a higher altitude. There are at least two possible interpretations of this relationship. The first explanation is that the cirque formation is dependent on pre-existing topography with cirques forming at the head of valleys, which occurs at higher elevations further inland. The second interpretation is that this relationship demonstrates the importance of access to moisture for glacier survival similar to studies in Iceland and the Kamchatka Peninsula (e.g. Benn & Evans 2010; Barr & Spagnolo 2013; Principato & Lee 2014; Barr & Spagnolo 2015b; Ipsen *et al.* 2018).

A positive linear relationship between cirque distance to coastline and longitude shows that cirques that developed on the western islands of the Faroe Islands are further from the coastline than those to the east. This relationship likely exists because island size increases along an east-west gradient. Additionally, the cirque floor, which functions as a proxy of palaeo-ELAs, generally increased inland likely reflecting the role of precipitation in regulating the altitude of former glaciers (Barr & Spagnolo 2015b). However, the timing of glacial occupation in these cirques is not known, and the landforms likely formed over multiple glaciations. The time transgressive nature of cirques makes it difficult to identify one unique explanation for the relationship between palaeo-ELA and distance to coastline. Crest *et al*. (2017) provide exposure ages from the central and eastern Pyrenees and interpret that cirque glacial erosion was higher during deglacial periods, such as the Younger Dryas, than during glacial periods. Barr *et al.* (2019) suggest that cirque growth is episodic and erosion is greatest during periods of marginal glaciation, and chronologic constraints of cirques on the Faroe Islands are needed to understand their chronology and landform development over time. Bennike *et al.* (2018) note that the size and extent of an ice sheet covering the Faroe Islands are unknown, so distinguishing episodes of marginal glaciation is not possible.

In addition to the distance to coastline, palaeo-ELAs generally increased along an east-west gradient with a positive linear relationship between palaeo-ELAs and longitude (Table 3). The climate on the smaller islands on the eastern side of the Faroe Islands are more sensitive to fluctuations in ocean currents than the larger islands on the western side of the Faroe Islands Palaeo-ELAs in the east are lower than palaeo-ELAs in the west further supporting the influence of the ocean and access to moisture source for cirque glaciers to grow. High palaeo-ELAs are present further inland on the western, larger islands of Esyturoy, Streymoy, and Vagar. This spatial trend highlights the importance of cirque distance to coastline or is a result of episodic cirque formation considering the time transgressive nature of cirque formation and available topography with high palaeo-ELAs forming during marginal glaciations (Crest *et al.* 2017; Barr *et al.* 2019; Oien *et al* 2020). A trend of higher precipitation values on the eastern side of the islands compared to the west, similar to the one seen at present (Table 1), may have influenced the formation of cirque glaciers over time. This pattern suggests that precipitation was likely a key control over glacier formation in the Faroe Islands, but topography might have also played an important role. Modern meteorological data show increased precipitation inland compared to the coastline (Cappelen 2019), and there is a statistically significant relationship between cirque area and distance to coastline (Table 2). The larger size of inland cirques compared to coastal cirques may be related to the episodic formation of the cirques (Barr *et al.* 2019) or to the fact that the larger landmass size provides more topographic availability for cirques to form (Oien *et al.* 2020).

Cirque morphology, global comparison, and structural control

Cirque length-to-width ratio is indicative of the mechanism that has dominated their development. Where L/W is greater than 1, cirques are considered to have been mostly occupied and eroded by valley glaciers; where L/W is between 0.5 and 1, cirques are considered to have been mostly occupied and eroded by cirque-type glaciers; and where L/W is less than 0.5, cirques are considered to have been highly eroded by post-glacial processes (Damiani & Pannuzi 1987). The average L/W ratio in this study is 1.1±0.03 (Table 4). Therefore, most of the cirques have been occupied and eroded by cirque-type and valley glaciers. The minimum L/W ratio of 0.58 (Table 4) suggests that postglacial erosion is not a dominant process shaping the morphology of cirques on the Faroe Islands.

Cirques on the Faroe Islands are smaller in terms of length and width than cirques in other regions of the globe (e.g. Brook *et al.* 2006; Evans 2006b; Bathrellos *et al.* 2014; Principato & Lee 2014). Cirques on the Faroe Islands have the smallest length and width measurements compared to a global dataset (summarized in Ipsen *et al.* 2018). The low elevation of the Faroe Islands limited the development of its cirque glaciers in comparison to cirques present in study areas with higher elevations and higher latitudes than the Faroe Islands. For example, the highest elevation of land on the Faroe Islands is 880 m while neighboring Iceland has a maximum land elevation of 2110 m and 1344 m in Scotland and 2469 m in Norway. No modern glaciers are present in cirques on the Faroe Islands, as the current climate is too warm to retain ice in these low elevation cirques. Significant ELA lowering must have occurred during the LGM, although the timing of cirque glacier occupation in the Faroe Islands is not known. Modern ELAs of cirque glaciers on Tröllaskagi (Iceland) are approximately 992 m a.s.l. (Caseldine & Stotter 1993), which, assuming a comparable climate between Iceland and the Faroe Islands, suggests that ELA lowering of at least 617 m is required for glaciers to form in cirques on the Faroe Islands.

