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Selley, Heather ; Harrison, Stephan; Glasser, Neil; Wünderlich, Olaf; Colson, Daniel; Hubbard, Alun

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tel: +44 1970 62 2400
email: is@aber.ac.uk

Rock glaciers in central Patagonia

Heather Selley, Centre for Polar Observation & Modelling, University of Leeds, Leeds, LS29JT, UK

Stephan Harrison*, College of Life and Environmental Sciences, Exeter University, Cornwall Campus, Penryn, TR10 9EZ, UK

Neil Glasser, Department of Geography and Earth Sciences, Aberystwyth University, Llandinam Building, Penglais Campus Aberystwyth, SY23 3DB, Wales, UK

Olaf Wünderlich, Predio Ana-Rosi, km 21, Ruta 7 Sur lugar Valle Simpson, Comuna y Provincia de Coyhaique, XI Region de Aysén, del General Carlos Ibañez del Campo, CHILE

Daniel Colson, Joint Nature Conservation Committee (JNCC), Peterborough, PE1 1JY, UK

Alun Hubbard, Institute of Geography and Earth Sciences, Aberystwyth University, Llandinam Building, Penglais Campus Aberystwyth, SY23 3DB, Wales, UK

Centre for Arctic Gas Hydrate, Environment and Climate, UiT – The Arctic University of Norway, Tromsø, Norway

*Corresponding author: Stephan Harrison (stephan.harrison@exeter.ac.uk)

Key words: Rock glacier, Inventory, Patagonia, Permafrost, Solar Radiation

1 **Abstract**

2 Active rock glaciers are ice and debris-cored landforms common in cold arid mountains. They
3 have not been widely described in the Patagonian Andes of southern South America and here
4 we provide the first rock glacier inventory for the Jeinimeni region to the east of the
5 contemporary North Patagonian Icefield. Detailed analysis of available satellite imagery and
6 fieldwork demonstrates the presence of 89 rock glaciers across the study region, covering a
7 total of 14.18 km². Elevation is the primary control on rock glacier distribution with 89%
8 existing between 1600 and 1900 m.a.s.l. Aspect also plays a significant role on rock glacier
9 formation with 80% preferentially developed on southerly slopes receiving lower solar
10 insolation.

11

12

13 **1. Introduction**

14 Rock glaciers are cryospheric landforms formed by the accumulation of ice and debris (Brenning
15 et al. 2012; Lui et al. 2013) that creep downslope by the deformation of internal ice (Barsch
16 1996; Haeberli et al. 2006; Berthling 2011; French and Williams 2013, Benn and Evans 2014).
17 Commonly, rock glaciers have extremely slow flow rates, typically only a few centimetres a year
18 (Stenni et al. 2007) and the viscous flow of the debris and ice matrix produces a distinctive
19 surface of ridges, furrows and a steep frontal slope ('toe' or 'snout') (Barsch 1996; Degenhardt
20 and Giardino 2003; Paul et al. 2003; Haeberli et al. 2006; Jansen and Hergarten 2006; Berthling
21 2011). They play a significant role controlling sediment supply in mountainous regions,
22 accounting for up to ~60% of all mass transport in some mountainous areas (Degenhardt 2009).
23 The high insulation capacity of the surface rock cover has been demonstrated to slow the melt
24 of ice within rock glaciers compared to glaciers (Stenni et al. 2007; Gruber et al. 2016); they
25 therefore potentially represent important sources of freshwater runoff in semi- and arid-
26 mountains (e.g. Brenning 2005; Rangecroft et al. 2014).

27

28 There has been considerable debate over the origin of rock glaciers based on assessment of
29 their internal structure (Potter 1972; Barsch 1978; Whalley and Martin 1992; Humlum 1996;
30 Haeberli et al. 2006; Krainer and Ribis 2012). Two main schools of thought have emerged: the
31 'permafrost school' versus the 'continuum school' (Berthling 2011). Additionally, a landslide
32 model of development has been proposed (Johnson 1974; Whalley and Martin 1992). Despite
33 the considerable amount of research undertaken to understand the origin of rock glaciers, little

34 consensus has been achieved. However, most workers accept that they reflect persistent
35 permafrost conditions (e.g. Berthling 2011). In many regions rock glaciers are currently
36 developing from glaciers and debris-covered glaciers (Shroder et al. 2000; Monnier and Kinnard
37 2015) and this evolution is likely to continue given future climate warming (Jones et al. 2018).

