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3 Title: Controls on the altitude of Scandinavian cirques: what do they tell us about palaeoclimate?

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38 **ABSTRACT**

39 Cirques are glacially eroded, bowl-shaped depressions, characterised by steep headwalls and flat
40 or overdeepened floors. Given their association with past glaciers, cirques are sometimes used as
41 proxies for palaeoclimate. However, cirques are shaped over multiple glacial cycles, and their
42 usefulness as palaeoclimate indicators therefore remains open to question. In this paper, we map
43 3984 glacier-free cirques across the Scandinavian Peninsula and analyse variations in cirque floor
44 altitude (CFA). We explore the relationships between CFAs and cirque aspect, latitude, longitude,
45 and distance to the coast. We test the validity of using CFAs as indicators of palaeoclimate through
46 comparison with the equilibrium-line altitudes (ELAs) of 513 modern cirque glaciers. Results
47 indicate that both CFAs and modern cirque-glacier ELAs decrease with latitude and vary with
48 aspect, being generally lowest on east-facing slopes. However, the clearest and strongest trend in
49 both CFAs and modern cirque glacier ELAs is an increase in elevation with distance from the
50 modern coast (i.e., distance 'inland'). This likely indicates that similar climatic gradients,
51 particularly an inland reduction in precipitation, acted to regulate former sites of glacier initiation
52 (reflected by CFAs) and modern glacier ELAs. This would imply that CFAs are a useful proxy for
53 palaeoclimate. However, we note that both CFAs and modern ELAs reflect the general topography
54 of this region (with increasing elevations moving inland), and the glacial history of the area
55 (indirectly linked to palaeoclimate) may have played a role in regulating where cirques have
56 formed. For these reasons, we suggest that palaeoclimatic interpretations derived from CFAs
57 should be treated with caution.

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70 **1.0 Introduction**

71 The equilibrium-line altitude (ELA) is the elevation on a glacier surface where net annual
72 accumulation and ablation are equal. Therefore, the ELA is largely determined by regional climate
73 (the dominant control on accumulation and ablation) (Nesje, 1992; Ohmura et al., 1992; Ipsen et
74 al., 2017; Ohmura and Boettcher, 2018), though other local topoclimatic factors (e.g. topographic
75 shading, snow and ice redistribution and aspect) also contribute (Olyphant, 1977; Morris, 1981;
76 Torsnes et al., 1993; Coleman et al., 2009; Hughes, 2010; Křížek and Mida, 2013). Given this
77 association, glacier ELAs are often used to infer spatial and temporal variations in climate and
78 palaeoclimate (e.g. Sutherland, 1984; Caseldine and Stötter, 1993; Torsnes et al., 1993; Oien et
79 al., 2020; Rea et al., 2020). Therefore, palaeo-ELAs are important as palaeoclimatic indicators
80 because they are the result of changed precipitation and temperature, which control glacial surface
81 mass balance over time and cirques are one way of obtaining palaeo-ELAs (e.g. Torsnes et al.,
82 1993; Kern and László, 2010; Barr and Spagnolo, 2015a; Barr and Spagnolo, 2015b; Barr et al.,
83 2017; Pearce et al., 2017; Ipsen et al., 2017; Wallick and Principato, 2020).

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85 The most robust way to estimate palaeo-ELAs is to generate 3D reconstructions of former
86 glaciers. However, a number of simpler methods are also used, particularly when considering
87 ELAs across large and/or remote areas. One of the simplest ways is to map and measure cirque
88 floor altitudes (CFAs) (e.g. Torsnes et al., 1993; Kern and László, 2010; Barr and Spagnolo, 2015a;
89 Barr and Spagnolo, 2015b; Barr et al., 2017; Pearce et al., 2017; Ipsen et al., 2017; Wallick and
90 Principato, 2020). The premise behind this approach is that cirques (bowl-shaped depressions,
91 characterised by steep headwalls and flat or overdeepened floors sometimes occupied by small
92 lakes; Evans and Cox, 1974; Vilborg, 1977; Fredin et al., 2013) are formed where glaciers develop
93 and erode their underlying bedrock. When these glaciers are relatively small and largely confined
94 to the cirque (e.g., at the onset and termination of glacial cycles), the CFA (i.e., the lowest point
95 within a cirque) roughly approximates the glacier's ELA. Though this approach only provides an
96 approximation of the ELAs of former cirque glaciers, it has been widely used to investigate
97 regional patterns in palaeo-ELAs, and sometimes to make associated inferences about
98 palaeoclimate (e.g. Evans, 1999; Benn and Lehmkuhl, 2000; Barr and Spagnolo, 2015b). Despite
99 this widespread use, there are several caveats associated with using CFAs as indicators of former

100 cirque glacier ELAs. In particular, since cirque glaciers form at different times in different places,
101 regional trends in CFA are unlikely to reflect palaeo-ELA trends at any single point in time. This
102 raises questions about the usefulness of CFAs as proxies for palaeoclimate.

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104 In this study, we map the distribution of glacier-free cirques in the Scandinavian Mountains and
105 analyse variations in the associated CFAs. We compare these patterns with the ELAs of modern
106 cirque glaciers in the region (Oien et al., 2020). The aim is to establish how palaeoclimatic
107 information can most efficiently be extracted from cirque floor elevation distributions, despite
108 their potentially time-transgressive origins, evolution and occupation (Rudberg, 1994; Evans,
109 1999; Barr and Spagnolo, 2013). The Scandinavian Mountains are well suited to this study, as they
110 lie on a passive margin, have a comparatively well-constrained glacial history, and both cirques
111 and extant cirque glaciers are widespread.

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113 **2.0 Study Area**

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115 *2.1 Geology and Geography*

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117 The study area (Figure 1) extends ~2000 km N-S along the Scandinavian Mountains, and up to
118 400 km W-E from the Norwegian Sea inland into Sweden. Topographic elevations typically
119 increase inland, extending up to ~1500 m in the north and ~2400 m in the south. The geology is
120 mostly a result of the Caledonian orogeny, from 400-700 Ma (Holtedahl, 1920; Stephens, 1988;
121 Lidmar-Bergström, et al., 2000), when collisions between orogenic belts and exotic terranes
122 created a series of Precambrian and Palaeozoic crystalline metamorphic rocks (Etzelmüller et al.,
123 2007). The closure of the Iapetus Ocean and collision with Laurentia caused crustal thickening,
124 generating a stable crust that makes up the Fennoscandian Shield (Stephens, 1988). The majority
125 of cirques in the south are located within areas classified as upland mountains with moderate slopes
126 and alpine relief (Etzelmüller et al., 2007). This region is known for extensive plateaux steeply cut
127 by glacial valleys (Etzelmüller et al., 2007). More recently, glacial isostatic adjustment due to the
128 demise of the Fennoscandian ice sheet has resulted in an uplift of up to ~1 to 15 mm yr⁻¹ across
129 the Scandinavian Peninsula (Lambeck et al., 1998a; Lambeck et al., 1998b; Steffen and Kaufmann,
130 2005; Angus and Peltier, 2010).

131 *2.2 Glaciation*

132 Extensive glaciers and ice sheets have repeatedly occupied and shaped the Scandinavian landscape
133 over multiple Quaternary (and pre-Quaternary) glacial cycles (e.g. Mangerud, 2008; Mangerud et
134 al., 2011; Fredin et al., 2013; Olsen et al., 2013a; Olsen et al., 2013b; Hughes et al., 2016; Stroeven
135 et al., 2016). These glaciations have generated a wide range of erosional and depositional features,
136 resulting in a dramatic landscape of elongated overdeepened basins (often occupied by lakes),
137 fjords, glacial valleys, and cirques. At present, thousands of glaciers occupy the Scandinavian
138 Mountains, ranging in size from small cirque glaciers to extensive ice caps (Nesje, 2009; NVE,
139 2017)

140 *2.3 Climate*

141 Climatic patterns across the Scandinavian Peninsula are heavily influenced by the North Atlantic
142 Oscillation (NAO) and Arctic Oscillation (AO) (Nesje, 2008). These systems regulate pressure
143 gradients, which control temperature, precipitation, and storms. The interplay of these pressure
144 systems sometimes results in comparatively warm (between 0 and 2°C) wet (up to 2000 mm/year
145 in the southern coastal region) winters, or cold (between 0 and -16°C, particularly in the northern
146 region) dry winters (Norwegian Meteorological Institute, 2021). In the southern Scandinavian
147 Mountains, precipitation is also regulated by the Jet Stream, with a dominant wind direction from
148 the S/SW, and can reach 6000 mm/year in coastal areas but decreases dramatically inland to 500-
149 750 mm/year (Torsnes et al., 1993; Nesje et al., 2008; Nesje, 2009; Winsvold et al., 2014;
150 Norwegian Meteorological Institute, 2021). Winter precipitation (Figure 1b) and summer
151 temperatures (Figure 1a) are the main climatic controls on modern-glacier surface mass balance
152 (Ohmura et al., 1992; NVE, 2017; Ohmura and Boettcher, 2018; Oien et al., 2020).