The bedrock of the Faroe Islands is Tertiary basalt and somewhat similar to the Upper Tertiary basalt bedrock of Iceland. Principato & Lee (2014) suggested that the basalt of Iceland is easier to erode horizontally as opposed to vertically due to lithological weakness. The average circularity of approximately 1 for cirques on the Faroe Islands supports this suggestion of a horizontal plane of weakness in the Tertiary basalt bedrock of the island. Additionally, cirques on the Faroe Islands have a larger altitudinal range than those in Iceland (Ipsen *et al.* 2018) suggesting that the Tertiary basalt of the Faroe Islands are easier to erode vertically than the basalt on Iceland assuming the cirques in both places were occupied by eroding glaciers for a comparable amount of time throughout the Quaternary. This speculative difference in erosion rates may be related to the age of the rocks, with older basalt on the Faroe Islands compared to Iceland. The six-stage tectonic evolution of the Faroe Islands and three phases of extension, faulting, and folding (Walker 2010) likely led to weaknesses facilitating the carving of the landscape by cirque glaciers. Structure of the rocks appears to be more significant than rock lithology, as cirques are carved into both the Enni and Malinstindur Formations (Fig. 4).

Cirque aspect and dispersion

The northern mode for aspect of cirques on the Faroe Islands follows the general trend of cirques orientated poleward in the northern hemisphere (e.g. Aniya & Welch 1981; Evans & Cox 1995; Brook *et al*. 2006; Barr & Spagnolo 2015a). Evans (1977, 1990, 2006b) inferred that where aspect of cirques shows a particularly strong poleward bias, former cirque glaciers likely developed under comparatively dry and cloud-free ablation season conditions. This NNE orientation has been demonstrated in many studies of cirques (e.g. Andrews & Dugdale 1971; Trenhaile 1976; Embleton & Hamann 1988; Barr & Spagnolo 2015a). At least half of the cirques in this study have orientations to the south, west, and east. The variation in orientation of cirques on the Faroe Islands suggests that the ablation season was likely cloudy and that winter precipitation played a role in cirque glacier formation, too. Although summer temperatures for the Lateglacial to Holocene transition are documented in palaeoclimate proxy records from Scotland (e.g. Brooks & Langdon 2014; Whittington *et al.* 2015), Iceland (e.g. Rundgren 1995), and several study sites in Scandinavia (summarized in Eldevik *et al.* 2014), the percentage of seasonal cloud cover is not documented specifically in previous studies. Studies of Holocene lake core records on the Faroe Islands provide evidence for increased windiness during cold conditions and variable wind directions (Andresen *et al.* 2006; Olsen *et al.* 2010), which likely also influences snow accumulation in cirques and results in variability in aspect. Mîndrescu *et al.* (2010) demonstrated that wind patterns influenced cirque aspect in Romania, and wind direction likely influences cirques on the Faroe Islands as well.

The importance of distance to coastline also influences palaeo-ELAs of cirques with a large dispersion in aspect, as the southerly and western facing cirques are further from the coastline and have higher palaeo-ELAs than cirques with a northern or eastern aspect. The age of ice occupation in the cirques is not known, but it is likely ice was present when the East Iceland current was stronger than today. The dispersion in aspect may also be related to the time transgressive nature of glacier occupation in these cirques. In northwest Greece, Hughes *et al.* (2007) interpreted that glaciers formed in south-facing cirques during the most extensive glaciation and severe climatic conditions, while cirques with a northern and easterly aspect formed during more marginal glacial conditions. García-Ruiz *et al.* (2000) show that cirques in the Central Spanish Pyrenees also have a large dispersion in aspect, and that the aspect was partly controlled by pre-glacial relief. It is possible that pre-glacial topography influences cirque formation on the Faroe Islands as well.

Morphologic limitations

The morphologic structure of cirques on the Faroe Islands is complex, ranging from simple cirques to compound cirques, staircase cirques, and cirque complexes (Benn & Evans 2010). The palaeo-ELA calculations using the minimum point technique should be used with caution due to the complex structure of a majority of the cirques on the Faroe Islands. Only 26 cirques in our dataset contained the simple bowl shape of a cirque with well-defined headwalls, toewalls, and cirque floors, which limits our ability to provide precise palaeo-ELA calculations using the THAR and CF methods. Quantification of cirque types on the Faroe Islands is beyond the scope of this study, but understanding the distribution and morphology of these varying cirque types may lead to new insights on cirque processes of formation and post-glacial erosion.