38

39 The large-scale distribution of active rock glaciers is predominantly controlled by climate. They
40 are concentrated in periglacial areas characterised by low temperatures and low insolation on
41 shaded slopes with plentiful debris supply from talus slopes and rock headwalls (e.g. White
42 1979; Parson 1987; Brenning 2005; Berthling and Etzelmüller 2007; Summerfield 2014).
43 Topographic factors, such as cirque width, the degree of rock wall fracture and, the height of
44 bounding rock headwalls contribute to varying levels of debris supply (Chueca 1992) and it has
45 been hypothesised that rock headwalls play a crucial role in determining the environmental
46 niches within which rock glaciers may develop (Olyphant 1983; Burger et al. 1999; Haeberli et
47 al. 1999; Humlum 2000; Haeberli et al. 2006). A consensus has emerged which argues that rock
48 glaciers require suitable niches in which to develop, determined by a combination of three
49 dominant characteristics: low solar insolation, sufficient talus supply to maintain them and
50 climatic conditions conducive to the development of perennial ice. The degree of influence of
51 these environmental and geological conditions varies regionally, suggesting a complex interplay
52 of topoclimatic factors in driving rock glacier development (Kinworthy 2016).

53

54 Rock glaciers can be classified according to their activity status (Wahrhaftig and Cox 1959) as
55 active, inactive and fossil (relict). Active rock glaciers move downslope through gravity-driven

56 creep as a consequence of the deformation of ice they contain (Barsch, 1992,1996). Commonly,
57 active landforms are characterised by flow-like features (i.e. spatially organised morphometric
58 features, e.g. distinctive surface micro-relief of furrow-and-ridge topography), steep (~30-35°)
59 and sharp-crested front- and lateral-slopes, a 'swollen' appearance of the rock glaciers body,
60 individual lobes, and an absence of vegetative cover (Martin and Whalley 1987; Haeberli et al.
61 2006; Harrison et al. 2008). These distinctive morphometric features reflect the viscoplastic
62 properties of the rock glacier. Inactive rock glaciers also contain ice, but are immobile (e.g.
63 Seligman 2009).

64

65 The presence of rock glaciers in either their active or relict forms has been widely used as
66 permafrost and climatic indicators. For instance, the altitude of rock glacier termini or fronts
67 (minimum altitudinal fronts or MAF) are assumed to mark the lower limit of discontinuous
68 permafrost (Giardino and Vitek 1988; Barsch 1996). Moreover, the active layer with insulating
69 debris surface covers the ice acting as buffer against high frequency (i.e. seasonal to diurnal)
70 temperature fluctuations (Angillieri 2009). The degradation of permafrost and therefore rock
71 glaciers, associated with projected atmospheric warming, can therefore impact water supplies
72 in the dry Andes and other arid mountain regions (e.g. Trombotto et al. 1999; Brenning 2005;
73 Rangecroft et al. 2015).

74

75 Many rock glacier inventories have been created to establish their regional significance and
76 distribution to better understand the environmental variables controlling development and,
77 recently, their potential role as buffered hydrological stores (Schrott 1996; Brenning 2005;

78 Rangecroft et al. 2013, 2014). Rock glacier inventories have been created from many of the
79 world's mountain regions including the European Alps (e.g. Dramis et al. 2003; Kellerer-
80 Pirklbauer et al. 2012; Marcer et al., 2017), Newland Alps (Sattler et al., 2016), the Pyrenees
81 (e.g. Chueca 1992), North American Sierra Nevada (e.g. Millar and Westfall 2008) and the
82 central parts of the South American Andes (e.g. Trombotto et al. 1999; Brenning 2005;
83 Rangecroft et al. 2014). However, relatively little attention has been paid to the southern Andes
84 until recently (e.g. Falaschi et al. 2015). Here we develop a first rock glacier inventory for the
85 mountains to the south of Lago General Carrera/Buenos Aires between the borders of Chile and
86 Argentina and investigate primary controls on their distribution.

87

88

89 **2. Study Region**

90 Our study region lies in the Jeinimeni National Reserve in Chilean territory in the Central
91 Patagonian Andes on the Chilean and Argentinean border at $46^{\circ} 52' 0''$ S, $72^{\circ} 4' 0''$ W (Figure 1).
92 It is situated directly east of the North Patagonian Icefield (NPI), one of three major ice masses
93 which currently exist in southern South America (Harrison and Glasser 2011). Previous
94 fieldwork in the southern side of the area making up the National Reserve identified rock
95 glaciers in the mountains between Cerro Tamango (1712m) at the western end of the
96 Chacabuco Valley and Cerro Opportus (2021 m) 34km to the east. The regional climate is
97 dominated by the Southern Hemisphere westerlies and proximity to the Pacific Ocean
98 (Villarroel et al. 2013). The presence of the NPI to the west produces an extremely steep west-
99 east precipitation gradient (Figure 1) and the Jeinimeni region lies in the rainshadow of the NPI

100 with low annual precipitation (Figure 1). Glacier development here is hence severely limited by
101 regional precipitation availability. During the late Pleistocene, fast flowing outlet lobes of an
102 expanded Patagonian Ice Sheet (PIS) extended eastwards along the Chacabuco Valley to the
103 south of Jeinimeni and to the north to the east of Lago Buenos Aires. Only the highest
104 mountains in the region remained uncovered by ice during the Last Glacial Maximum (LGM) at
105 around 24-22.5 ka BP (Hubbard et al. 2005; Boex et al. 2013).