153 **3.0 Methods**

154 We mapped glacier-free cirques using a 10 x 10 m digital terrain model (DTM) with a vertical
155 accuracy of $\pm 1-6$ m, overlain with 10 m contours from the Norwegian mapping authority
156 (Kartverket; Hoydedata.no) (Figure 2). Most of the mapped cirques coincide with cirque locations
157 identified by Rudberg (1994) and the definition of a cirque by Evans and Cox (1974) and Vilborg
158 (1984). Once mapped, we divided cirques by latitude into southern $<64^\circ\text{N}$ and northern $>64^\circ\text{N}$
159 sub-populations ('macro-regions'), following Oien et al. (2020). The division is roughly based on

160 climate, with the northern macro-region defined as ‘polar/subpolar’ due to its proximity to the
161 polar front while the southern macro-region is ‘temperate’ due to the influence of the North
162 Atlantic Current (Tveito et al., 2000; Oien et al., 2020).

163 Each cirque was mapped as a polygon (Figure 2): we extracted the CFA as the single lowest
164 elevation DTM grid cell contained within the polygon (Figure 3a). To assess possible controls on
165 CFA, several other attributes were derived: cirque aspect was calculated using the GIS tool ACME
166 (Spagnolo et al., 2017) (i.e. aspect is defined as the mean azimuth (0-360°) determined from every
167 pixel converted to radians and averaged within the cirque) (Evans, 1977; Evans, 2006b; Barr and
168 Spagnolo, 2015a); cirque latitude and longitude were recorded using the centroid of each feature;
169 and cirque distance from the modern coast, excluding fjords (Norwegian Sea, Figure 3) was
170 calculated in ArcGIS (following Oien et al., 2020). In addition to mapping cirques, the ELAs of
171 513 modern cirque glaciers (Figure 3b) in the region were analysed, based on the dataset from
172 Oien et al. (2020).

173

174 **4.0 RESULTS**

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176 *4.1 Cirque-floor altitudes (CFAs)*

177 A total of 3984 glacier-free cirques were mapped throughout the Scandinavian Mountains: 2947
178 in the northern region, and 1037 in the southern region (Figure 3). For the population as a whole,
179 CFAs range from 23 m to 2088 m (Table 1). In the northern region, the mean CFA (591 m) is
180 notably lower than in the southern region (1195 m). Cirques in the northern region are also
181 typically closer to the modern coastline (mean distance = 40.8 km) than those in the south (mean
182 distance = 104.7 km) (Table 2).

183

184 *4.2. CFA variations with latitude and longitude*

185 For the population as a whole, CFAs show a statistically significant, $p < 0.01$, decline to the north
186 and east (Figure 4), although the linear regression between CFA and latitude is stronger ($R^2 =$
187 0.441) than between CFA and longitude ($R^2 = 0.212$). Despite these general trends, considerable
188 variability is present between each (southern and northern) region. For example, in the northern
189 region, CFAs decline with latitude (Figure 5; $R^2 = 0.113$, panel a), but more weakly than for the
190 entire cirque population. In the southern region, CFAs rise then fall with latitude (Figure 6; $R^2 =$

191 0.114, panel a). Overall, it appears that the population-wide latitudinal trend in CFA is partly a
192 reflection of differences between the northern and southern regions (Figure 4a). In both the
193 northern and southern regions, CFAs show an eastward rise then fall with longitude (Figure 5b,
194 Figure 6b). The ELAs of modern cirque glaciers in the region show broadly similar latitudinal and
195 longitudinal trends to those highlighted for the CFA population (and sub-populations) but as
196 expected, lie a few hundred metres above (Figure 4a, 4b, 5a, 5b, 6a, 6b).

197

198 *4.3. CFA variations with aspect*

199 The mean vector aspect for the entire cirque population is 35.5° , which compares with 40.7° for
200 modern cirque glaciers. However, these values show some regional variation. In the northern
201 region, the cirque and modern cirque glacier vector means are 36.5° and 42.8° , respectively. In the
202 southern region, these values are 33.2° and 38.4° , respectively (Figure 7). However, overlapping
203 95% confidence intervals suggest that inter-regional differences in mean aspect (Figure 7) are
204 unlikely to be statistically significant. CFAs and modern cirque glacier ELAs show some
205 variability with aspect. For example, E-facing cirques typically have lower CFAs by ~ 150 m
206 (median = 642 m) than those facing S/SW (median = 828 m) (Figure 8), for the entire population.
207 Fourier (harmonic) regression (Evans and Cox, 2005; Evans, 2006a) indicates that these
208 relationships show no statistically significant overall trends, $p > 0.05$ (Table 3). Aspect vector
209 strength for the entire cirque population is 29%, which compares to 69% for the modern cirque
210 glaciers. This difference likely stems from the entire cirque population reflecting conditions during
211 multiple periods of past glaciation, whereas the distribution and aspect of modern cirque glaciers
212 reflects conditions during a single ‘snapshot’ of marginal glaciation (i.e., the present) when
213 topoclimatic factors (e.g. shading) play a strong role in regulating glacier location. This is
214 consistent with the ‘law of decreasing glacial asymmetry with increasing glacier cover’ (Evans,
215 1977).

216

217 *4.4. CFA variations with distance to the coast*

218 The attribute most strongly related to CFA is the distance to the modern coastline, with the
219 population as a whole (7.7 m/km; $R^2 = 0.750$; RMSE = 211; Figure 4d) and northern (7.7 m/km;
220 $R^2 = 0.701$; RMSE = 182; Figure 5d) and southern (4.9 m/km; $R^2 = 0.465$; RMSE = 227; Figure
221 6d) sub-regions showing a statistically significant increase inland, $p < 0.01$ (Table 3). This trend is

222 also seen in modern cirque glacier ELAs as a whole (5.8 m/km; $R^2 = 0.668$; RMSE = 177; Figure
223 4d) and within the northern (6.1 m/km; $R^2 = 0.621$; RMSE = 134; Figure 5d) and southern (3.8
224 m/km; $R^2 = 0.548$; RMSE = 155; Figure 6d) regions. For both CFAs and modern cirque glacier
225 ELAs, the relationship with distance to the coastline is stronger in the northern region (where
226 cirques and glaciers are also typically closer to the coast) than in the southern region. The inland
227 increase in CFAs and modern cirque glacier ELAs follows the overall topographic gradient of the
228 Scandinavian Mountains, with elevations increasing inland. These data illustrate that in each
229 region, distance from the modern coastline is the individual variable that shows the strongest
230 relationship with CFA (as indicated by R^2 and RMSE). In each region, multiple regression of CFA
231 against latitude, longitude and distance from the modern coastline returns the highest R^2 and
232 lowest RMSE. However, distance from the modern coastline dominates these relationships (i.e. it
233 is consistently the variable with the strongest t value), and they only differ slightly from those
234 based on CFA and distance from the coastline alone (Table 3).