Conclusions

This study represents the first analysis of 116 cirques on the Faroe Islands using ACME. Results indicate that there are over 39 statistically significant relationships between cirque morphometric parameters, palaeo-ELAs, and distance to coastline. Strong, positive linear relationships between palaeo-ELAs and cirque distance to coastline support the hypothesis that cirques with lower palaeo-ELAs are closer to the coastline than cirques with higher palaeo-ELAs similar to findings in Iceland and Kamchatka. This relationship demonstrates that cirques are dependent on pre-existing topography and/or shows the importance of access to moisture for glacier survival. Linear relationships between longitude and palaeo-ELA are indicative of palaeo-precipitation patterns along an east-west gradient. High dispersion is observed in cirque aspect, and this result shows evidence of cloudy ablation seasons in the past and/or of the time transgressive nature of glacier occupation in these cirques. The small size and low elevation of ice-free cirques on the Faroe Islands compared to a global dataset suggest that it is difficult for cirque glaciers to survive interglacial and warm climatic conditions in the Faroe Islands. The chronology of ice occupation in cirques on the Faroe Islands is unknown, but it is likely that cirques formed during episodic or marginal glaciations considering the time transgressive nature of cirque formation and available topography.

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Author Contributions – This project was conceived by SP with input from KW. KW collected GIS data and measurements, and both authors analyzed data and conducted statistical analyses. Fieldwork was conducted together. KW and SP equally contributed to writing this manuscript with SP making final revisions and edits to figures.

Data Availability Statement – Table S1 contains all cirque locations. Additional data that support the findings of this study are available from the corresponding author upon reasonable request.

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Fig. 1. A. Location of study area in the northern North Atlantic Ocean B. Arctic DEM showing the Faroe Islands and weather stations at Tórshavn and Strond Kraftstation. DEM created from DigitalGlobe, Inc. imagery (Porter *et al.* 2018). Dashed lines show latitude and longitude grid.

Fig. 2. A. Image of cirques on Kunoy, data from Google Earth, Maxar Technologies, Image Landsat Copernicus. B. Close up image of one cirque with red line outlining polygon used for input into ACME (data from Google Earth, Maxar Technologies, Image Landsat Copernicus). L = length; W = width. C. Cirque shape verified using slope of DEM raster from the Faroe Islands with headwall, cirque-floor, and toewall based on changes in slope. Scale is approximate due to figure resizing.

Fig. 3. A. Photograph of cirque with box around person (1.6 m) for scale. B. Photograph of same cirque with person (in box) walking up toewall of cirque.

Fig. 4. DEM with dots showing cirque locations. DEM(s) created from DigitalGlobe, Inc. imagery (Porter *et al.* 2018). Bedrock lithology includes various formations as labeled in legend,

with Prestfjall and Hvannhagi Formations abbreviated as P, H Fm. (modified from Passey & Bell 2007).

Fig. 5. Interpolation surfaces using the results from the CF ELA (A), THAR ELA (B), and MP ELA (C) on the Faroe Islands created using Inverse Distance Weighting (IDW) in ArcGIS. The pattern demonstrates that cirques with low ELAs are located close to the ocean and cirques with higher ELAs are further from the ocean and also shows the relationship with longitude. These relationships are present regardless of which method is used to reconstruct palaeo-ELAs.

Fig. 6. A. Distance to coastline versus palaeo-ELA of cirque glaciers reconstructed using the THAR method. B. Longitude versus palaeo-ELA of cirque glaciers reconstructed using the THAR method.

Fig. 7. Linear histogram of aspect data. Mean direction of aspect for each study area (VM) and mean resultant length or dispersion (RL) are calculated using the methods of Davis (1986).

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Table 1. Mean annual temperature (MAT), mean annual precipitation (MAP), summer temperature (Summer T), and winter precipitation (Winter P) collected from weather stations in Tórshavn and Strond Kraftstation. Temperature and precipitation data are provided by the Danish Meteorological Institute (Cappelen, 2012). Monthly temperature data were only available from the Tórshavn station.

Table 2. Correlation coefficients for relationships between morphometric parameters measured in this study including (L) length, (W) width, (Z_{range}) altitude range, (L/W) length to width ratio, circularity, perimeter, 2D area, longitude, latitude, mean slope, (HI) hypsometric integral, and distance to coastline. One star values highlighted in blue indicates significance at $p = 0.05$; two stars highlighted in green indicate significance at $p < 0.01$, and values highlighted in yellow show no statistically significant relationship.

Table 3. Correlation coefficients for relationships between palaeo-ELAs and distance to coastline, area, latitude, and longitude. The THAR and CF method include a sample size of 26 while the MP shows the comparison with both the entire dataset (n = 116) and the subset of 26 cirques. ** $p < 0.01$; * $p < 0.05$.

