



## Understanding controls on cirque floor altitudes: insights from Kamchatka

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1 **Understanding controls on cirque floor altitudes: insights from Kamchatka**

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10

11 **Abstract**

12 Glacial cirques reflect former regions of glacier initiation and are therefore used as indicators of past  
13 climate. One specific way in which palaeoclimatic information is obtained from cirques is by  
14 analysing their elevations on the assumption that cirque floor altitudes are a proxy for climatically  
15 controlled equilibrium-line altitudes (ELAs) during former periods of small-scale (cirque-type)  
16 glaciation. However, specific controls on cirque altitudes are rarely assessed, and the validity of using  
17 cirque floor altitudes as a source of palaeoclimatic information remains open to question. In order to  
18 address this, here we analyse the distribution of 3520 ice-free cirques on the Kamchatka Peninsula  
19 (eastern Russia) and assess various controls on their floor altitudes. In addition, we analyse controls  
20 on the mid-altitudes of 503 modern glaciers, currently identifiable on the peninsula, and make  
21 comparisons with the cirque altitude data. The main study findings are that cirque floor altitudes  
22 increase steeply inland from the Pacific, suggesting that moisture availability (i.e., proximity to the  
23 coastline) played a key role in regulating the altitudes at which former (cirque-forming) glaciers were  
24 able to initiate. Other factors, such as latitude, aspect, topography, geology and neotectonics seem to  
25 have played a limited (but not insignificant) role in regulating cirque floor altitudes, though south-  
26 facing cirques are typically higher than their north-facing equivalents, potentially reflecting the impact  
27 of prevailing wind directions (from the SSE) and/or variations in solar radiation on the altitudes at

28 which former glaciers were able to initiate. Trends in glacier and cirque altitudes across the peninsula  
29 are typically comparable (i.e., values typically rise from the north and from the south, inland from the  
30 Pacific coastline, and where glaciers/cirques are south-facing), yet the relationship with latitude is  
31 stronger for modern glaciers, and the relationship with distance to the coastline (and to a lesser degree  
32 with aspect) is notably weaker. These differences suggest that former glacier initiation (leading to  
33 cirque formation) was largely regulated by moisture availability (during winter months) and the  
34 control this exerted on accumulation; whilst the survival of modern glaciers is also strongly regulated  
35 by the variety of climatic and nonclimatic factors that control ablation. As a result, relationships  
36 between modern glacier mid-altitudes and peninsula-wide climatic trends are more difficult to identify  
37 than when cirque floor altitudes are considered (i.e., cirque-forming glaciers were likely in climatic  
38 equilibrium, whereas modern glaciers may not be).

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40

41 *Keywords:*

42 cirques; glacier; palaeoclimate, climate; ELA

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## 64 **1. Introduction**

65 Glacial cirques are bowl-shaped hollows formed by the erosive action of mountain glaciers (Evans  
66 and Cox, 1995; Mîndrescu and Evans, 2014). Cirques reflect former regions of glacier initiation (i.e.,  
67 where topoclimatic conditions formerly allowed the development of glaciers), and as a result, they are  
68 often used as a source of palaeoclimatic information (e.g., Anders et al., 2010; Mîndrescu et al., 2010;  
69 Bathrellos et al., 2014). One specific way in which palaeoclimatic information is obtained from a  
70 population of cirques is by analysing spatial variability in their altitudes (e.g., Linton, 1959;  
71 Derbyshire, 1963; Davies, 1967; Peterson and Robinson, 1969; Hassinen, 1998; Principato and Lee,  
72 2014) on the assumption that cirque floor altitudes are a proxy for the climatically controlled  
73 equilibrium-line altitudes (ELAs) of former cirque glaciers (i.e., glaciers that formerly occupied, and  
74 were contained within, cirques) (see Flint, 1957; Meierding, 1982; Porter, 1989; Benn and Lehmkuhl,  
75 2000). The analysis of cirque floor altitudes is also key to understanding the role played by glaciers in  
76 eroding and regulating mountain topography at a near global scale—as part of a test for the buzzsaw  
77 hypothesis (see Oskin and Burbank, 2005; Mitchell and Montgomery, 2006; Mitchell and Humphries,  
78 2015). However, specific controls on cirque floor altitudes are rarely assessed, meaning that the  
79 validity of using cirque floor altitudes as a source of palaeoclimatic information or for testing the  
80 buzzsaw hypothesis remains questionable (see Peterson and Robinson, 1969; Hassinen, 1998). In light  
81 of this, the aim of the present study is to assess the relative importance of various controls (i.e.,  
82 latitude, aspect, proximity to the coast, topography, geology, tectonics, and volcanic activity) on  
83 cirque floor altitudes across the Kamchatka Peninsula (eastern Russia) in the hope that some of the  
84 information derived can be applied to cirque populations elsewhere globally. Kamchatka is well  
85 suited for this purpose, as the peninsula harbours a large cirque population; is topographically diverse;  
86 has varied, but comparatively simple, climate patterns; and is occupied by numerous modern  
87 glaciers—the altitudinal distribution of which is also studied here.

88

## 89 **2. Study area**

### 90 *2.1. Topography and geology*

91 The Kamchatka Peninsula is located in far eastern Russia and separates the Sea of Okhotsk to the west  
92 from the North Pacific to the south and east. The peninsula is ~ 1250 km long and is dominated by  
93 three distinct mountain regions: the Sredinny Mountains, the Vostochny Mountains, and the Eastern  
94 Volcanic plateau (EVP) (see Fig. 1). The NE–SW orientation of these mountain chains reflects their  
95 formation at the margin of the Kuril-Kamchatka subduction zone, now located ~ 150 km off the  
96 eastern shore of the peninsula (see Fig. 1). This proximity to the actively subducting North Pacific  
97 plate makes Kamchatka one of the most volcanically active arc segments on Earth (DeMets et al.,  
98 1990; Bindeman et al., 2010), currently occupied by ~ 300 extinct and 29 active volcanoes (shown in  
99 Fig. 1) (Ponomareva et al., 2007). This volcanic history is reflected by the region’s bedrock, which is  
100 dominated by Quaternary and Miocene-Pliocene volcanic complexes (see Persits et al., 1997;  
101 Avdeiko et al., 2007).

102

103 [Approximate location of Fig. 1]

104

## 105 **2.2. Glaciation**

106 At present, Kamchatka is occupied by 503 glaciers (see Fig. 2). Though these glaciers are  
107 comparatively small (with a mean surface area of ~ 1.7 km<sup>2</sup>) (see Khromova et al., 2014), we see  
108 evidence that the peninsula was extensively glaciated at various periods during the Late Quaternary  
109 (see Zamoruyev, 2004; Barr and Clark, 2011, 2012). The geomorphological record of former  
110 glaciation (summarised by Barr and Solomina, 2014) appears to indicate that the most extensive phase  
111 of ice advance occurred during the middle Pleistocene (c. 130-140 ka; Marine Isotope Stage, MIS, 6),  
112 when an ice sheet (~ 445,000 km<sup>2</sup>) likely covered the entire peninsula. During the early part of the late  
113 Pleistocene (c. 60-31 ka; MIS 3) glaciers were less extensive (covering ~ 193,000 km<sup>2</sup>) and were  
114 smaller still (covering ~ 90,000 km<sup>2</sup>) at the global Last Glacial Maximum (gLGM; MIS 2). Additional  
115 small-scale phases of ice advance occurred during the Late Glacial and Holocene (see Barr and  
116 Solomina, 2014). Many of the peninsula’s 3520 glacier-free cirques (see Fig. 3) were likely occupied  
117 during a number of these glacial phases, with active glacial erosion intensified during the onset and

118 termination of glaciations, when glaciers were largely confined to their cirques (see Barr and  
119 Spagnolo, 2013). The morphometry (i.e., size and shape) of cirques on the peninsula has already been  
120 analysed to yield some palaeoclimatic information (see Barr and Spagnolo, 2013); here we provide  
121 specific consideration of their altitudinal distribution and its significance.