235

236 **5.0 DISCUSSION**

237 Cirque morphology, aspect, and elevation, including CFAs, are thought to represent a time-
238 transgressive record of climatic and glaciological conditions during former periods when cirques
239 were occupied periodically by erosive (warm-based) ice (Meierding, 1982; Barr and Spagnolo,
240 2013; Ipsen et al., 2017). These conditions occurred multiple times during the Quaternary (and
241 pre-Quaternary) in Scandinavia, but usually towards the onset and termination of each glacial
242 cycle. By contrast, modern cirque glacier ELAs only (or largely) reflect climatic conditions at a
243 single period in time (i.e., the present), when glaciers are experiencing generalised retreat. Given
244 this difference, here we discuss the factors that potentially control CFAs and modern cirque glacier
245 ELAs and assess if, and how, these differ. From this, we consider what CFAs can tell us about
246 palaeoclimate.

247

248 *5.1. Factors controlling CFAs and modern cirque glacier ELAs*

249 *5.1.1. Climate*

250 Across the study region, the northward decline in CFAs and modern cirque glacier ELAs (Figure
251 4a), although to some degree a function of the two sub-regions, suggests that a latitudinal decline
252 in air temperatures played a role in regulating the altitude at which former mountain glaciers were

253 able to initiate (generating cirques) and regulates where cirque glaciers are currently able to exist
254 (Renseen et al., 2001; Fredin, 2002; Ipsen et al., 2017). However, since this latitudinal decline in
255 CFAs is far less apparent when sub-populations (i.e., northern and southern) are considered (Figure
256 5a & 6a), it is likely that this control mostly operates over large spatial scales (Bakke et al., 2008).
257 More locally, there is evidence that topographic sheltering and/or shading (as reflected by cirque
258 and cirque glacier aspects) plays a role in regulating CFAs and modern ELAs, suggesting that
259 glacier initiation and sustenance was/is promoted at lower altitudes on east-facing slopes (Figure
260 8) (Olyphant, 1977; Hassinen, 1998).

261 Despite the evidence for air temperature and aspect-related controls, the strongest region-wide
262 pattern in both CFAs and modern cirque glacier ELAs is an increase with distance inland, which
263 corresponds to present-day prevailing wind direction (W/SW to E/NE). Similar inland trends are
264 found in other regions and are thought primarily to reflect a limit to favourable glacial conditions,
265 imposed by a gradual inland reduction in precipitation (Peterson and Robinson, 1969; Nesje et al.,
266 2008; Principato and Lee, 2014; Barr and Spagnolo 2015a; Barr et al., 2017; Ipsen et al., 2018;
267 Wallick and Principato, 2020). In Scandinavia specifically, this logic implies that, exposure to
268 moisture from the Norwegian Sea is a key factor controlling former sites of glacier initiation and
269 modern glacier ELAs (Bakke et al., 2008; Nesje et al., 2008; Evans, 2011; Oien et al., 2020).
270 Present-day precipitation shows a strong relationship with modern cirque glacier ELAs in
271 Scandinavia (Winkler et al., 2009; Oien et al., 2020). Our CFA study suggests that
272 palaeoprecipitation gradients similar to present-day might have existed during periods of the
273 Quaternary (or earlier) when cirques formed and were subsequently re-occupied by cirque glaciers.
274 This long-term stability of climatic gradients in the region has been suggested previously, as other
275 palaeoclimatic proxies have shown, for example, that maritime wet conditions were recurrent
276 throughout the Holocene in the coastal part of the southern region of Scandinavia (Seppä and
277 Birks, 2001; Bjune et al., 2005; Bakke et al., 2008). Furthermore, palaeoclimate models, extending
278 through the last glaciation maximum and Younger Dryas, show an overall pattern of precipitation
279 decreasing inland (e.g. Ressen et al., 2001; Forsström, 2005; Rea et al., 2020).

280 For the region as a whole, and the two sub-regions, the inland increase in CFAs has a slightly
281 steeper gradient than the increase in modern ELAs. Barr and Spagnolo (2015b) found a similar
282 trend between CFAs and modern glacier ELAs in Kamchatka (Eastern Russia). They attributed
283 this difference to the fact that CFAs reflect sites of former glacier initiation (largely controlled by

284 snowfall), while modern glacier ELAs are also strongly regulated by the variety of topoclimatic
285 factors which control ablation (i.e., the link to precipitation is weakened, and modern glaciers can
286 survive even in regions with limited snowfall). This difference in the factors controlling CFAs and
287 modern ELAs might also apply in Scandinavia. However, it is also possible that the steeper inland
288 CFA gradient (when compared to modern glacier ELAs) in Scandinavia reflects the control of ice
289 sheet growth on areas suitable for cirque formation (see Section 5.1.3).

290

291 *5.1.2. Topography*

292 Topographic availability exerts a control on where glaciers can develop, e.g. high-altitude glaciers
293 can only form where high-altitude topography exists. Therefore, regional trends in CFAs and
294 modern glacier ELAs likely partly reflect topographic (i.e. mountain elevation) gradients. Oien et
295 al (2020) considered the potential role of topography in controlling modern cirque glacier ELAs
296 across Scandinavia and found that mean topography and modern ELAs increase inland with similar
297 gradients. Results from the present study reveal that CFAs also increase inland, with very similar
298 (but slightly steeper) gradients. Studies in other regions globally have contemplated the possible
299 role that topographic gradients play in regulating CFAs (e.g., Peterson and Robinson, 1969;
300 Hassinen, 1998; Dahl and Nesje, 1992; Anders et al., 2010; Mitchell and Humphries, 2014; Barr
301 and Spagnolo, 2015b; Barr et al., 2017; Wallick and Principato, 2020). Though these studies
302 acknowledge the role of topography, most conclude by suggesting that palaeoprecipitation
303 gradients (as indicated by cirque distance from the coast) are likely the dominant control on CFAs.
304 In Scandinavia specifically, Hassinen (1998), focusing on an area at the very north of our study,
305 considered the inland increase in CFAs to reflect palaeoprecipitation gradients combined with
306 topographic trends (i.e., mountain heights gradually increase to the east, but at a slower rate than
307 CFAs). Similarly, Oien et al. (2020) concluded that inland precipitation reduction and topographic
308 gradients likely act together to regulate modern cirque glacier ELAs in the Scandinavian
309 Mountains. The results from the present study support the idea that, as with modern cirque glacier
310 ELAs, trends in CFAs are, to some degree, dictated by topography. This is illustrated in Figure 9,
311 which suggests that neither ELA gradients nor topographic gradients alone can explain the inland
312 cirque distribution observed in Scandinavia. The former fails to explain the absence of high-
313 altitude cirques near the coast (Figure 9a), and the latter fails to explain the absence of low-altitude

314 cirques further inland (Figure 9b). However, when both inland ELA gradients and topographic
315 gradients are considered, observed CFA trends are understandable (Figure 9c).

316

317 5.1.3. *Glacial history*

318

319 During glacial periods, large ice masses readily develop in the Scandinavian Mountains and
320 coalesce to form an ice sheet (e.g. Mangerud, 2008; Mangerud et al., 2011; Fredin et al., 2013;
321 Olsen et al., 2013a; Hughes et al., 2016). In Scandinavia, these large ice masses first occupy the
322 highest mountains of the interior of the southern region, and gradually advance and coalesce to
323 cover the entire peninsula (Fredin, 2002; Kleman et al., 2008; Mangerud et al., 2011; Olsen et al.,
324 2013a; Olsen et al., 2013b). Once a landscape is submerged by ice, ‘new’ cirques cannot form and
325 existing cirques experience minimal modification. Thus, in interior locations (i.e., far from the
326 coast), the formation of ‘new’, and modification of existing, cirques likely stop comparatively
327 early during the onset of glacial periods (when the local ELA is still relatively high), since the
328 landscape quickly becomes entirely submerged by largely cold-based (i.e. non erosive) ice
329 extending from local high-altitude regions of ice-sheet initiation. By contrast, in coastal locations
330 the local ELA may drop close to sea level (as indicated by CFAs), before the landscape is
331 submerged by an ice sheet (Rudberg, 1994; Dahl et al., 1997; Hassinen, 1998; Nesje, 2009).