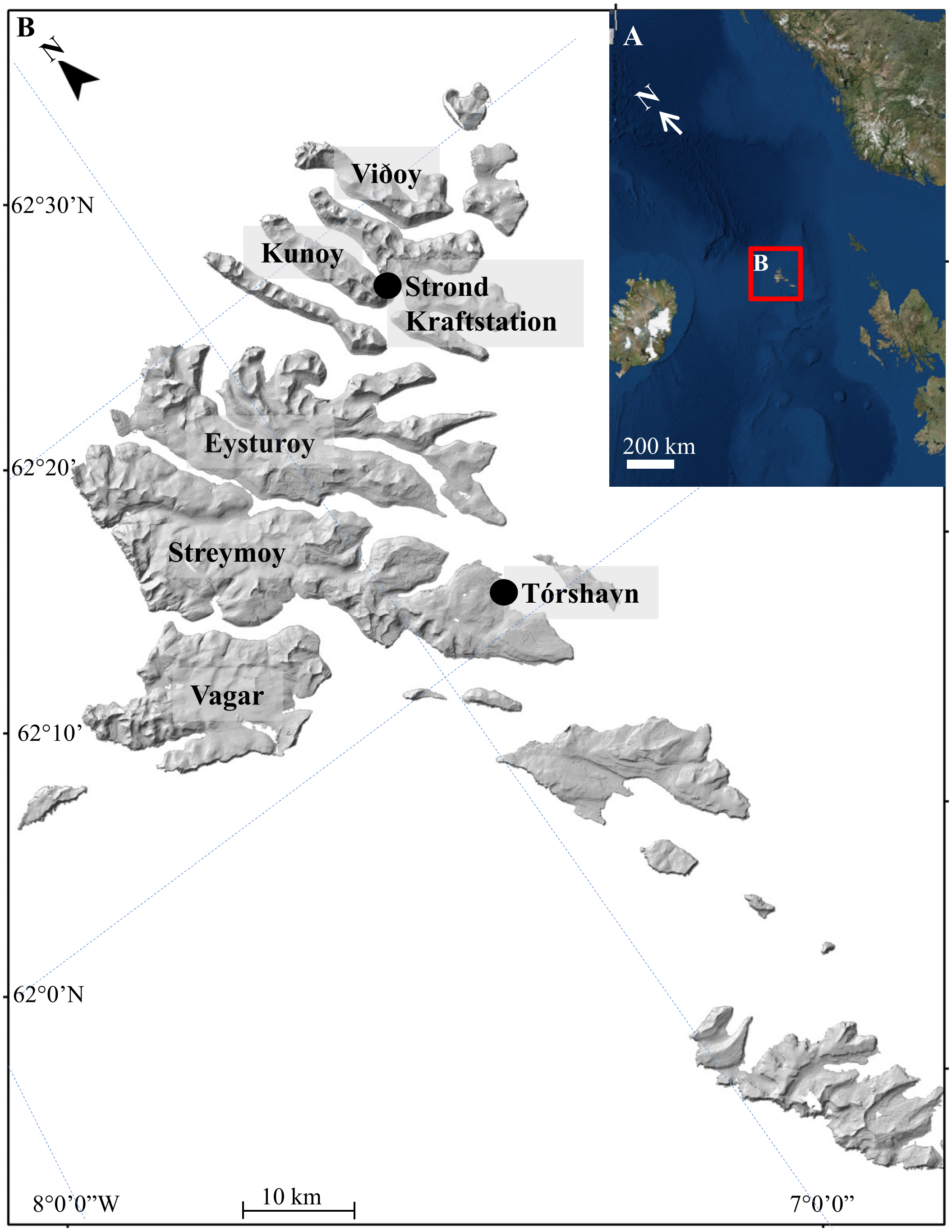
Table 4. Summary statistics of morphometric parameters for all cirques measured with ACME including (L) length, (W) width, (L/W) length to width ratio, (P) Perimeter, 2D area, (Circ) Circularity, (Z_{range}) altitude range, (Min. elev.) minimum elevation, (Max. elev.) maximum elevation, (Mean elev.) mean elevation, mean slope, and distance to coastline.