122  
123 [Approximate location of Fig. 2]

124 [Approximate location of Fig. 3]

125  
126  
127 **2.3. Climate**

128 Because of Kamchatka's length and diverse topography, present-day climatic conditions across the  
129 peninsula vary considerably. However, in general, winter climate is dominated by the Siberian High,  
130 which drives cryoarid conditions from the interior of east Siberia in a SE direction across the  
131 peninsula (see Fig. 4), whilst summer conditions are dominated by the North Pacific High, which  
132 drives warm, moist air masses inland, from SE to NW (Shahgedanova et al., 2002; Yanase and Abe-  
133 Ouchi, 2007) (see Fig. 4). These climatic patterns result in distinct regional variations in climate, from  
134 a maritime Pacific coast to a continental interior (Čermák et al., 2006). This is exemplified by the  
135 strong SE-NW precipitation gradient, which shows the importance of the North Pacific in regulating  
136 moisture distribution across the peninsula (see Figs. 4A–D). The Sea of Okhotsk, to the west of the  
137 peninsula, serves as a secondary source of moisture, and its importance appears to peak in summer  
138 (Fig. 4B) and diminish in winter (Fig. 4C). This seasonal variation likely reflects the growth of sea ice  
139 in the Sea of Okhotsk during winter, limiting evaporation and minimising the inland advection of  
140 moisture (Fetterer et al., 2002) (see Fig. 4D). By contrast, the North Pacific remains largely devoid of  
141 sea ice throughout the year (Fetterer et al., 2002), and winter precipitation across the peninsula is  
142 almost entirely regulated by proximity to this source (see Figs. 4C and 4D),

143  
144 [Approximate location of Fig. 4]

145

146

### 147 **3. Methods**

148 The cirques analysed in this study were mapped from satellite images (Landsat 7 ETM+) and digital  
149 elevation model (DEM) data (ASTER GDEM v.2, with a grid cell resolution of 30 m, and an absolute  
150 vertical accuracy of ~ 17 m; ASTER GDEM Validation Team, 2011) by Barr and Spagnolo (2013).  
151 To assess controls on cirque floor altitudes (Alt), the latitude ( $\phi$ ), longitude ( $\lambda$ ), aspect ( $\theta$ ), and  
152 shortest distance to the modern coastline (x) (hereafter referred to as distance to the modern coastline)  
153 of each cirque was quantitatively analysed, and the role of topography, geology, tectonics, and  
154 volcanic activity was also considered. Floor altitudes were measured as the single lowest DEM grid  
155 cell within each cirque (calculated from the ASTER GDEM). Cirque distance to the coastline was  
156 calculated using the ArcGIS Euclidean distance tool (an approach adopted by Principato and Lee,  
157 2014). Latitude and longitude were measured from the centre point of each cirque; and aspect was  
158 measured as the outward direction of each cirque's median axis (see Evans, 1977; Evans and Cox,  
159 1995).

160

### 161 **4. Results**

#### 162 **4.1. Cirque floor altitudes**

163 The 3520 glacier-free cirques on the Kamchatka Peninsula have floor altitudes that range from 122 to  
164 1919 m (asl) (see Fig. 3 and Table 1). These cirques are subdivided into six populations based on the  
165 regions illustrated in Fig. 1. These include cirques on (i) the western slopes of the north Sredinny  
166 Mountains (referred to here as the NW Sredinny); (ii) the eastern slopes of the north Sredinny  
167 Mountains (referred to here as the NE Sredinny); (iii) the central Sredinny Mountains; (iv) the western  
168 slopes of the south Sredinny Mountains (referred to here as the SW Sredinny); (v) the eastern slopes  
169 of the south Sredinny Mountains (referred to here as the SE Sredinny); and (vi) the Vostochny  
170 Mountains and EVP (see Table 1).

171

172 [Approximate location of Table 1]

173

#### 174 **4.2. Variations in cirque floor altitudes with latitude and longitude**

175 When the entire cirque data set is considered (as in Fig. 3), cirque floor altitudes are found to rise  
176 from the north and from the south, to a peak at  $\sim 55.5^\circ\text{N}$  (see Fig. 5a and Table 2). Similarly, floor  
177 altitudes rise from the east and the west, though the westward rise is much stronger than the eastward  
178 (Fig. 5B). These trends are statistically significant ( $p < 0.001$ ), but variations in their nature and  
179 strength within and between regions are notable (see Figs. 5A and 5B, and Table 2).

180

181 [Approximate location of Fig. 5]

182 [Approximate location of Table 2]

183

184

#### 185 **4.3. Aspect-related variations in cirque floor altitudes**

186 When Kamchatkan cirques are considered according to their median axis aspect ( $\theta$ ), it is apparent that  
187 there are notable aspect-related variations in cirque floor altitudes. Specifically, south-facing cirques  
188 tend to have higher floor altitudes than north-facing examples (see Fig. 5C and Table 3). For example,  
189 when the entire cirque data set is considered, Fourier (harmonic) regression reveals that cirques facing  
190  $170^\circ$  (SSE) have floor altitudes that are typically 163 m higher than those facing  $350^\circ$  (NNW) (Fig.  
191 5C). Though a comparatively low proportion of variance is accounted for through this regression ( $r^2 =$   
192  $0.03$ ), the relationship is highly significant ( $p < 0.001$ ). The trend of lower floor altitudes for north-  
193 facing cirques is consistent for all populations of cirques on the Peninsula, though some have cirque  
194 floor altitude minima toward the NNW and some toward the NNE (see Fig. 5C and Table 3).

195

196 [Approximate location of Table 3]

197

#### 198 **4.4. Cirque floor altitudes relative to the modern coastline**

199 When the entire Kamchatkan cirque data set is considered, cirque floor altitudes appear to increase  
200 inland with distance from the modern coastline (see Fig. 5D and Table 4). When distance from the



201 modern Pacific coastline alone is considered, this relationship is maintained (Fig. 5E and Table 4).  
202 However, when distance from the modern Okhotsk coastline alone is considered, an overarching,  
203 statistically significant relationship is not apparent (Fig. 5F and Table 4). Regional variations in these  
204 relationships are also notable. For example, some populations (e.g., in the NW Sredinny) show no  
205 statistically significant relationships (see Table 4).

206 [Approximate location of Table 4]

207

## 208 **5. Controls on cirque floor altitudes**

209 Here, potential controls on cirque floor altitudes across the Kamchatka Peninsula are considered, with  
210 a specific focus on the controls exerted by climate, topography, geology (lithology), tectonics, and  
211 volcanic activity.

212

### 213 **5.1. Climatic controls on cirque floor altitudes**

214 The role of palaeoclimate in regulating cirque floor altitudes on the Kamchatka Peninsula is assessed  
215 through consideration of cirque latitude (Fig. 5A), aspect (Fig. 5C), and distance to the modern  
216 coastline (Figs. 5D–F). These factors are analysed on the assumption that they are proxies for  
217 palaeoclimate. In a very general sense, latitude is considered a proxy for palaeotemperature—based  
218 on the consideration that glaciers can develop, and thereby generate cirques, at lower altitudes as  
219 latitude increases (i.e., as mean annual air temperature decreases). Aspect is considered a proxy for  
220 local climatic conditions. Specifically, direct solar radiation and/or variations in prevailing wind  
221 direction. This is based on the following assumptions: (i) glaciers can develop, and thereby generate  
222 cirques, at lower altitudes on poleward-facing slopes where the total receipt of direct solar radiation is  
223 minimised (see Evans, 1977); (ii) low altitude glaciers can also form, and thereby generate cirques, on  
224 slopes that have an aspect deflected slightly east of poleward, because these slopes receive much of  
225 their direct solar radiation in the morning when air temperatures are relatively low and ablation is  
226 therefore limited (this is referred to as the morning:afternoon effect); (iii) low altitude glaciers can  
227 form, and thereby generate cirques, on slopes with other aspects in situations where prevailing winds

228 lead to the accumulation and preservation of snow and ice on leeward slopes (see Evans, 1977, 1990).  
229 Distance to the modern coastline is considered a proxy for palaeoprecipitation. This is based on the  
230 assumption that (i) the formation of low altitude glaciers and their cirques often depends on relatively  
231 high winter precipitation (i.e., snowfall); (ii) as at present (see Fig. 4), moisture availability during  
232 periods of cirque development was strongly controlled by proximity to the coastline; (iii) the position  
233 of the modern coastline could be considered broadly representative of conditions during periods of  
234 cirque formation (i.e., when they were occupied by cirque glaciers), as supported by the fact that even  
235 during periods of full glaciation (e.g., at the LGM when eustatic sea level was lowered by 130 m and  
236 the peninsula was covered by a series of ice fields) the peninsula's overall shape varied little from  
237 present (see Fig. 1).

238         Though we make this simple subdivision between different cirque attributes and the climatic  
239 conditions they potentially reflect, it appears (Fig. 4) that this is an oversimplification in some cases  
240 (e.g., precipitation also varies with latitude, although to a minor extent when compared to  
241 temperature, and temperature also varies with distance from the coastline, although to a minor extent  
242 than precipitation; see Fig. 4). Despite this, these divisions provide a framework for discussing the  
243 relative importance of different factors in regulating cirque floor altitudes on the Kamchatka  
244 Peninsula. This is discussed below, with a distinction made between interior and coastal cirque  
245 populations.

#### 246 247 **5.1.1. Interior populations**

248 The interior populations of cirques comprise those of the NW, central, SW, and SE Sredinny  
249 Mountains. These populations are defined by their considerable distance from the modern coastline  
250 and by the fact that proximity to the North Pacific is not the clear dominant control on cirque altitudes  
251 (i.e., regional climate is not dominated by air masses from the North Pacific).