332 This means that in Scandinavia low-altitude cirques can only develop in coastal locations, and not
333 in interior regions. It is reasonable to assume that the lowest elevation cirques, particularly those
334 along the modern-day coast in the northern region (Figure 3a), would only be filled at times of
335 extensive glaciation (Agrell, 1977; Olyphant, 1977; Dahl et al., 1997; Batchelor et al., 2019). This
336 spatial difference in glacial history is likely to enhance the inland trend in CFAs (already dictated
337 by climate and topography – see sections 5.1.1., and 5.1.2.) (Figure 9d) and might help explain
338 why inland gradients in CFAs are slightly steeper than modern ELA gradients.

339

340 5.1.4. *Additional factors*

341 In previous studies elsewhere, spatial variations in glacio-isostatic adjustment and former glacial
342 erosion rates (linked to ice dynamics and subglacial geology) have been considered as possible
343 explanations for region-wide trends in CFA (e.g., Bakke et al., 2005; Barr and Spagnolo, 2015b;
344 Barr et al., 2017). However, in Scandinavia, there is little evidence to suggest that these factors

345 control the trends in CFAs. For example, all the cirques analysed in this study are currently
346 experiencing glacio-isostatic uplift (Rosentau et al., 2012), and those in interior regions are
347 experiencing more rapid and greater uplift than in coastal locations (Rosentau et al., 2012). This
348 means that cirques in interior locations may be further below the altitude at which they formed
349 than is the case for coastal cirques. If so, correcting CFAs for residual glacial isostatic adjustment
350 would increase the inland gradient. In fact, glacial isostatic adjustment may help partly explain
351 why the inland gradient in CFAs is steeper than for modern ELAs, since the former may have been
352 affected by differential uplift since deglaciation, while the latter reflects the contemporary climate
353 and is therefore independent of isostatic adjustment.

354

355 While there is regional variability in cirque lithology, there are no broad-scale trends to suggest
356 that bedrock resistance increases with distance from the coast, certainly not in any way that
357 explains overall trends in CFAs (unlike Delmas et al., 2014; Delmas et al., 2015). Finally, the
358 dynamics of former cirque glaciers may have varied regionally, and there is evidence to indicate
359 that coastal glaciers may have been more dynamic (with higher mass turnover). Additionally, the
360 coastal, low-elevation glaciers would have only been covered by the ice sheet at maximum extent,
361 and may have experienced greater time of active cirque glacier occupation than those in the interior
362 that would have been shielded by cold-based ice (Olsen et al., 2001; Bakke et al., 2005; Batchelor
363 et al., 2019). Any spatial differences in glacier dynamics are likely to result in differences in CFAs
364 on the order of tens of metres (e.g. Dahl et al., 1997; Barr et al., 2017), not the hundreds of metres
365 difference between the coast and peak mountains as observed.

366

367 *5.2. Limitations of CFAs as palaeoclimate indicators*

368 As outlined above, when glaciers are small, and largely confined to their cirques (i.e., during
369 periods of cirque glaciation), CFAs roughly approximate cirque glacier ELAs, and could
370 therefore be used (with some caveats) as a source of quantitative palaeoclimate information
371 (precipitation and/or temperature). However, this palaeoclimatic information only becomes
372 useful when it can be assigned to a particular time period. This requires geochronometric dating
373 to establish when cirque-confined glaciers last occupied a landscape. This is possible through
374 surface exposure dating (e.g., Barth et al., 2016; Barth et al., 2017), but it is expensive and
375 impractical to apply to large populations, particularly when (as in the present study) thousands of

376 cirques are considered. Without chronological information for many cirques, the palaeoclimatic
377 inferences that can be drawn from populations are limited. Despite this caveat, trends in CFA
378 may reflect general, long-lasting or recurrent palaeoclimatic gradients – i.e. compound
379 (palimpsest) gradients from the superimposition of several glacial phases. However, where CFAs
380 track topography (as in the present study), isolating and quantifying the climatic component is
381 difficult. Where CFA trends differ from modern ELA or climate trends, this might indicate
382 changing climate (i.e., precipitation) patterns through time (e.g., Evans, 1999). However, in
383 almost all cases, trends in CFA generally track modern climate/ELA (Peterson and Robinson,
384 1969; Hassinen, 1998; Anders et al., 2010; Barr and Spagnolo, 2015b; Barr et al., 2017; Wallick
385 and Principato, 2020), and obtaining any useful palaeoclimatic information (beyond establishing
386 that broad precipitation gradients have changed little through time – as observed in the present
387 study) relies on interpreting differences between the two (e.g., Barr and Spagnolo, 2015b).
388 However, in Scandinavia, even extracting palaeoclimatic information in this way is complicated
389 by the potential role that the glacial history has played in regulating CFAs (Section 5.1.3.).

390 **6.0 CONCLUSIONS**

391 In this study, 3984 cirque floor altitudes (CFAs) and 513 modern cirque glacier ELAs were
392 analysed across the Scandinavian Peninsula. We investigated trends in these data to establish
393 controls on past and present glaciers in the region, and to establish what palaeoclimatic information
394 can be obtained from CFAs. The main study findings are:

- 395
396 1. Latitudinal and aspect-related trends in CFA and modern glacier ELAs suggest that air
397 temperatures and local shading played, and continue to play, a role in regulating sites of
398 mountain glaciation across the Scandinavian Peninsula.
- 399 2. The dominant trend in CFAs and modern glacier ELAs across the region is an increase
400 inland i.e., increasing with distance from the coast. These trends likely reflect the combined
401 influence of climatic gradients (controlling past and present ELAs), and topographic
402 gradients (restricting where glaciers and cirques can form). In the case of CFAs,
403 unravelling controls on the increase inland is further complicated by spatial differences in
404 glacial history (in particular, ice sheet growth in the interior during glacial periods,
405 preventing the formation of low altitude cirques).

406 3. Results from the present study, supported by other studies, suggest that individual CFAs
407 can yield useful (quantitative), but limited, palaeoclimate information. However, given the
408 potential role of climate, topography, and glacial history (and the difficulties with
409 disentangling these controls), palaeoclimatic interpretations derived from cirque
410 populations and/or CFA trends should be treated with caution.

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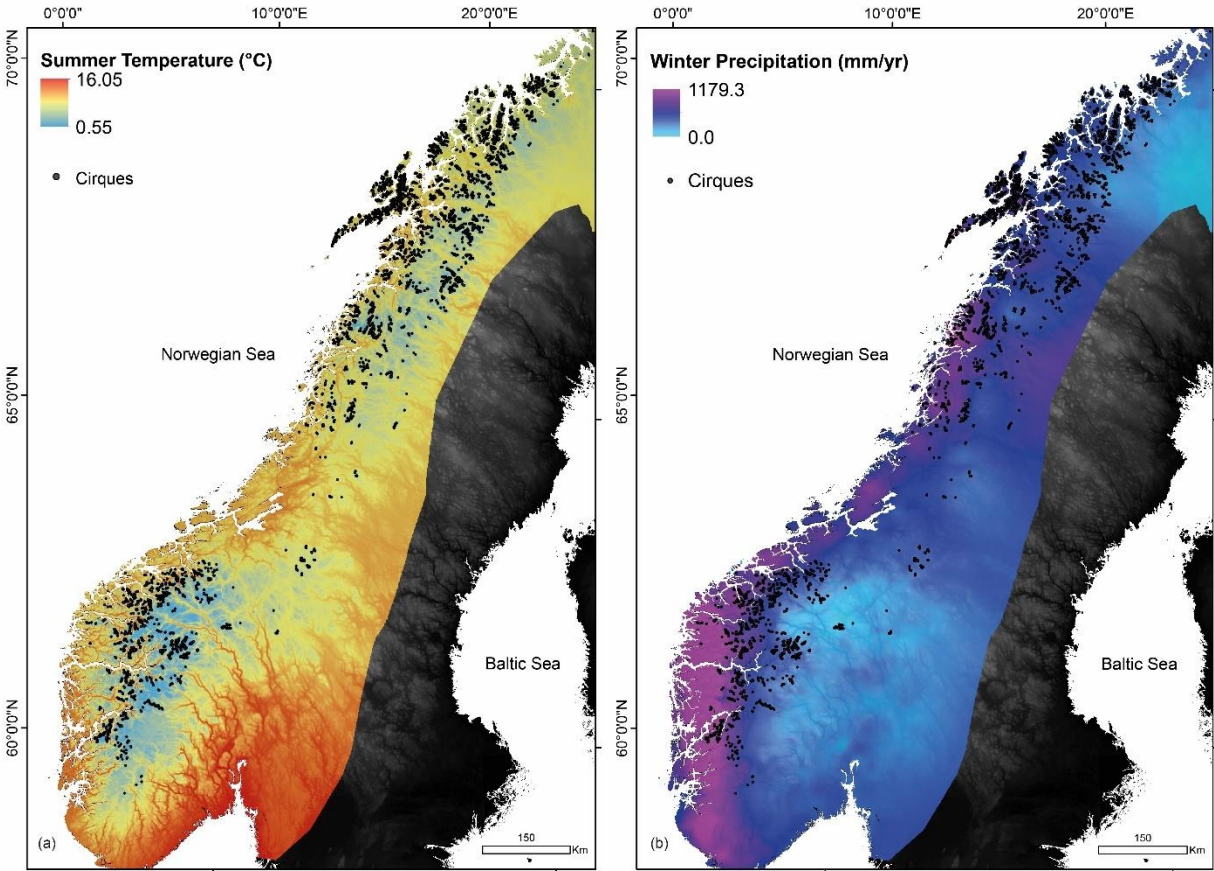
415 **7.0 ACKNOWLEDGEMENTS**