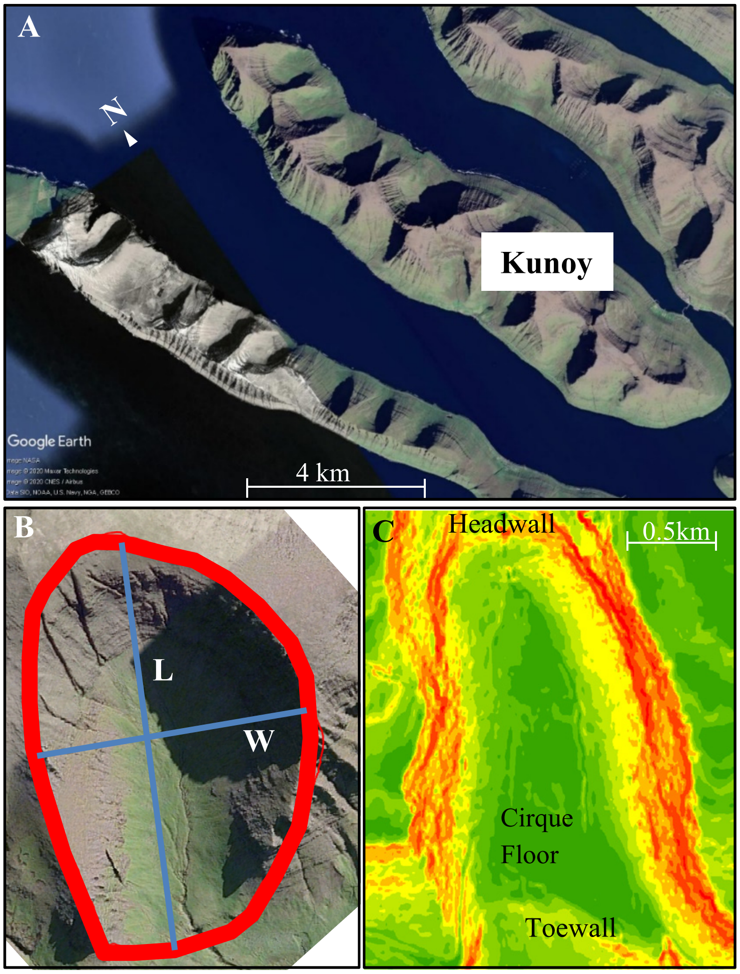
Table 5. Comparison of palaeo-ELA results. MP is calculated using the entire dataset (n = 116) and for the subset of cirques with morphological parameters that enabled use of the CF and THAR palaeo-ELA reconstruction techniques (n = 26).

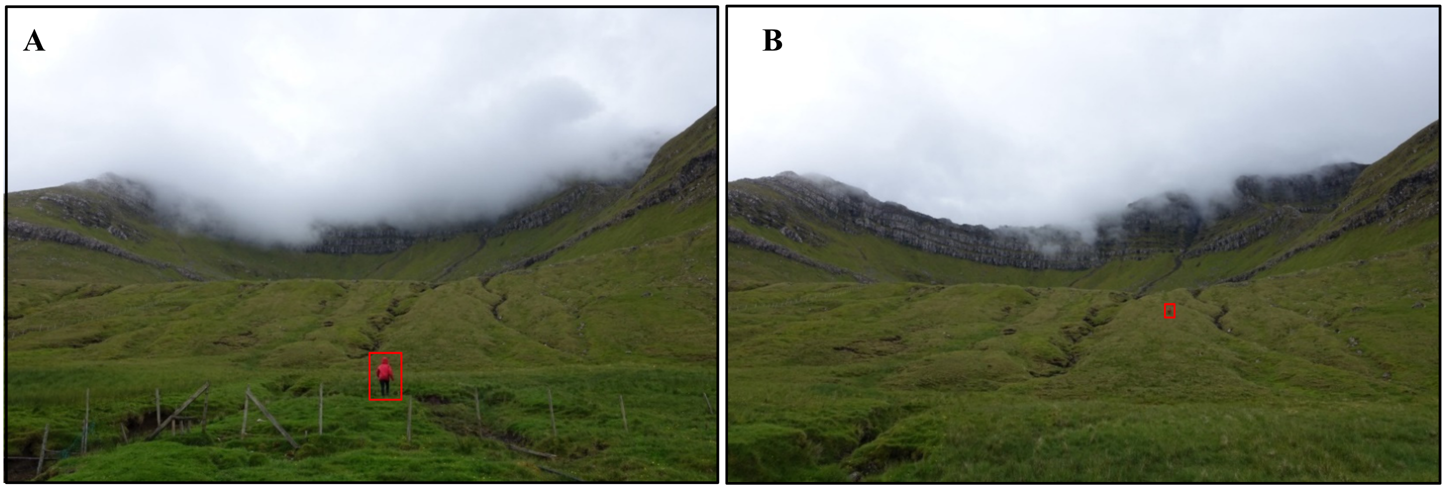
Table 6. Aspect versus select morphologic parameters. Direction of aspect is defined as 316° – 45° = north, 46° – 135° = east, 136° - 225° = south, and 226°- 315° = west. Variables quantified include (L) length, (W) width, (L/W) length to width ratio, (P) Perimeter, 2D area, (Circ.) Circularity, (Z_{mean}) average elevation, mean slope, distance to coastline, and MP palaeo-ELA.