252         In the NW Sredinny Mountains, the only factor showing a statistically significant relationship  
253 with cirque floor altitudes is aspect. This is emphasised in Table 5, where a series of models are used  
254 to predict cirque floor altitudes across the peninsula. In the NW Sredinny, floor altitudes are typically

255 lowest for NE-facing (23°N) cirques (see Table 3). This trend might indicate that aspect-related  
256 variations in direct solar radiation have had an impact on the altitude at which former glaciers have  
257 developed. Alternatively, the trend might reflect prevailing winds from the south or west during  
258 former periods of glaciation allowing comparatively low altitude cirques to preferentially develop on  
259 NE-facing slopes. The lack of any clear relationship between cirque floor altitudes and proximity to  
260 the sea or ocean might reflect comparatively limited variability in cirque distance from the coastline in  
261 this area where the peninsula is comparatively narrow (i.e., cirque distance to the coastline ranges by  
262 81 km, relative to a mean of 103 km for all other regions). Alternatively, the lack of any clear  
263 relationship between cirque floor altitudes and proximity to the sea or ocean might indicate that the  
264 development of former glaciers in this region was largely dictated by controls on ablation (i.e., air  
265 temperatures and total direct solar radiation). The region is currently one of the most arid in  
266 Kamchatka (see Figs. 4A-D), and this aridity is intensified during winter months (i.e., during the  
267 accumulation season) when the Sea of Okhotsk is occupied by sea ice (see Fig. 4D). Aridity in this  
268 region was likely intensified during former periods of glaciation, as glaciers along the Pacific coast of  
269 Kamchatka intercepted moisture-bearing winds from the North Pacific and the extent and duration of  
270 ice in the Okhotsk Sea increased. Former aridity in the NW Sredinny may have limited widespread  
271 cirque development to areas where ablation was minimal (i.e., on slopes with NE aspects). Aridity  
272 may also explain why cirques in this region have comparatively high minimum floor altitudes (i.e.,  
273 the lowest cirque floor is 570 m asl), as restricted accumulation prevented the development of low  
274 altitude glaciers.

275 In the central Sredinny Mountains, cirque floor altitudes show statistically significant  
276 relationships with latitude, aspect, and distance to the Okhotsk coastline. However, the two most  
277 important components, as suggested by the lowest root mean square error (RMSE) of a series of tested  
278 models, are cirque latitude and aspect (see Table 5). Floor altitudes are typically lowest for NW-  
279 facing (351°N) cirques (see Table 3), potentially indicating that, though the altitudes at which former  
280 glaciers were able to initiate (and thereby form cirques) were not strongly controlled by moisture  
281 availability (i.e., a strong relationship with distance to the modern coastline is not apparent),

282 prevailing winds from the east of south may have allowed glaciers to develop at lower altitudes on  
283 leeward (NW-facing) slopes. These prevailing winds may have brought moisture to the eastern coast,  
284 which would have been largely intercepted by the Vostochny Mountains (see Barr and Spagnolo,  
285 2014), thus keeping the central sector of the Sredinny Range comparatively moisture starved and,  
286 hence, the higher cirque floor altitudes here.

287 In the SW Sredinny Mountains, cirque floor altitudes show statistically significant  
288 relationships with latitude, aspect, and distance to the Okhotsk coastline; and the model that best fits  
289 the observed data (i.e., with the lowest RMSE) is based on a regression of all three of these variables  
290 (see Table 5). Interestingly, cirque floor altitudes appear to increase with latitude (see Table 2). This is  
291 counter to what might be expected if latitudinal variations in temperature exerted a control on cirque  
292 altitudes. In fact, the trend likely reflects covariance between distance to the Okhotsk coastline and  
293 latitude in this region, with proximity to the coastline increasing with decreasing latitude ( $r^2 = 0.65$ ;  $p$   
294  $< 0.001$ ). This indicates that the former has a stronger influence on cirque floor altitudes than the  
295 latter, and a regression model based on cirque aspect and distance to the Okhotsk coastline alone  
296 might be favoured (see Table 5). Aspect-wise, floor altitudes are typically lowest for NNE-facing  
297 ( $13^\circ\text{N}$ ) cirques (see Table 3), potentially indicating that the morning:afternoon effect had an impact on  
298 the altitude at which former glaciers were able to develop and thereby erode cirques.

299 In the SE Sredinny Mountains, cirque floor altitudes show statistically significant  
300 relationships with latitude, aspect, and distance to the Pacific coastline. Again (as in the SW  
301 Sredinny), cirque floor altitudes appear to increase with increasing latitude (see Table 2), and latitude  
302 and distance to the Pacific coastline covary ( $r^2 = 0.93$ ;  $p < 0.001$ ), suggesting that latitude specifically  
303 is unlikely to regulate cirque floor altitudes. In fact, the model that best fits the observed data is based  
304 on a regression of cirque aspect and distance to the Pacific coastline alone (see Table 5). Floor  
305 altitudes are lowest for cirques facing a little W of N ( $352^\circ\text{N}$ ), potentially reflecting the role of  
306 prevailing winds from the east (between NNE and SSE).

307

### 308 **5.1.2. Coastal populations**

309 The coastal populations of cirques comprise those of the NE Sredinny Mountains and Vostočny/EVP  
310 region. Both populations have cirque floor altitudes that show statistically significant relationships  
311 with latitude, aspect, and (in particular) distance to the Pacific coastline (see Table 5). However, the  
312 apparent relationship between cirque floor altitudes and latitude in these coastal populations is likely  
313 to reflect a covariance between latitude and distance to the Pacific coastline (with  $r^2$  values of 0.11  
314 and 0.12, respectively;  $p < 0.001$ ). The RMSE derived using all three variables is only slightly lower  
315 (~ 7% and ~ 2% lower, for the NE Sredinny and Vostočny/EVP, respectively) than when based on  
316 distance to the modern Pacific coastline alone—likely reflecting the dominance of proximity to the  
317 coastline (regulating moisture availability) as a control on the altitudes at which former glaciers were  
318 able to initiate and thereby erode cirques (see Table 5). The importance of moisture availability and  
319 the supply of moisture from the North Pacific are emphasised by the fact that the lowest-lying cirques  
320 in the entire data set are present in these coastal populations (i.e., cirques are found more than 300 m  
321 below those in other populations) (see Fig. 3 and Table 1). In these coastal populations, floor altitudes  
322 are typically lowest for NW-facing cirques (with aspects of 317 and 346°N for the NE Sredinny and  
323 Vostočny/EVP, respectively), and in fact, these regions show notably large aspect-related variations in  
324 cirque floor altitudes when compared to interior populations (see alt range in Table 3). This would  
325 support the notion that winds from the North Pacific, to the SE, not only brought moisture to allow  
326 glacier development in coastal areas but also promoted the growth of comparatively low altitude  
327 glaciers on slopes that were in the lee of these prevailing winds.

328

### 329 **5.1.3. Climatic controls on cirque floor altitudes across the peninsula as a whole**

330 Despite regional variations (outlined in sections 5.1.1 and 5.1.2), when the entire data set of cirques  
331 across the Kamchatka Peninsula is considered, floor altitudes show statistically significant  
332 relationships with latitude, aspect, and distance to the modern coastline (see Tables 2, 3, and 4).  
333 However, evidence suggests that the relationship between latitude and cirque floor altitude can often  
334 be explained by covariance with distance to the modern coastline (see Table 2). There is clear  
335 evidence that aspect has played a role in regulating the altitude at which former glaciers have been

336 able to initiate (see Fig. 5C and Table 3) and thereby generate cirques, with north-facing slopes  
337 allowing the development of comparatively low altitude glaciers (see Fig. 5C). Despite this, the  
338 regression model that best fits all observed cirque floor altitudes across the peninsula is based on  
339 distance to the modern Pacific coastline alone (a model based on regression of all of three variables  
340 has an ~ 11% greater RMSE) (see Table 5). The strength of this relationship appears to indicate that  
341 moisture availability played a key role in regulating the altitude at which glaciers were able to develop  
342 and erode cirques. This is supported by the fact that when distance to the modern coastline and  
343 distance to the modern Pacific coastline are considered (Figs. 5D and 5E), there is not only a general  
344 increase in cirque floor altitudes inland, but also an increase in the minimum altitude at which cirques  
345 are found. This would appear to suggest a palaeoglaciation level (see Evans, 1990; Mîndrescu et al.,  
346 2010) below which glaciers have been unable to initiate and thereby generate cirques (perhaps driven  
347 by precipitation gradients). The importance of proximity to the North Pacific, rather than the Sea of  
348 Okhotsk, likely reflects the fact that, as at present during former periods of cirque-type glaciation, this  
349 was the dominant source of moisture/precipitation to much of the peninsula, particularly during winter  
350 months (i.e., during the accumulation season) (see Figs. 4C and 4D), most likely because the Okhotsk  
351 was largely covered by sea ice.