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420 comments, and suggestions.

421 **8.0 FIGURES**

422

423



424

425 Figure 1. (a) Mean summer air temperature (JJA) and (b) total winter precipitation (DJF) patterns

426 for present-day Scandinavia (NVE, 2017). Winter precipitation and summer temperatures are

427 averaged over 30 years from 1971-2000 (NVE, 2017).

428

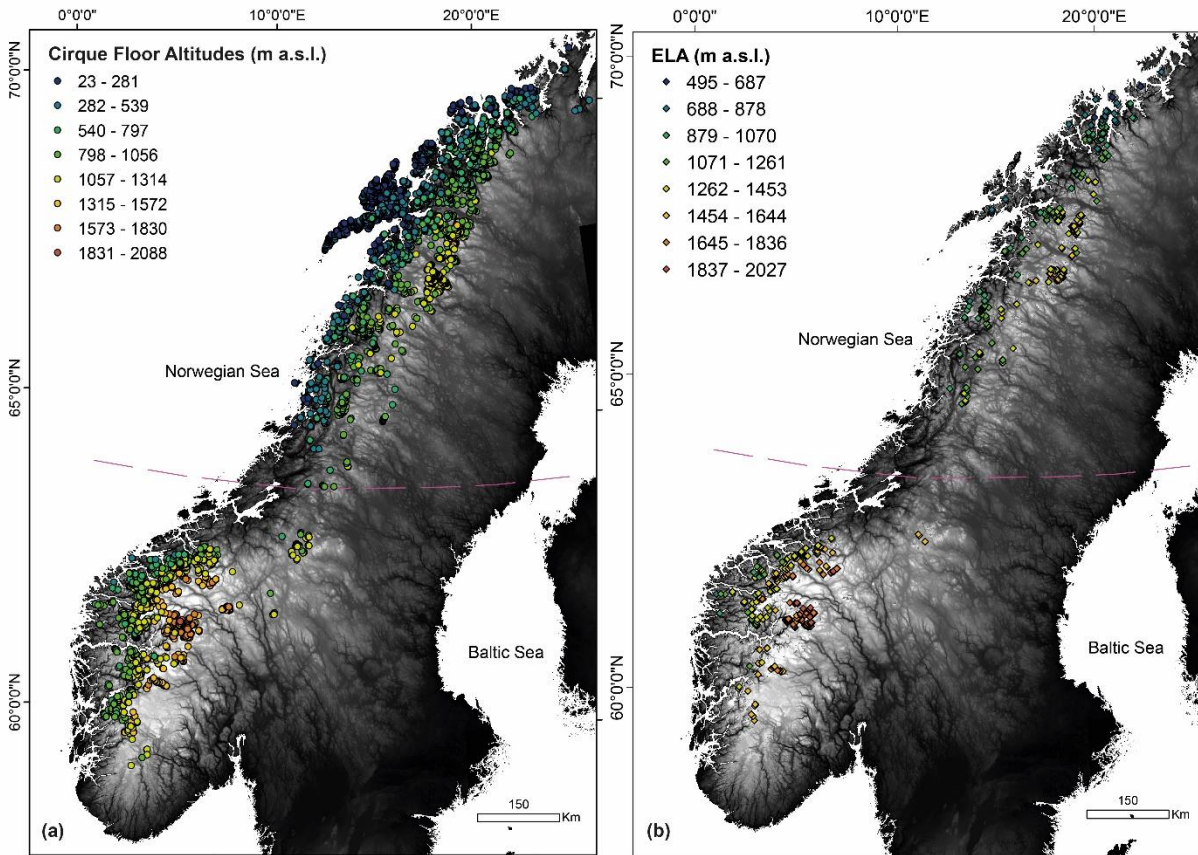


429

430 Figure 2. An example of two of the mapped glacier-free cirque outlines (in pink) overlaid in

431 Google Earth, located at 62°28'43.97"N 7°57'41.59"E.

432



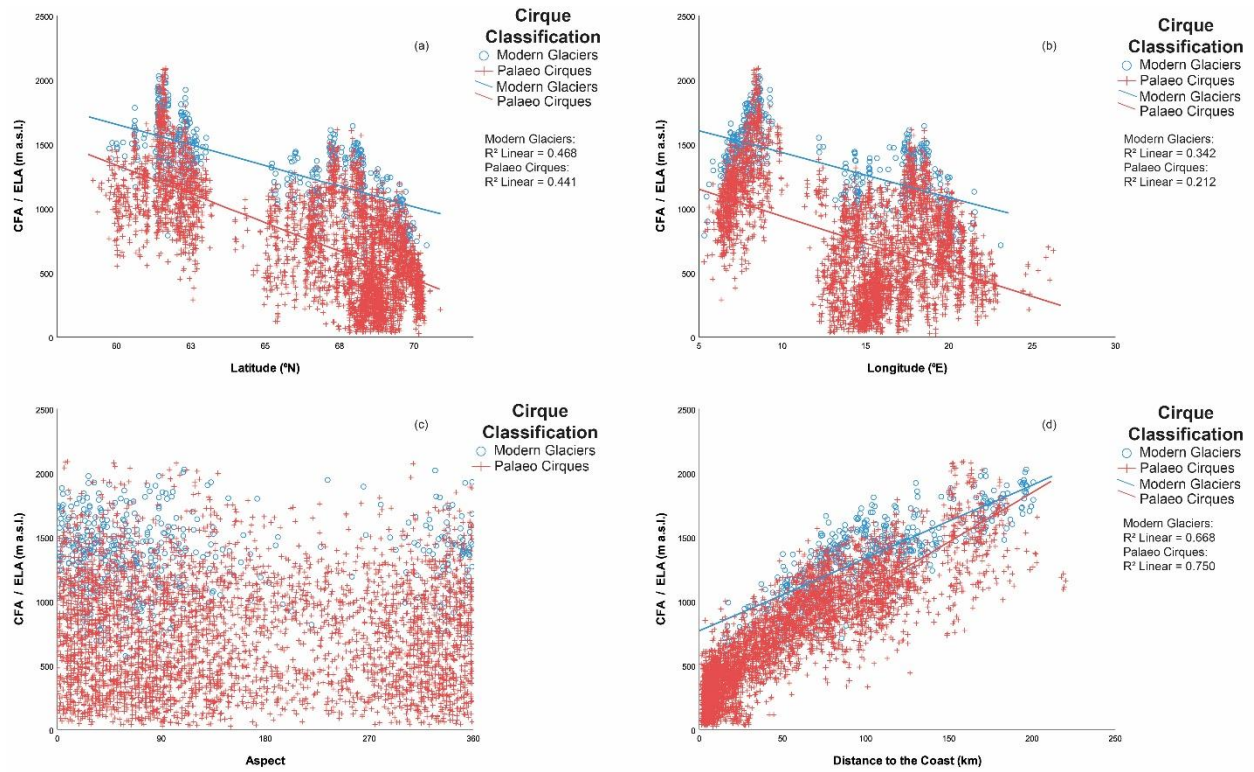
434

435 Figure 3. (a) Cirque floor altitudes and (b) modern-glacier ELAs. The dashed line separates

436 regions termed in the text as the northern and southern regions.