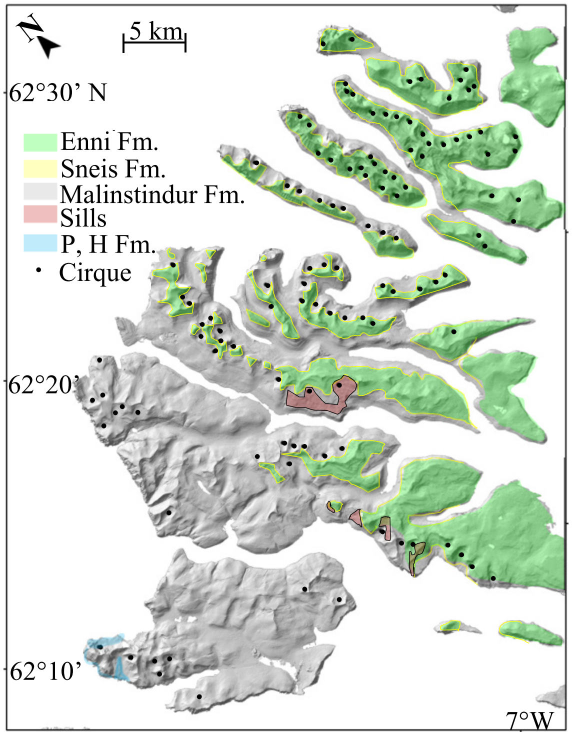
Supporting Information

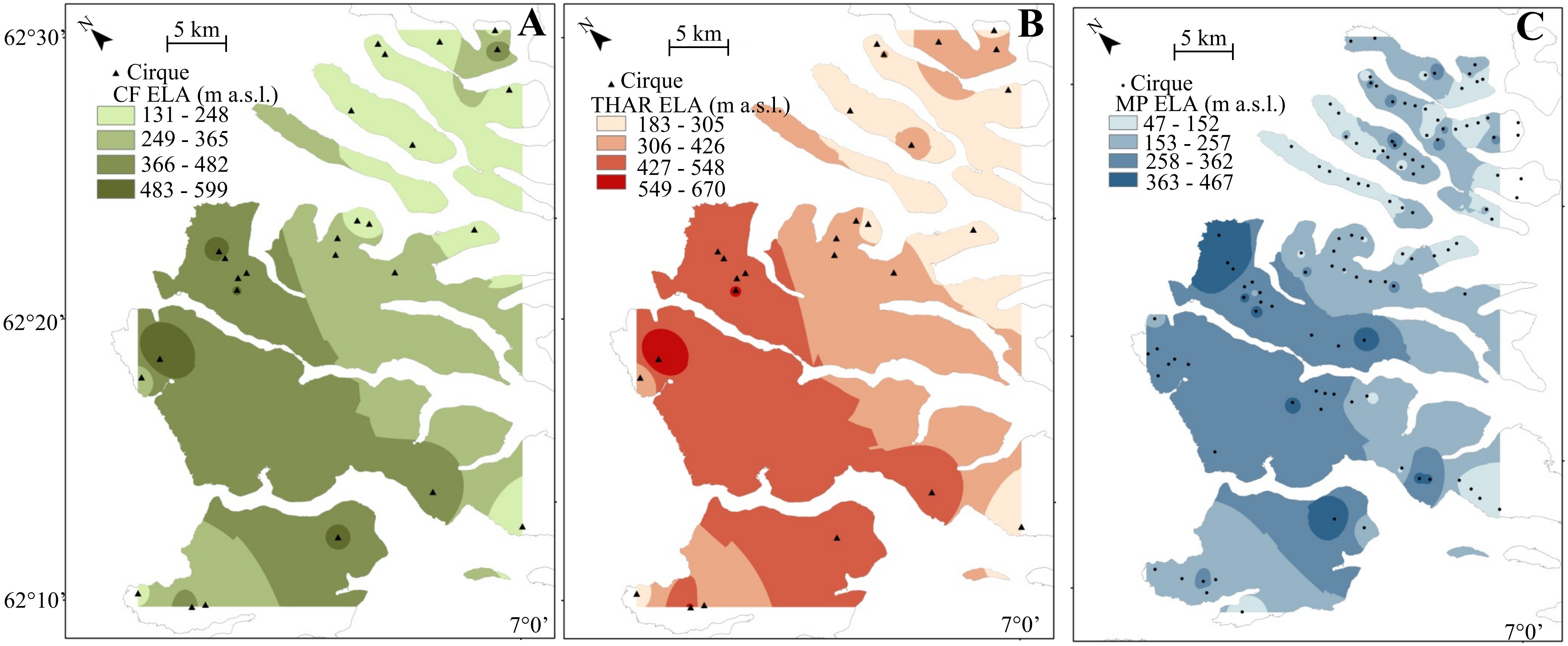
Table S1. Latitude and longitude of all cirques used in this study. DD = decimal degrees.