352

353 [Approximate location of Table 5]

354

## 355 **5.2. Topographic controls on cirque floor altitudes**

356 Cirque altitudes in a given region are partly controlled by mountain altitudes, with high altitude  
357 glaciers only able to initiate, and thereby generate high altitude cirques, where high altitude  
358 topography exists. As a result, the inland increase in cirque floor altitudes seen across the Kamchatka  
359 Peninsula (Figs. 5D and 5E) could reflect the absence of high altitude topography in coastal areas  
360 (rather than reflecting a climatic trend). For example, such topographic gradients have been found to  
361 partly explain cirque floor altitude trends in Scandinavia (Hassinen, 1998) and Tasmania (Peterson  
362 and Robinson, 1969), though in both cases palaeoprecipitation gradients are considered the dominant

363 control (see section 5.5). However, across the Kamchatka Peninsula an overall topographic trend  
364 inland is not apparent (see Fig. 6), and in fact, the maximum and mean topography along the Pacific  
365 coast of Kamchatka often extends well above cirque floor altitudes, with volcanic peaks (active and  
366 inactive) extending up to 2500 m above local cirque floor altitudes (Fig. 6). Thus, variation in  
367 topography is not considered to explain the overall trends in cirque floor altitudes across Kamchatka,  
368 though topography undoubtedly has some influence at a regional scale. For example, some high  
369 altitude, cirque-free peaks and ridges across the peninsula are too steep or have too little  
370 accommodation space to have allowed erosive, cirque-forming glaciers to develop (see Barr and  
371 Spagnolo, 2014). Aspect-related differences in floor altitudes between cirque populations to the east  
372 and west of the Sredinny Mountains might partly reflect a structural/topographic control on the  
373 altitudes at which former glaciers were able to initiate. However, even on different sides of the central  
374 mountain divide, ridges occupied by cirques show a range of orientations (see Fig. 1), giving little  
375 reason to believe that such structural control can explain these overarching trends.

376

377 [Approximate location of Fig. 6]

378

### 379 **5.3. Geological controls on cirque floor altitudes**

380 Because cirque formation is limited to regions where lithology has ‘allowed’ bedrock to be eroded  
381 into bowl-shaped hollows, regional variations in bedrock erodibility can potentially influence cirque  
382 shape (see Delmas et al., 2014, 2015) and altitude (see Mîndrescu and Evans, 2014). However, Barr  
383 and Spagnolo (2013) used a one-way analysis of variance (ANOVA) to estimate the variability in  
384 cirque floor altitudes accounted for by differences in lithology on the Kamchatka Peninsula and found  
385 little evidence for any significant relation between variables.

386

### 387 **5.4. Tectonic and volcanic controls on cirque floor altitudes**

388 As noted in section 2.1, the Kamchatka Peninsula lies close to the Kuril-Kamchatka trench, where the  
389 North Pacific plate actively subducts beneath the Eurasian plate at a rate of  $\sim 79 \text{ mm y}^{-1}$  (DeMets et

390 al., 1990; Bindeman et al., 2010). Because of this proximity, much of the peninsula is tectonically  
391 active, with uplift and deformation taking place during the past 70 Ma (Fedotov et al., 1988). In  
392 particular, Quaternary uplift should be taken into consideration when analysing cirque floor altitudes  
393 across the region, as uplift can result in cirques being displaced from altitudes at which they were  
394 formed (see Bathrellos et al., 2014). However, direct estimates of Quaternary vertical displacements  
395 on the Kamchatka Peninsula are scarce. Currently available estimates are listed in Table 6 and show  
396 regional variability; but based on visual comparison, there appear to be no systematic trends that  
397 might explain the patterns in cirque floor altitudes identified in the present study. In general the only  
398 systematic orographic trend across the peninsula is that mountain complexes become younger from  
399 west to east, reflecting the eastward migration of the Kurile-Kamchatka trench and associated  
400 volcanic front since the late Eocene. Despite this, there is little evidence that the age of each massif  
401 has had significant impact on cirque floor altitudes, as they show little systematic variation with  
402 distance from the modern Kurile-Kamchatka trench. This might indicate that the peninsula's cirques  
403 were formed during the late Quaternary, once periods of large-scale mountain building were  
404 complete.

405         Quaternary volcanic activity on the Peninsula has undoubtedly had (and continues to have) an  
406 impact on the dynamics of the region's glaciers (see section 6.3, in Barr and Solomina, 2014) through  
407 geothermal activity, eruptions, and tephra cover (ash blanketing). However, a lack of detailed  
408 understanding of volcanic activity on the peninsula during the last glaciation (c.f. Ponomareva et al.,  
409 2007) means that we are currently unable to account for these factors (particularly when considering  
410 impacts on cirque distribution). Despite this, most of these effects are expected to be relatively local  
411 and are unlikely to show geographical trends comparable to those found for cirque floor altitudes.

412

413 [Approximate location of Table 6]

414

## 415 **5.5. A global comparison**



416 As noted in section 1, controls on cirque floor altitudes are rarely assessed within the published  
417 literature. Despite this, a number of studies have analysed cirque floor altitudes across specific regions  
418 (e.g., Linton, 1959; Davies, 1967; Derbyshire, 1963; Peterson and Robinson, 1969; Hassinen, 1998;  
419 Evans, 1999; Anders et al., 2010; Principato and Lee, 2014) and at a near-global scale (e.g., Mitchell  
420 and Humphries, 2015). A common trend is that cirque floor altitudes are found to vary considerably,  
421 even within single mountain ranges (see Flint, 1957; Anders et al., 2010). At a global scale (i.e., when  
422 a comparison is made between different study regions), cirque floor altitudes are found to decrease  
423 with increasing latitude (see Mitchell and Humphries, 2015), though identifying such trends within  
424 specific regions is more difficult (see Evans, 1999). Cirque floor altitudes are also often found to vary  
425 as a function of cirque aspect, with poleward-facing cirques found at lower altitudes than those on less  
426 climatically favourable (in terms of glacier growth and survival) slopes (see Evans, 2006a). However,  
427 though this trend is found in a number of mountain ranges globally (see Evans, 2006c) and applies to  
428 modern glaciers (see Evans and Cox, 2005; Evans, 2006b,c, 2011), it is not ubiquitous (see Evans and  
429 Cox, 1995; Evans, 1999). Another characteristic common to many cirque populations globally is that  
430 floor altitudes are found to increase inland (e.g., Peterson and Robinson, 1969; Hassinen, 1998;  
431 Principato and Lee, 2014). In many cases, this is attributed to the role of precipitation in regulating the  
432 altitude of former glaciers, though the potential influence of other, nonclimatic, factors is also  
433 recognised (see Peterson and Robinson, 1969; Hassinen, 1998; Principato and Lee, 2014). For  
434 example, in SW Tasmania, Peterson and Robinson (1969) found evidence of an inland increase in  
435 cirque floor altitudes, and attribute this to an inland palaeoprecipitation gradient. However, they also  
436 recognised that, because cirque floor altitudes follow the overall topographic trend, other factors  
437 including spatial variability in topography, lithology, and structure may partly explain observed  
438 trends. Similarly, across northern Scandinavia, Hassinen (1998) found cirque floor altitudes to  
439 increase inland along a 210-km transect. This was attributed to an inland decrease in  
440 palaeoprecipitation combined with the influence of topography (i.e., the heights of the local  
441 mountains gradually increase inland but at a slower rate than cirque floor altitudes).

442 Thus, when cirque floor altitudes in other populations globally are considered, many of the  
443 trends identified in the present study are observed. Specifically: (i) though there is evidence for  
444 latitudinal control on cirque floor altitudes at a global scale, clear trends are often difficult to identify  
445 within individual study regions; (ii) cirque floor altitudes are typically lower on climatically  
446 favourable (often poleward-facing) slopes, though this trend is not ubiquitous; (iii) cirque floor  
447 altitudes often increase inland; (iv) spatial variability in topography, lithology, and structure may  
448 partly explain observed trends in cirque floor altitudes, but the influence of such controls is often  
449 difficult to unambiguously identify.

450

## 451 **6. Comparison with modern glaciers**

452 In section 5.1, it is suggested that cirque floor altitudes across the Kamchatka Peninsula primarily  
453 reflect climatic controls on the altitudes at which former glaciers were able to initiate. This assertion  
454 can be tested, to some degree, by considering the altitudes of modern glaciers. To this end, we have  
455 estimated the mid-altitude (mid-alt) (i.e., the average of the highest and lowest altitude—following  
456 Evans and Cox, 2005; Evans, 2006c) of 503 glaciers identifiable from satellite images (Landsat 8)  
457 across the Kamchatka Peninsula (see Fig. 2). A number of these glaciers, particularly the larger ones,  
458 with highest mid-altitudes, occupy active and inactive volcanoes; and their dynamics are partly  
459 controlled by this volcanic setting (Barr and Solomina, 2014). Others ( $n = 361$ ) are typical cirque  
460 glaciers that have likely experienced limited volcanic control because of their comparatively restricted  
461 extent.