437

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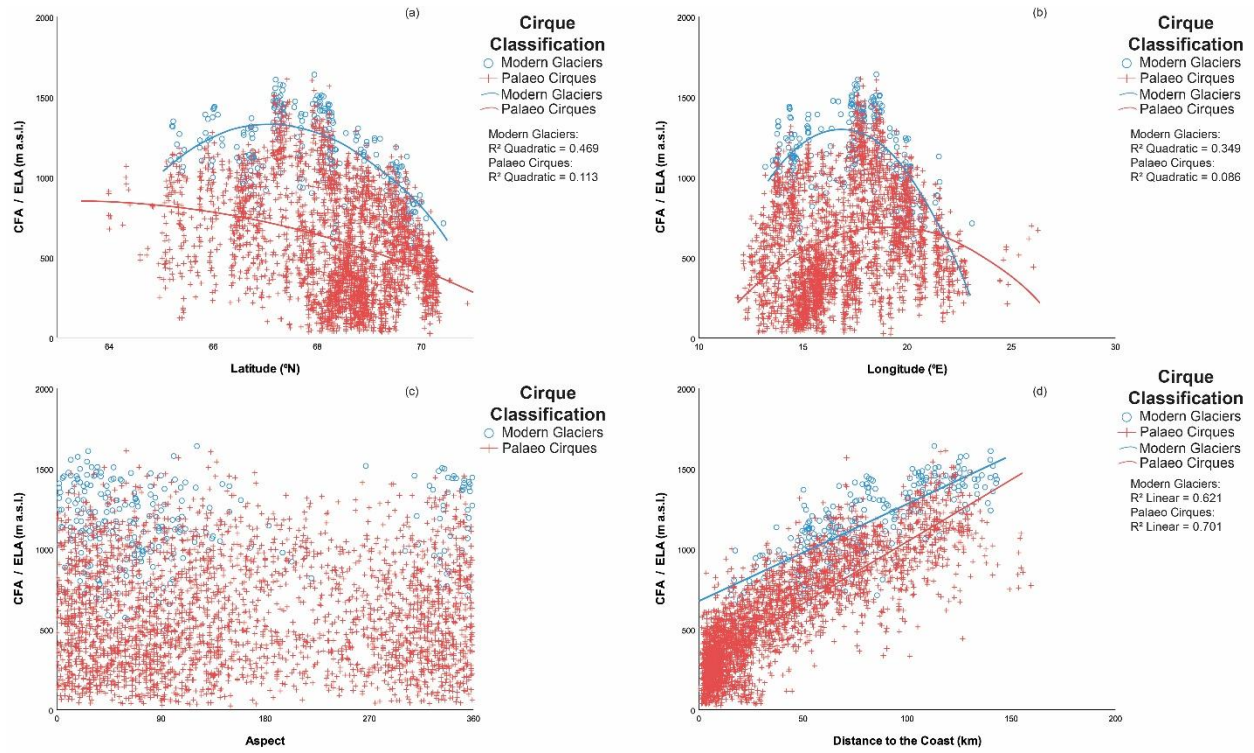
440 Figure 4. Variations in cirque floor altitudes and glacier ELAs, with: (a) latitude; (b) longitude;

441 (c) aspect; and (d) distance to the modern coastline.

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446 Figure 5. Variations in cirque floor altitudes and glacier ELAs in the northern region with: (a)

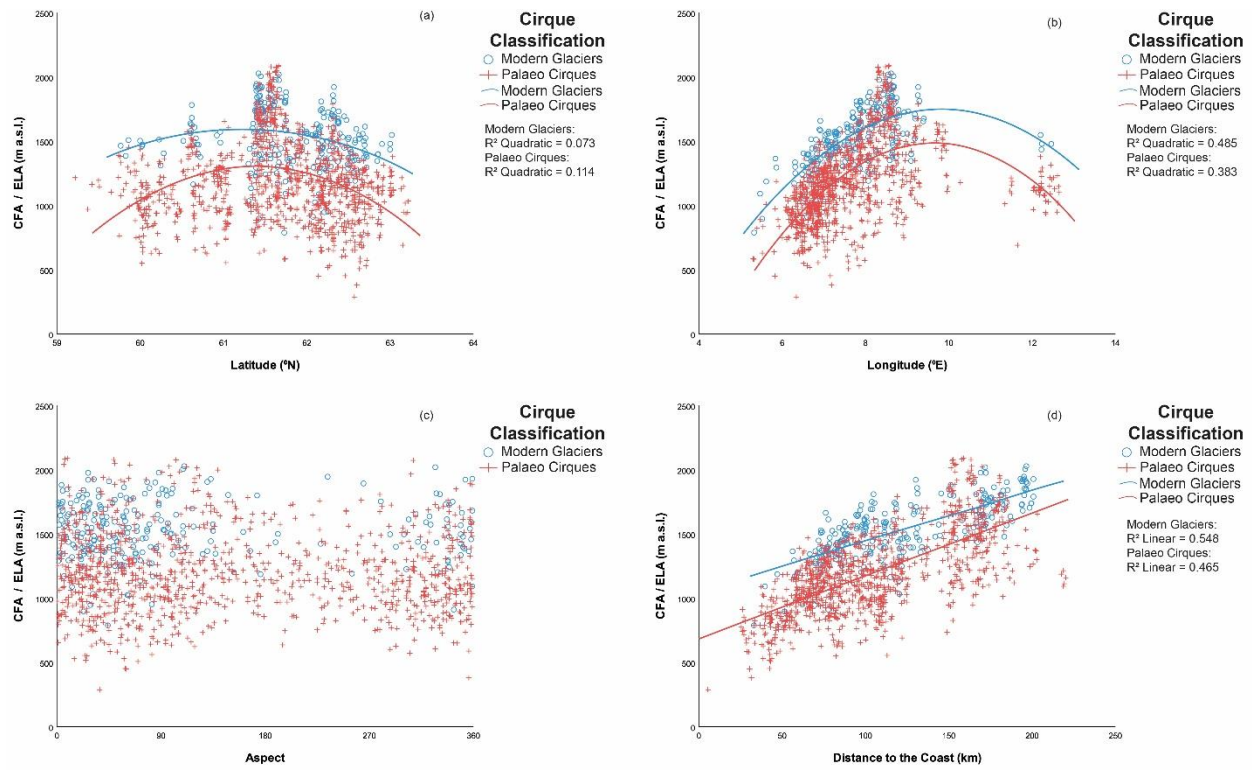
447 latitude; (b) longitude; (c) aspect; (d) distance to the modern coastline.