B
N
Viðoy
62°30'N
Kunoy
Strond
Kraftstation
Eysturoy
62°20'
Streymoy
Tórshavn
Vagar
62°10'
62°0'N
8°0'0"W
10 km
7°0'0"
A
N
B
200 km

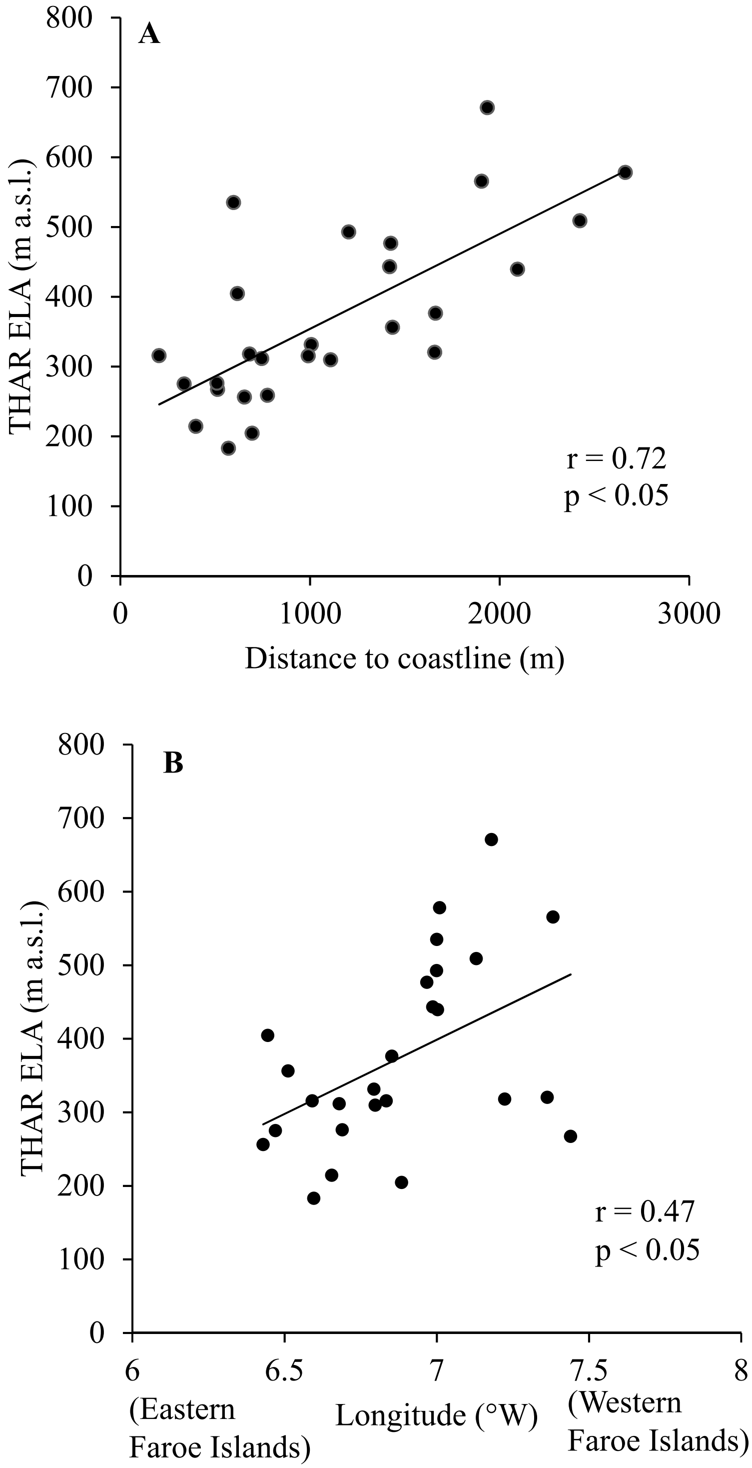

A
N
Kunoy
Google Earth
4 km
B
L
W
C
Headwall
0.5km
Cirque
Floor
Toewall

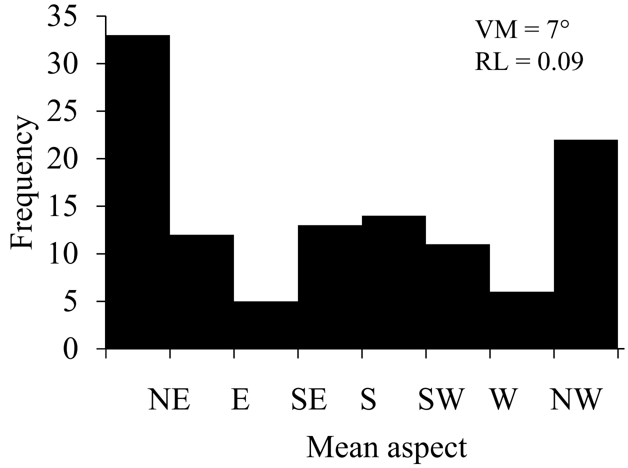

A
B


N
5 km
62°30' N
Enni Fm.
Sneis Fm.
Malinstindur Fm.
Sills
P, H Fm.
Cirque
62°20'
62°10'
7°W