462

### 463 **6.1. Trends in modern glacier mid-altitudes**

464 Modern glaciers on the Kamchatka Peninsula are distributed throughout the region's principle  
465 mountain groups (i.e., ~ 13% in the NW Sredinny; ~ 32% in the NE Sredinny; ~ 3% in the Central  
466 Sredinny; ~ 11% in the SW Sredinny, ~ 10% in the SE Sredinny; and ~ 31% in the Vostočny/EVP  
467 region). However, regional analysis of glacier mid-altitudes in a way that might be compared to cirque  
468 floor altitudes is not possible as some regions currently contain very few glaciers (e.g., in the central

469 Sredinny,  $n = 15$ ). When the entire data set is considered, glacier mid-altitudes range from 496 to  
470 2970 m (asl) (Fig. 2) and rise from the north and from the south (see Fig. 7A and Table 7). When  
471 cirque-type glaciers alone are considered, this relationship strengthens (Fig. 7A and Table 7). Glacier  
472 mid-altitudes are typically lowest where glacier accumulation area aspect (taken as the mean aspect of  
473 each glacier's upper half—i.e., above the mid-altitude) is  $311^\circ$  (190 m lower than at  $131^\circ$ ) (Fig. 7B)—  
474 a relationship significant at the 0.01 level (see Table 7). A similar outcome was obtained by Evans  
475 (2006c) who analysed the 398 Kamchatkan glaciers reported by the World Glacier Inventory. When  
476 cirque-type glaciers alone are considered, the relationship between altitude and aspect strengthens  
477 slightly, with glacier altitudes typically lowest where accumulation area aspect is  $272^\circ$ , though this  
478 relationship is only significant at the 0.05 level (see Fig. 7B and Table 7). Glacier mid-altitude  
479 increases with distance to the modern coastline (Fig. 7C) ( $r^2 = 0.36$ ,  $p < 0.001$ ). This relationship is  
480 maintained when distance to the Pacific coastline alone is considered ( $r^2 = 0.36$ ,  $p < 0.001$ ) (Fig. 7D)  
481 but is statistically insignificant with distance to the Okhotsk coastline. Similar, but slightly stronger,  
482 trends are found when cirque-type glaciers alone are considered (see Fig. 7 and Table 7).

483

484 [Approximate location of Table 7]

485

## 486 **6.2. Comparing modern glaciers and glacier-free cirques**

487 Given the data in Tables 2, 3, 4, and 7, it is apparent that trends in glacier mid-altitudes and cirque  
488 floor altitudes across the Kamchatka Peninsula are comparable (i.e., values typically rise from the  
489 north and from the south, inland from the Pacific coastline, and where glaciers/cirques are SE-facing).  
490 Despite this, there are also some notable differences in the strength of these relationships.  
491 Specifically, when glaciers are considered, the relationship with distance to the modern coastline (and  
492 to a lesser degree aspect) is notably weaker. This is demonstrated by the fact that the regression model  
493 that best fits glacier mid-altitudes across the peninsula is based on glacier latitude, aspect, and  
494 distance to the modern coastline (see Table 8); whereas the model that best fits all of the observed  
495 cirque floor altitudes is only based on distance to the modern Pacific coastline (see Table 5). Here we

496 consider three hypotheses to explain these differences. **Hypothesis 1:** present-day glaciers are not  
497 comparable to former cirques because of their varying size and type. Despite this, even when the  
498 study is limited to present-day cirque glaciers (i.e., excluding those draped over volcanic peaks),  
499 differences are still identifiable. In particular, considering cirque-type glaciers alone reduces the  
500 difference between glaciers and cirques with respect to the distance from modern coastline but  
501 accentuates the difference with respect to latitude (see Table 7). **Hypothesis 2:** unlike cirque floor  
502 altitudes, glacier mid-altitudes are not a good proxy for climate. Theoretically, snowline altitudes (a  
503 surrogate for ELA) of modern glaciers could represent a much better climatically controlled  
504 parameter, assuming glaciers are in equilibrium with climate. However, snowline data are only  
505 available for 137 Kamchatkan glaciers (from the WGMS and NSIDC, 2012) and are very similar to  
506 glacier mid-altitude estimates (i.e., the RMSE between mid-altitude and snowline estimates is 137 m,  
507  $r^2 = 0.89$ ). As a result, replacing mid-altitude estimates with snowline estimates has very little impact  
508 on the strength or pattern of resulting trends. **Hypothesis 3:** on the Kamchatka Peninsula, former  
509 glacier initiation (cirque development) was more strongly controlled by climate than is the case for  
510 (present-day) glacier survival (i.e., cirque-forming glaciers were likely in climatic equilibrium,  
511 whereas modern glaciers may not be). In particular, the altitude at which former glaciers were able to  
512 initiate (and thereby where cirques are found) was largely governed by moisture availability during  
513 winter months and its impact on accumulation (hence the strong association between cirque floor  
514 altitudes and distance to the modern coastline). By contrast, the current distribution of glaciers is also  
515 strongly controlled by the variety of factors that limit ablation and promote glacier survival under  
516 comparatively unfavourable climatic conditions: specifically, low summer air temperatures (hence the  
517 comparatively strong relationship between cirque floor altitudes and latitude) and local topoclimatic  
518 factors (such as topographic shading). Hence, evidence suggests one dominant control on glacier  
519 initiation but multiple controls on glacier survival.

520

521 [Approximate location of Table 8]

522

523 **7. Conclusions**

524 In this paper, controls on the altitudinal distribution of 3520 cirques and 503 modern glaciers across  
525 the Kamchatka Peninsula are considered. The main study findings can be summarised as follows:

526

- 527 • When the peninsula is considered as a whole, the dominant control on cirque floor altitudes is  
528 proximity to the Pacific, with values increasing steeply inland from the modern coastline.  
529 This pattern would appear to indicate that moisture availability was key in regulating where  
530 former glaciers were able to initiate and thereby erode cirques; and that the North Pacific was,  
531 and in fact still is, the dominant source of moisture to much of the region (particularly during  
532 the accumulation season).
- 533 • Other factors, such as latitude, topography, geology, tectonics, and volcanic activity seem to  
534 have played a limited role in regulating cirque floor altitudes across the peninsula; though  
535 there is a statistically significant and consistent relationship with aspect (with south-facing  
536 cirques typically having higher floors than north-facing equivalents). This trend reflects the  
537 impact of variations in solar radiation, and probably prevailing wind directions, on the altitude  
538 at which former glaciers were able to develop.
- 539 • Despite peninsula-wide trends, a distinction is made between interior and coastal populations,  
540 with distance to the coastline having the strongest influence on the latter.
- 541 • The mid-altitudes of modern glaciers on the peninsula appear to reflect variations in latitude,  
542 aspect, and proximity to the modern coastline. In general, trends in glacier and cirque  
543 altitudes are comparable (i.e., values typically rise from the north and from the south, inland  
544 from the Pacific coastline, and where glaciers/cirques are south-facing), yet the relationship  
545 with distance to the modern coastline (and to a lesser degree aspect) is weaker for modern  
546 glaciers.
- 547 • Apparent differences between controls on cirque and glacier altitudes across the peninsula  
548 may indicate that while former glacier initiation (leading to cirque formation) was largely  
549 regulated by controls on accumulation (i.e., the availability of snow and ice during winter

550 months); the survival of modern glaciers is also regulated by the variety of climatic and  
551 nonclimatic factors that control ablation, meaning that relationships between modern glaciers  
552 and peninsula-wide climatic trends are more difficult to identify.