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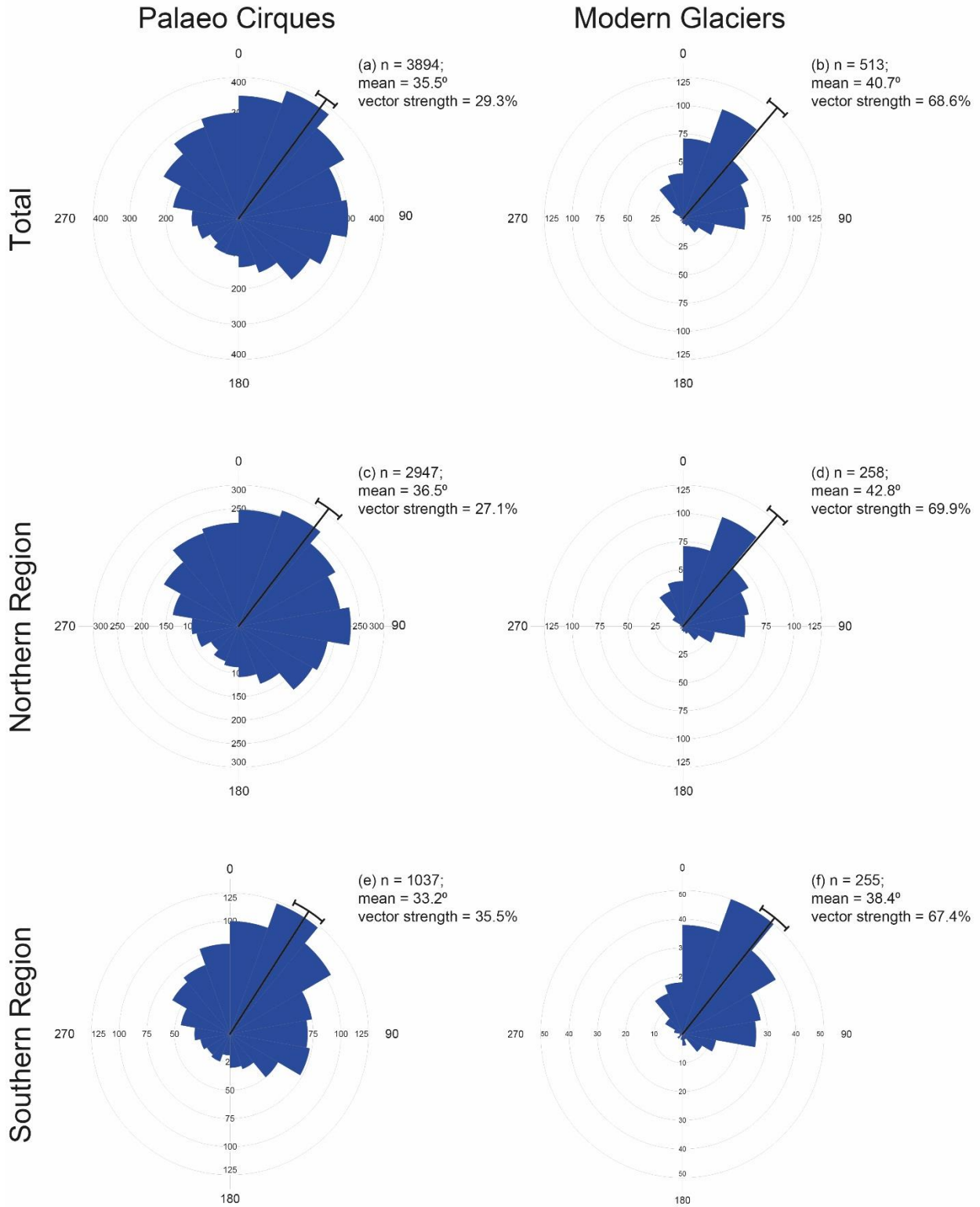


452

453 Figure 6. Variations in cirque floor altitudes and glacier ELAs in the southern region with: (a)

454 latitude; (b) longitude; (c) aspect; (d) distance to the modern coastline.

455



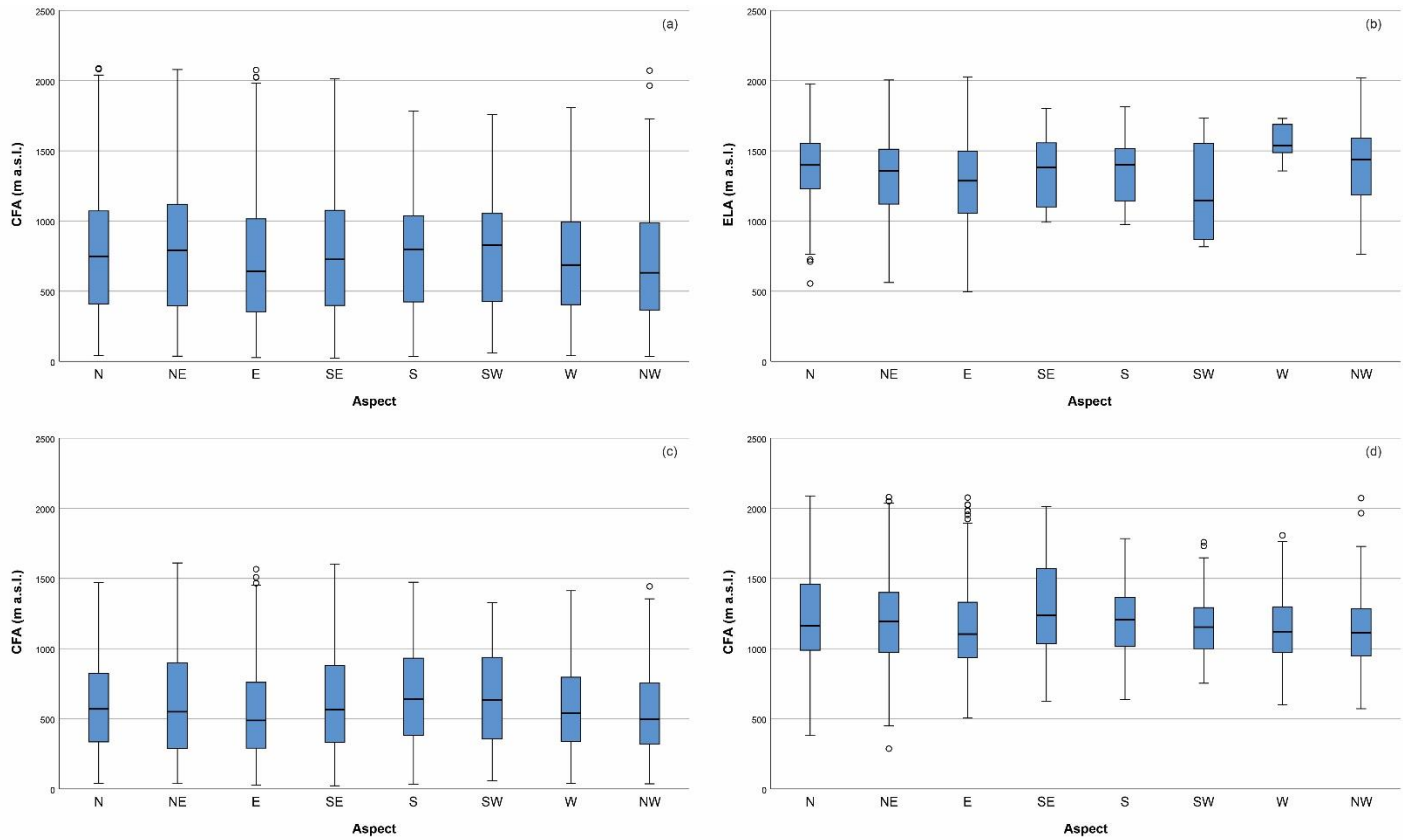
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458 Figure 7. Rose diagrams (linear scale of frequency with equal bin widths) of mean vector aspect