A
5 km
Cirque
CF ELA (m a.s.l.)
131 - 248
249 - 365
366 - 482
483 - 599
62°30'
62°20'
62°10'
7°0'
B
5 km
Cirque
THAR ELA (m a.s.l.)
183 - 305
306 - 426
427 - 548
549 - 670
7°0'
C
5 km
Cirque
MP ELA (m a.s.l.)
47 - 152
153 - 257
258 - 362
363 - 467
7°0'


A
THAR ELA (m a.s.l.)
Distance to coastline (m)
r = 0.72
p < 0.05
0
100
200
300
400
500
600
700
800
0
1000
2000
3000
B
THAR ELA (m a.s.l.)
Longitude (°W)
(Eastern
Faroe Islands)
(Western
Faroe Islands)
r = 0.47
p < 0.05
0
100
200
300
400
500
600
700
800
6
6.5
7
7.5
8


VM = 7°
RL = 0.09
Frequency
35
30
25
20
15
10
5
0
NE
E
SE
S
SW
W
NW
Mean aspect

	MAT (°C)	MAP (mm)	Summer T (°C)	Winter P (mm)
Tórshavn station 6011 1990-2003	6.8	1303	9.5	910
Strond Kraftstation station 33054 1990-2003	n/a	2989	n/a	2139

r	L	W	Z_{range}	L/W ratio	Circularity	Perimeter	2D area	Longitude	Latitude	Mean slope	HI	Distance to coastline
L	1	0.67*	0.55**	0.48**	0.20*	0.92**	0.89**	0.11	0.01	0.98**	0.40	0.24*
W		1	0.60**	0.24	0.06	0.89*	0.88**	0.08	-0.19*	0.37**	0.32**	0.36*
Z_{range}			1	0.32**	0.15	0.50**	0.45**	-0.24**	0.29**	0.48**	0.40**	0.13
L/W ratio				1	0.18	0.15	0.13	0.06	0.15	0.01	0.03	0.14*
Circularity					1	0.27*	0.18*	0.04	0.01	0.04	0.06	0.04
Perimeter						1	0.98**	0.12	-0.04	0.38**	0.32**	0.34**
2D area							1	0.09	-0.03	-0.38**	-0.30**	0.36**
Longitude								1	0.51**	-0.33*	-0.11	0.48**
Latitude									1	0.28**	-0.03	-0.29**
Mean slope										1	0.05	0.39*
HI											1	0.21*
Distance to coastline												1

ELA method	Distance to coastline	2D area	Latitude	Longitude
0.4 THAR ELA	0.72**	0.03	-0.06	0.47**
CF ELA	0.60**	-0.14	-0.10	0.45*
MP ELA, n = 26	0.60**	-0.22	-0.11	0.49**
MP ELA, n = 116	0.64**	-0.16*	0.04	0.42**

	L (m)	W (m)	L/W ratio	P (m)	2D area (km^2)	Circ.	Z_{range} (m)	Min. elev. (m)	Max. elev. (m)	Mean elev. (m)	Mean slope (degrees)	Distance to coastline (km)
Mean	950	890	1.09	3241	0.8	1.1	404	212	616	386	27	1.04
Median	942	833	1.05	3170	0.7	1.1	388	192	630	374	28	0.87
Minimum	261	285	0.58	1060	0.1	1.0	91	47	317	186	12	0.21
Maximum	2301	2085	2.24	6186	2.3	1.2	716	504	866	622	44	3.03
St. dev.	349	314	0.30	109	0.5	0.03	142	109	137	99	5.9	0.58

Method	MP (m)	MP (m)	CF (m)	THAR 0.4 (m)
n	116	26	26	26
Minimum	48	57	131	183
Maximum	505	505	600	671
Mean	213	257	324	375
Median	192	221	281	326
Standard Dev.	109	125	126	127
Standard Error	10	25	25	25

Table 6

Aspect	L (m)	W (m)	L/W	P (km^2)	2D area (km^2)	Circ.	Z_{mean} (m)	Mean Slope (degrees)	Dist. to coastline (km)	MP ELA (m)
North (n = 55)	873	873	1.02	3.09	0.71	1.09	365	28	0.71	212
East (n = 17)	1019	839	1.2	3.31	0.86	1.08	352	28	0.77	176
South (n = 27)	1078	914	1.22	3.46	0.90	1.07	425	26	1.17	231
West (n = 17)	928	954	1.01	3.3	0.82	1.07	341	25	1.15	221