553

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558

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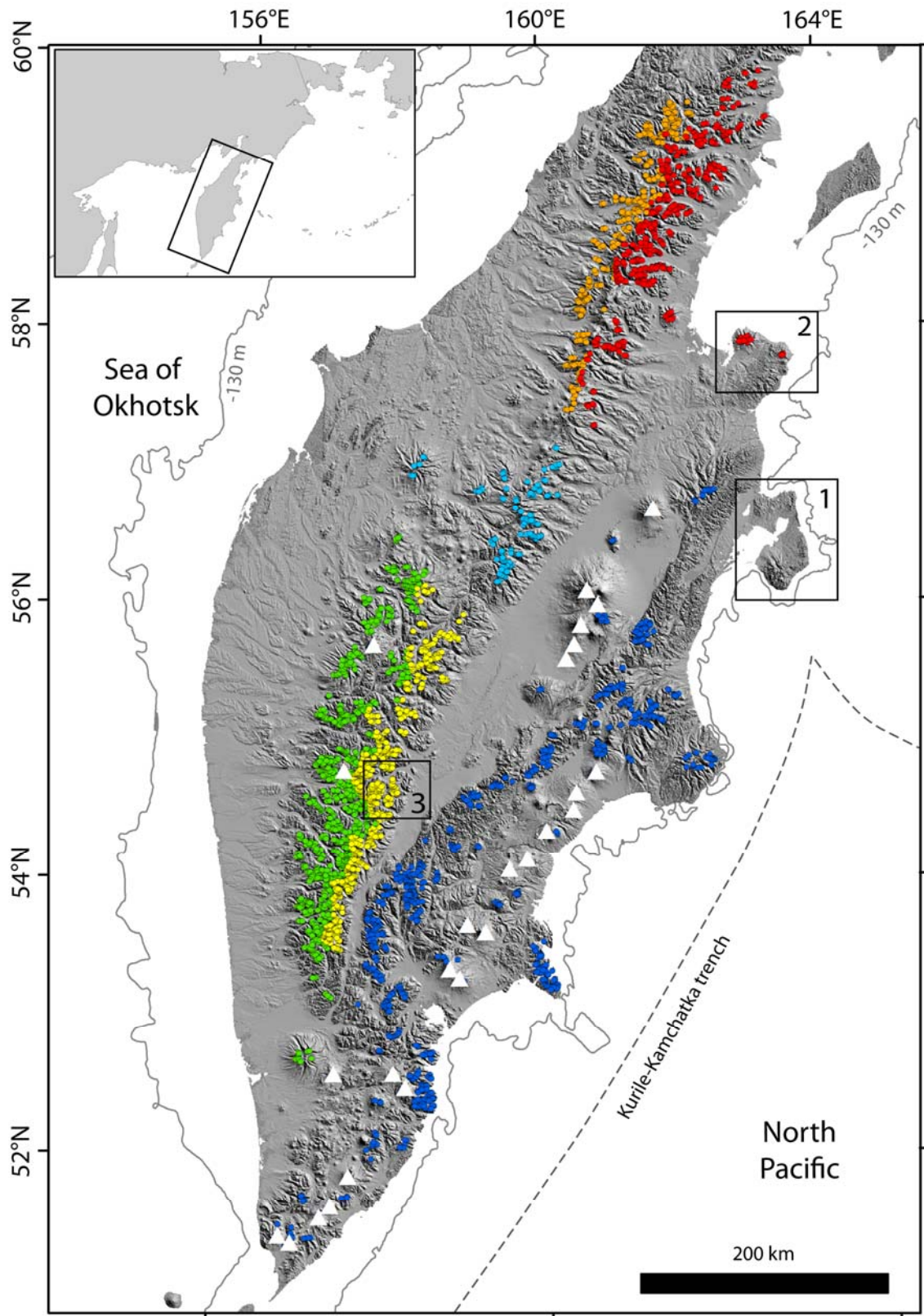
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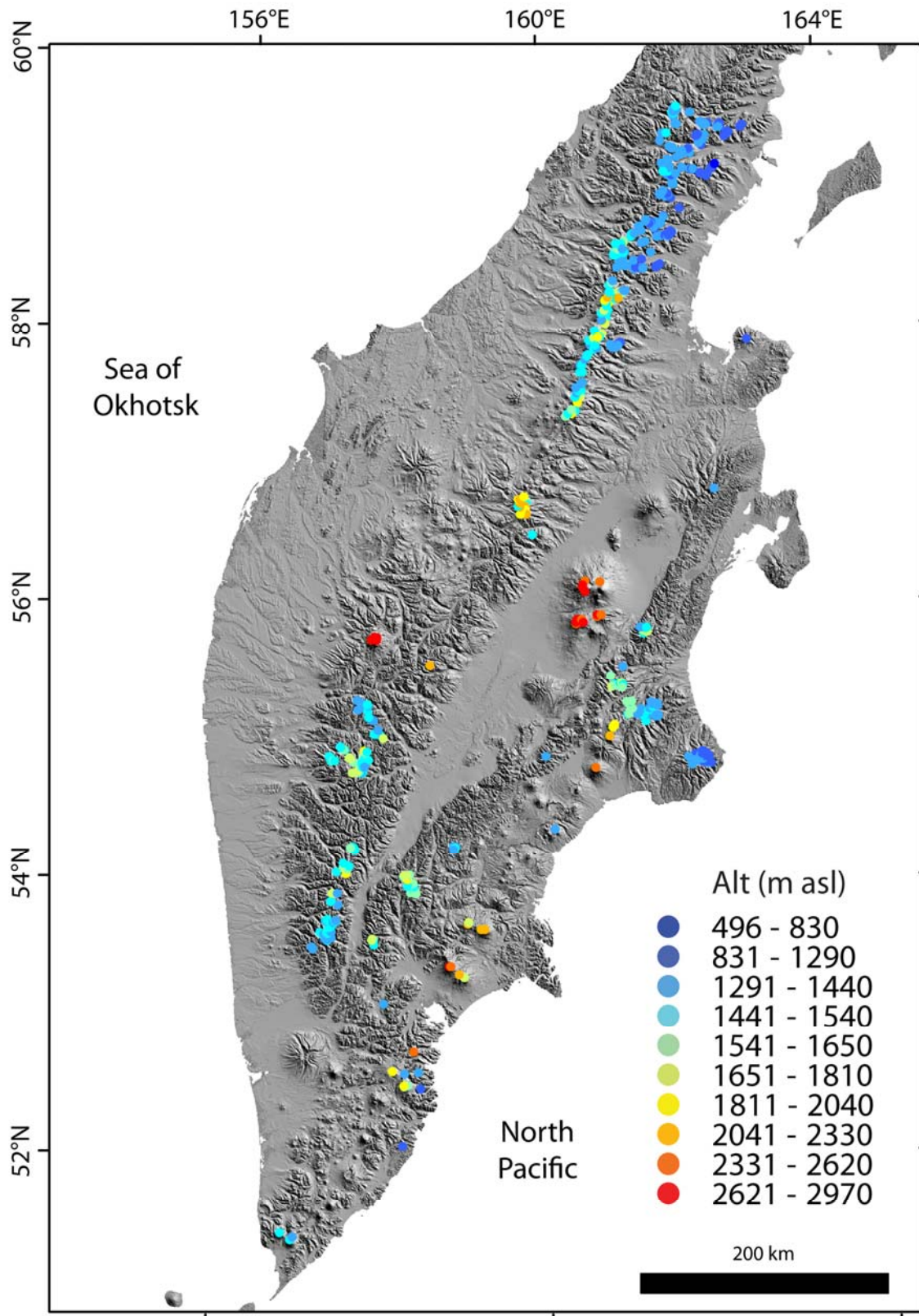
777 **Figures:**



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 779 Fig. 1. Shaded relief map of the Kamchatka Peninsula. In this image, mapped cirques are shown as  
 780 points, coloured according to region: NW Sredinny (orange), NE Sredinny (red), central Sredinny