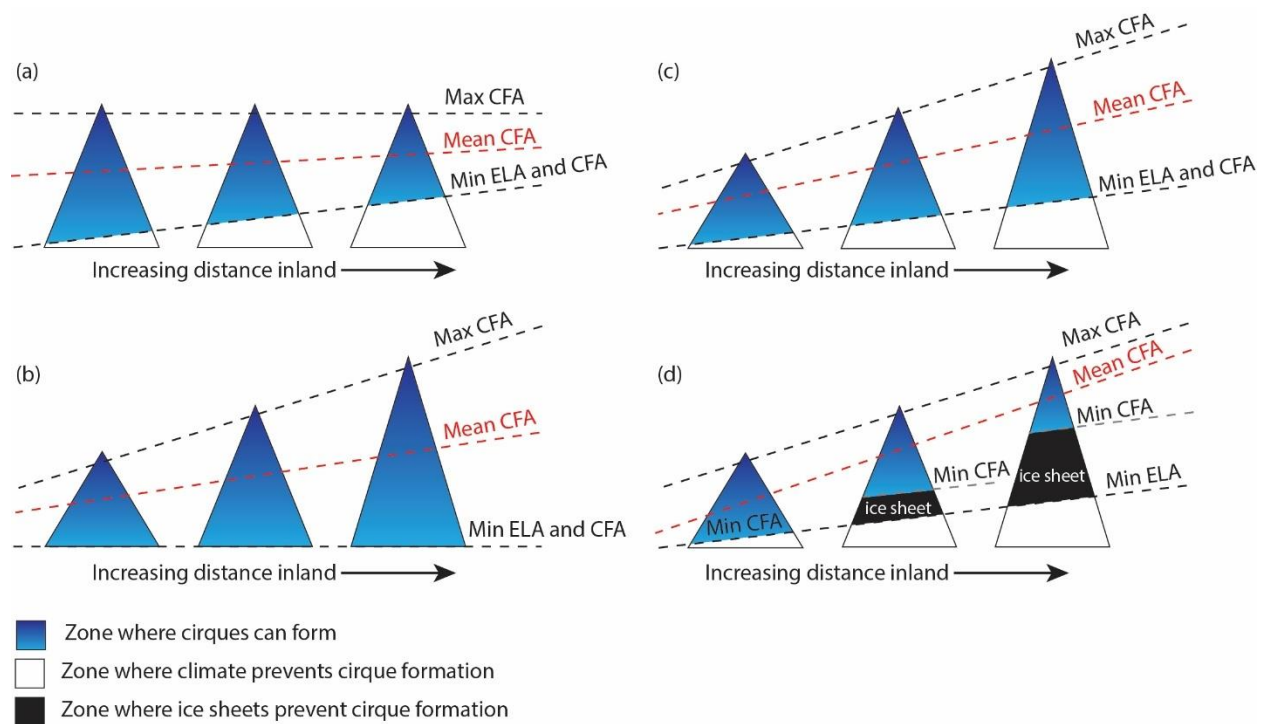
459 frequency and vector strength. (a) Entire cirque population, (b) entire modern cirque glacier

460 population, (c) cirques in the northern region, (d) modern cirque glaciers in the northern region,
 461 (e) cirques in the southern region, (f) modern cirque glaciers in the southern region. In each Rose
 462 diagram, the line represents the vector mean and the bar (on the end of each line) shows the 95%
 463 confidence interval.



464
 465
 466 Figure 8. Boxplots comparing the CFA or ELA with aspect for the (a) whole cirque dataset (b)
 467 modern cirque glaciers (c) northern cirque region (d) southern cirque region. The thick middle
 468 line indicates the median, the top and bottom of the box represent the 1st and 3rd quartiles and the
 469 edge of the whisker represent the range, maximum and minimum excluding outliers. Outliers
 470 (open circles) are defined as points which lie more than 1.5 box lengths beyond the interquartile
 471 range. The number of modern glaciers and cirques within each aspect group is shown in Table 4.

472
 473



474

475 Figure 9. Schematic illustration of potential drivers of the inland increase in minimum, mean and
 476 maximum CFAs observed in the present study. (a) Climatic gradient alone (as indicated by
 477 variability in climatic ELA), (b) topographic gradient alone, (c) climatic and topographic gradients,
 478 (d) climatic and topographic gradients, combined with spatial variability in glacial history, with
 479 the top of the black margin representing the minimum CFA (i.e., the formation of ice sheets at
 480 inland locations) and the bottom the minimum ELA. This illustration indicates that only scenarios
 481 (c) and (d) produce CFA distributions comparable to that seen in Figure 4d, despite the complex
 482 history of uplift in the Scandinavian Mountains (Nielsen et al., 2009; Steer et al., 2012; Pedersen,
 483 et al., 2021).

484

485 **9.0 TABLES**

486

487 Table 1: Cirque floor altitudes (cirques) and ELAs (modern mountain glaciers) across the
 488 Scandinavian Peninsula, subdivided by region.

489

	Total Population (cirques)	Northern Region (cirques)	Southern Region (cirques)	Total Population (glaciers)	Northern Region (glaciers)	Southern Region (glaciers)

Number:	3984	2947	1037	513	258	255
Min (m a.s.l.)	23	23	287	495	495	788
Max (m a.s.l.)	2088	1610	2088	2027	1639	2027
Mean (m a.s.l.)	745	591	1195	1339	1151	1528
Median (m a.s.l.)	721	541	1166	1368	1158	1519
Std. dev (m a.s.l.)	422	333	311	303	245	229

490

491

492 Table 2: Summary statistics for the CFAs/ELAs and distance to the coast within the northern and
 493 southern regions for cirques and modern glaciers. All characteristics were extracted using ACME
 494 (Spagnolo et al., 2017).

495

496

	Northern Cirques (n = 2947)			Northern Modern Glaciers (n = 258)		
	Mean	Median	Std. Deviation	Mean	Median	Std. Deviation
CFA/ELA (m a.s.l.)	591	541	333	1151	1158	245
Distance to the Coast (km)	40.83	27.01	36.3	67.73	64.97	33.16
	Southern Cirques (n = 1037)			Southern Modern Glaciers (n = 255)		
	Mean	Median	Std. Deviation	Mean	Median	Std. Deviation
CFA/ELA (m a.s.l.)	1195	1166	311	1528	1519	229
Distance to the Coast (km)	104.67	96.98	43.32	108.18	97.65	42.09

497

498

499

500 Table 3. Regression of cirque floor altitude (CFA) against latitude (Lat), longitude (Lon),
 501 distance from the modern coastline (D), and aspect (α). Significant relationships (i.e., where
 502 $p < 0.01^*$, $p < 0.05^{**}$), other than those based on multiple regression, are shown in Figs 3-5. For
 503 equations based on multiple regression, the coefficient and variable with the strongest t value are
 504 in **bold**.
 505

Region	Variable	Equation	p-value	R ²	RMSE (m)
Total	Lat	CFA = -88.74Lat + 6659.64	<0.01*	0.441	315
	Lon	CFA = -41.63Lon + 1356.03	<0.01*	0.212	374
	Dist (D)	CFA = 7.70D + 305.86	<0.01*	0.750	211
	Aspect (α)	Not stat. sig.	0.31	n/a	n/a
Northern	Lat, lon, dist (D)	CFA = -85.40Lat + 35.78Lon + 5.49D + 5598	<0.01*	0.778	199
	Lat	CFA = -9.60Lat ² + 1215.10Lat - 37603	<0.01*	0.113	314
	Lon	CFA = -8.95Lon ² + 342.36Lon - 2586	<0.01*	0.086	319
	Dist (D)	CFA = 7.69D + 277	<0.01*	0.701	182
	Aspect (α)	CFA = -23.90cos α - 1.24sin α + 596.45	0.03**	n/a	n/a
	Lat, lon, dist (D)	CFA = -108.46Lat + 51.38Lon + 5.58D + 6902	<0.01*	0.731	174
	Lat	CFA = -135.14Lat ² + 16589Lat - 507781	<0.01*	0.114	293
	Lon	CFA = -53.38Lon ² + 1030.40Lon - 3489	<0.01*	0.383	244
Southern	Dist (D)	CFA = 4.90D + 682	<0.01*	0.465	227
	Aspect (α)	Not stat. sig.	0.06	n/a	n/a
	Lat, lon, dist (D)	CFA = 121.92Lat - 65.04Lon + 6.54D - 6505	<0.01*	0.503	219

506
 507 Table 4. Number of modern glaciers and cirques within each aspect group. N, 337.5–22.5°; NE,
 508 22.5–67.5°; E, 67.5–112.5°; SE, 112.5–157.5°; S, 157.5–202.5°; SW, 202.5–247.5°; W, 247.5–
 509 292.5°; NW, 292.5–337.5
 510

	N	NE	E	SE	S	SW	W	NW
Modern glaciers (total)	136	181	114	25	10	4	6	37
Modern glaciers (North)	67	88	64	13	4	2	1	19

Modern glaciers (South)	69	93	50	12	6	2	5	18
Cirques (total)	742	779	629	477	263	233	316	545
Cirques (North)	527	534	475	371	210	176	237	417
Cirques (South)	215	245	154	106	53	57	79	128

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