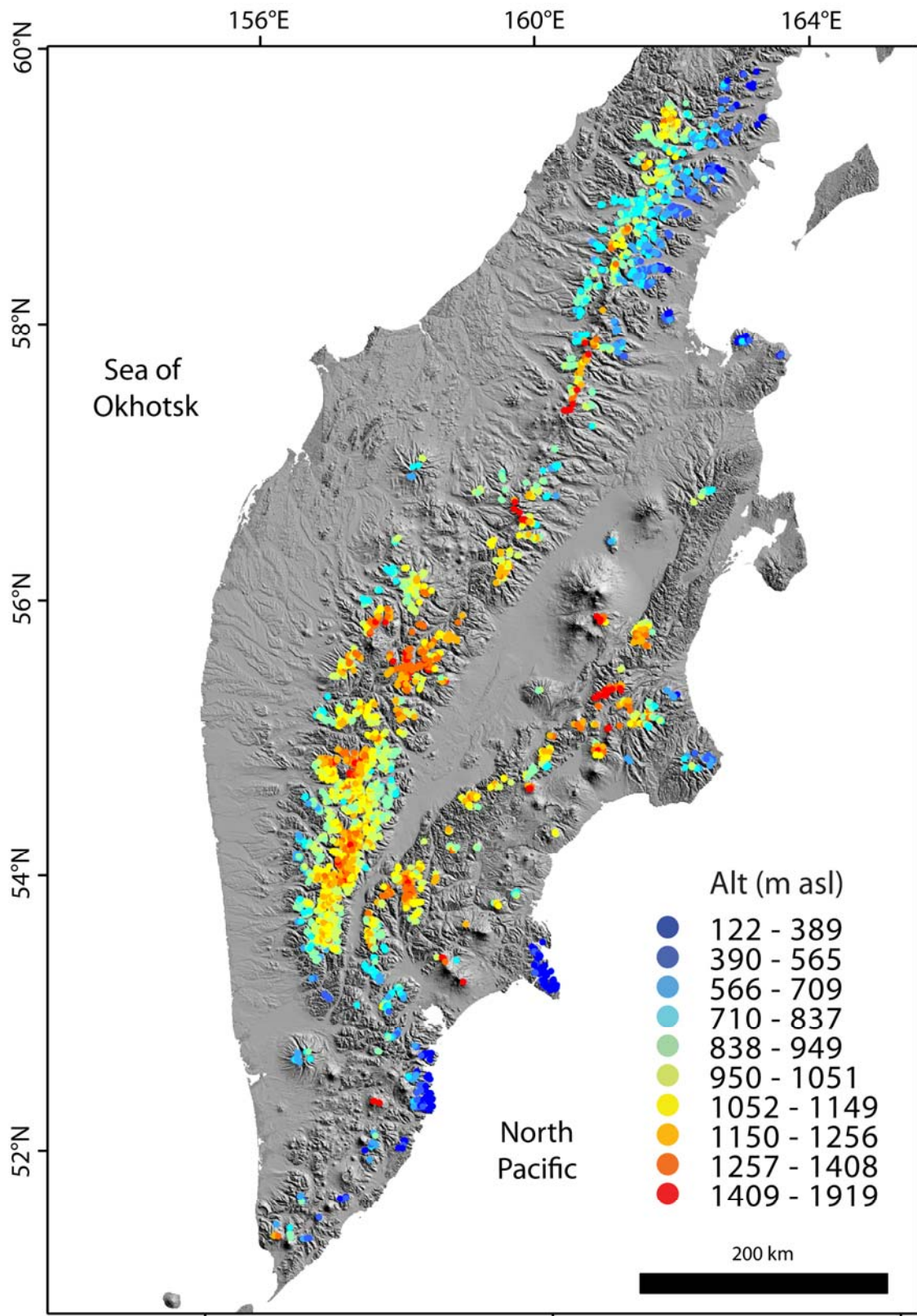
781 (light blue), SW Sredinny (green), SE Sredinny (yellow), Vostočny and EVP (dark blue). Also shown  
782 are active volcanoes (white triangles) (from Avdeiko et al., 2007) and the LGM coastline (given a 130  
783 m lowering of sea level relative to present). Boxed areas 1–3 are referred to in Table 6.  
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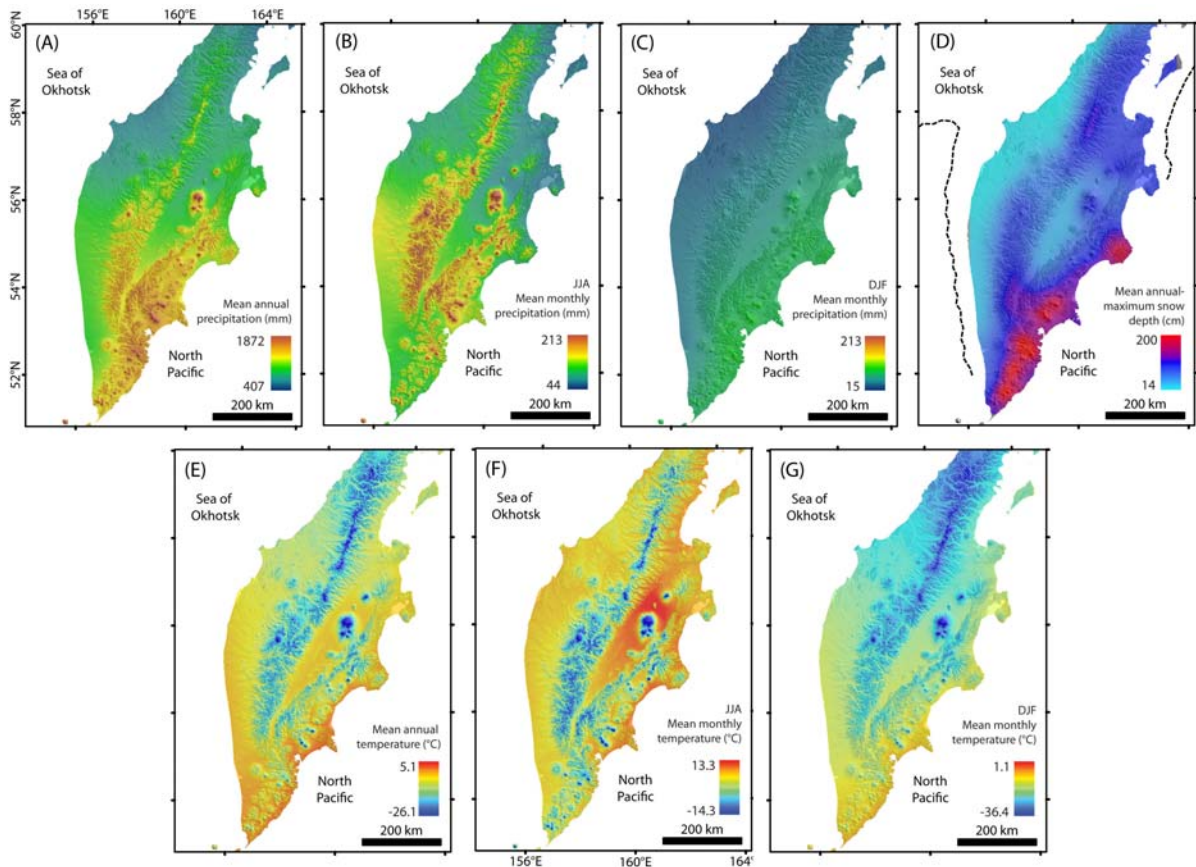
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Fig. 2. Modern glaciers on the Kamchatka Peninsula, coloured according to their mid-altitudes.



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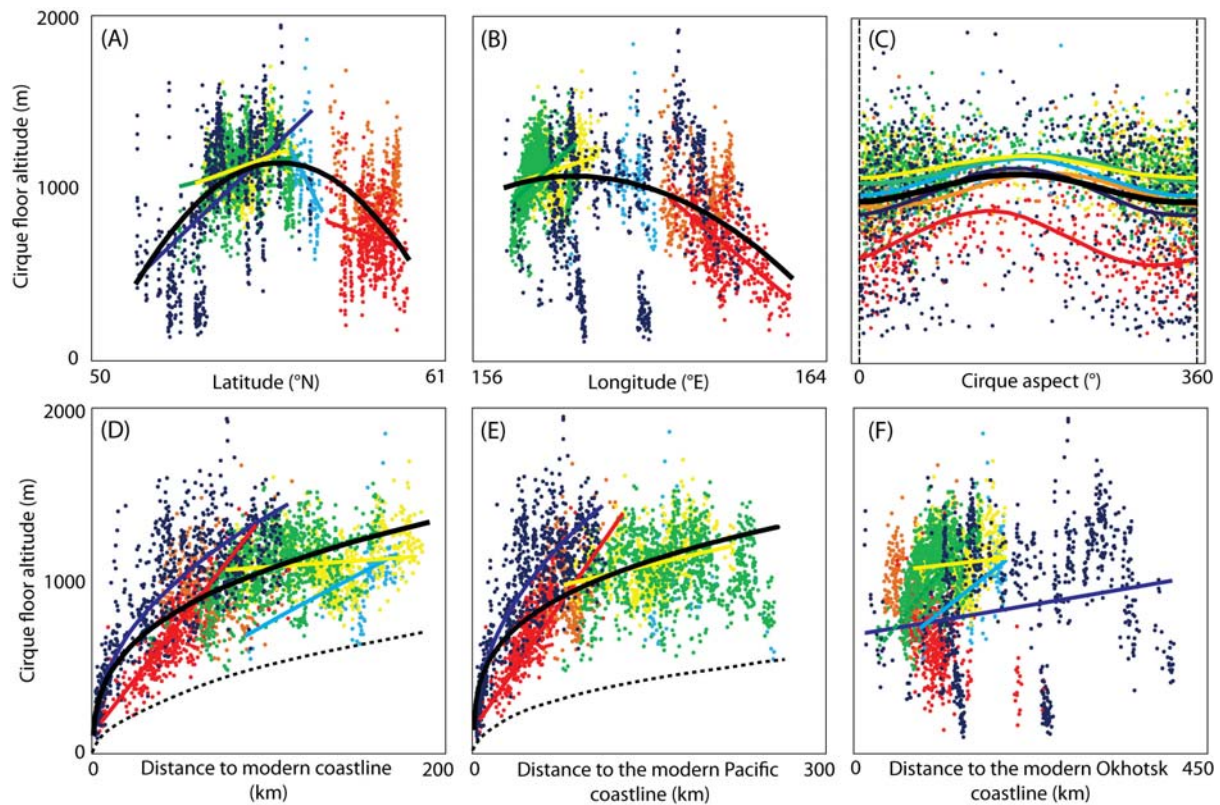
790 Fig. 3. Cirques on the Kamchatka Peninsula, coloured according to their floor altitudes.



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 792 Fig. 4. Modern climatic conditions across the Kamchatka Peninsula. (A) Mean annual precipitation.  
 793 Mean monthly precipitation during (B) June, July, August (JJA) and (C) December, January, February  
 794 (DJF). (D) Mean annual-maximum snow depth for the 1961-1990 period. The dashed line here  
 795 reflects the median sea ice extent during February (when sea ice is most extensive) for the 1979-2000  
 796 period (data from Fetterer et al., 2002). (E) Mean annual temperature. Mean monthly temperature  
 797 during (F) JJA and (G) DJF. Precipitation and temperature data are from regional climate grids  
 798 produced through interpolation between weather station data for the 1950-2000 period (see Hijmans et  
 799 al., 2005). The snow depth map (D) is produced through interpolation of data presented by  
 800 Matsumoto et al. (1997).

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803 Fig. 5. Variations in cirque floor altitudes on the Kamchatka Peninsula, with (A) latitude; (B)

804 longitude; (C) median axis aspect (analysis based on first-order Fourier regression, see Evans and

805 Cox, 2005); (D) distance to the modern coastline (either the Pacific Ocean or the Okhotsk Sea,

806 depending on which is the closer); (E) distance to modern Pacific coastline; and (F) distance to

807 modern Okhotsk coastline. In each image, the solid black line reflects the trend surface for the entire

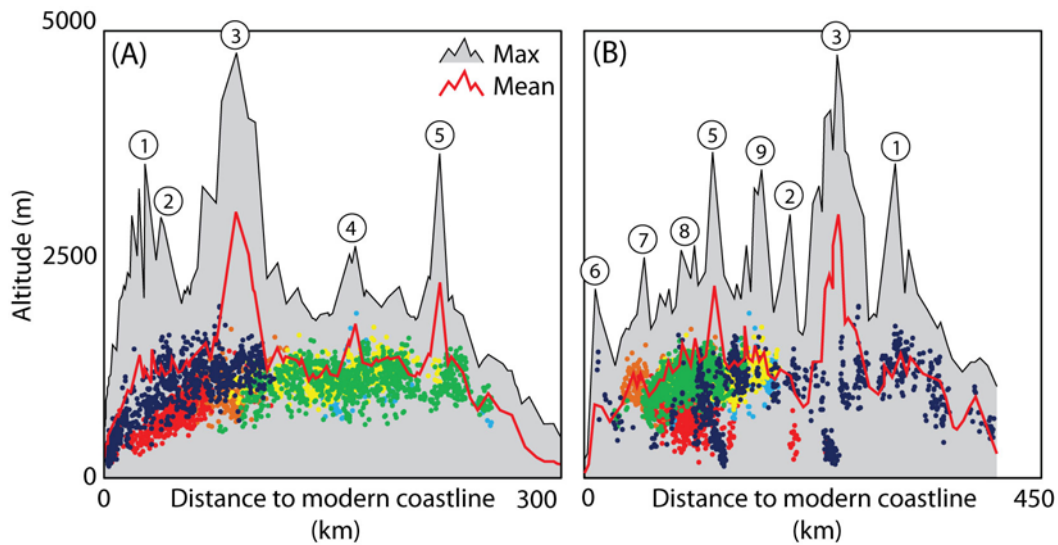
808 cirque data set, whilst coloured lines reflect different cirque populations (lines are only shown where

809 relationships are significant, i.e.,  $p < 0.001$ ). Colours correspond to regions shown in Fig. 1. The

810 dashed black lines in (D) and (E) reflect apparent lower boundaries to cirque floor altitudes. Trends

811 and  $r^2$  values are presented in Tables 2, 3, and 4, for panels (A)–(B); (C); and (D)–(F), respectively

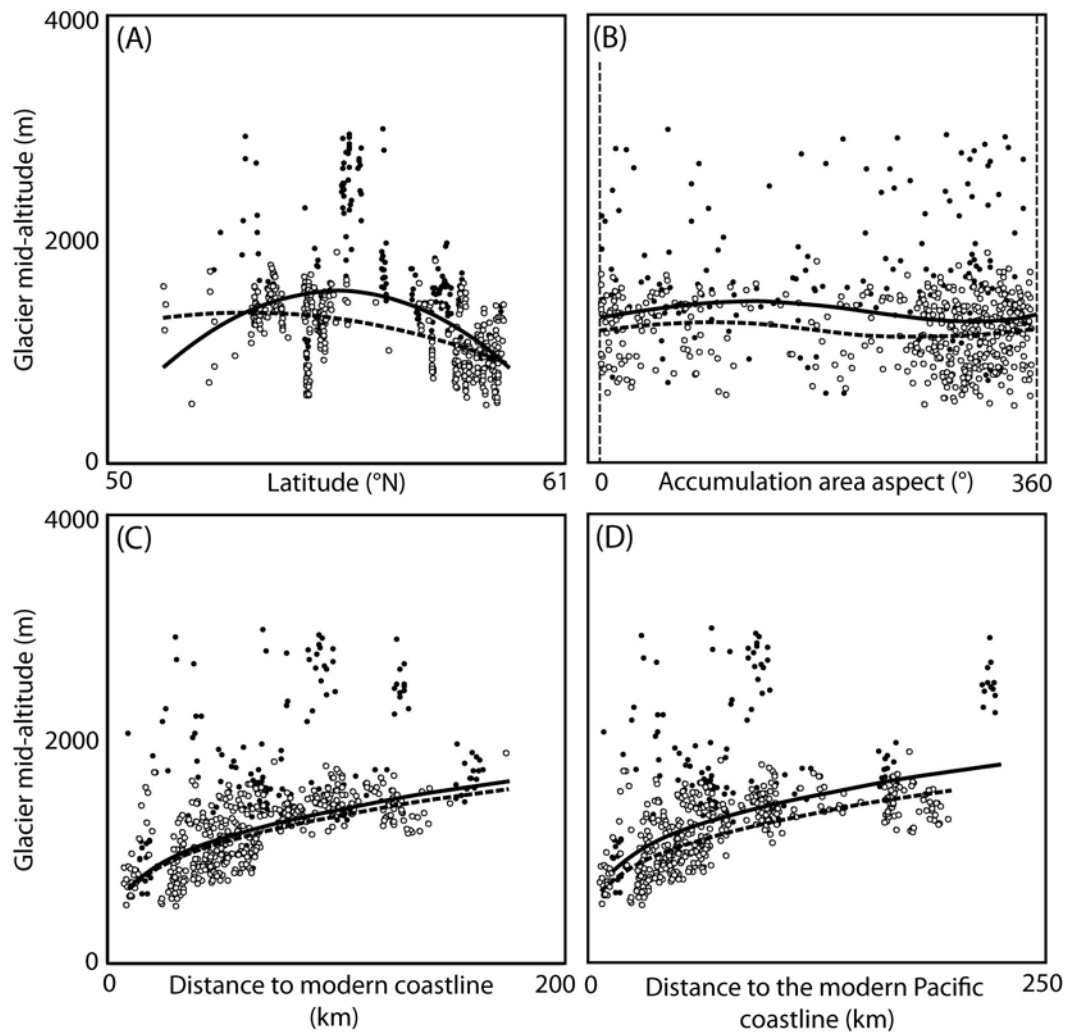
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814 Fig. 6. Variations in cirque floor altitude (coloured dots) and topography (based on the mean and  
 815 maximum altitude per 10 x 10 km grid), plotted relative to (A) the Pacific coastline and (B) the  
 816 Okhotsk coastline. The cirque altitude data is the same as shown in Figs. 5E and 5F. Numbered peaks  
 817 are volcanoes (or volcanic groups): (1) Kronotsky volcano; (2) Zhupanovsky volcano; (3)  
 818 Klyuchevskoy volcano; (4) Alney volcanic group; (5) Ichinsky volcano; (6) Koshelev and Kambalny  
 819 volcanoes; (7) Opala volcano; (8) Spokoiny volcano; (9) Kozelsky-Avachinsky-Koriaksky volcanic  
 820 group. See Ponomareva et al. (2007) for details about these volcanoes.

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823 Fig. 7. Mid-altitude data from modern glaciers on the Kamchatka Peninsula, with (A) latitude, (B)  
 824 accumulation area aspect, (C) distance to the modern coastline, and (D) distance to the modern Pacific  
 825 coastline. In each figure, white dots reflect cirque-type glaciers ( $n = 361$ ), whilst black dots are other  
 826 (larger) ice masses ( $n = 142$ ). The solid black lines reflect trend surfaces for the entire glacier data set,  
 827 whilst dashed lines reflect trends for cirque-type glaciers alone. Trends and  $r^2$  values are presented in  
 828 Table 7.

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