106
107

108 **3. Methods**

109 We developed the rock glacier inventory using photomorphic mapping from Google Earth
110 Imagery (5 - 30 m resolution) (version 7.1.7.2606, Google Inc., California, USA) (e.g. Rangescroft
111 et al. 2014; Schmid et al. 2015). The multi-temporal data available through Google Earth
112 reduces uncertainty in landform identification due to clouds, shadows and snow cover by
113 enabling a full inventory of the area by mosaicking imagery with varying dates between 2007
114 and 2015. Google Earth Pro data are exportable as KML file for further spatial analysis within
115 GIS software (e.g. ArcMap) (e.g. Schmid et al. 2015). Manual feature identification using
116 geomorphic indicators and subsequent digitisation was carried out (Baroni et al.
117 2004; Falaschi et al. 2014; Rangescroft et al. 2014; Jones et al. 2018). To ensure comparability
118 and accuracy polygons were reprojected to the WGS84 coordinate system. Topographic data
119 were extracted for the polygons and central flow lines from a ~30 m resolution digital elevation
120 model (DEM), NASA version 3.0 Shuttle Radar Topography Mission (SRTM) Global 1 arc-second
121 dataset (USGS 2015) within ArcMap (Schmid et al. 2015; Jones et al. 2018).

122

123 Rock glaciers were identified using two principal characteristics: 1) distinctive surface
124 morphology of ridges and furrows, formed as a result of compression and extension and
125 produced by differential ice and debris distribution and flow, and; 2) steep frontal slope
126 indicative of the limit of viscous flow of internal ice (e.g. Barsch 1996; Haeberli et al. 2006;
127 Berthling 2011). Several rock glaciers along the southern margin of the study area (to the east
128 of Cerro Tamango) were verified by field observation.

129

130 Rock glacier boundary digitisation follows Scotti et al. (2013) and Jones et al. (2018)
131 methodology. Polygons were digitised for each rock glacier identified, landforms were defined
132 and classified according to a well-established criteria (see Table 1). For each rock glacier, key
133 characteristics were identified and measured using the ruler tool and geometry calculations in
134 Google Earth Pro (Figure 2). Delineation of rock glaciers is challenging, digitising the upper
135 boundary can be arbitrary without data movement and evident furrow-and-ridge formations in
136 the rooting zone (Roer and Nyenhuis 2007; Krainer and Ribis 2012; Jones et al. 2018). Rock
137 glaciers were distinguished from other periglacial landforms, such as protalus ramparts or
138 lobes, by an application of a length: width ratio of less than 1 (unity) (Harrison et al. 2008; Jones
139 et al. 2018). Coalesced rock glaciers were differentiated from their source headwalls or talus
140 slopes (Jones et al. 2018).

141

142 The activity status of the rock glaciers was established based on assumed ice content using the
143 morphological classification system by Barsch (1996) (Table 1 and Figure 3). This uses

144 geomorphological and morphological criteria, including steepness of frontal slope, and
145 development of thermokarst pits indicating ice content. Rock glaciers were classified as “Relict”
146 and “Active” which includes both active and intact landforms (Jones et al. 2018).

147

148 Slope aspect is a key factor in the development of rock glaciers and this was determined using
149 the ArcMAP aspect spatial analyst tool, which divides aspect into 8 groups by proportioning-out
150 bearings of 0° to 360° (Burrough et al. 2015). Aspect density analysis was also undertaken
151 according to the analysis of Falaschi et al. (2015). The areas of each aspect for the study area
152 were calculated, and a density analysis carried out to establish the percentage of the study
153 area facing each direction. The proportion of rock glaciers located on each aspect was then
154 plotted against the aspect density of the study region.

155

156 To further assess the influence of solar radiation on rock glacier development in the region the
157 Potential Incoming Solar Radiation (PISR) was calculated for the study using the ‘Area Solar
158 Radiation’ toolbox in ArcMap. A mean figure was calculated for each of the years of imagery
159 available from 2007 to 2015, a mean raster layer was produced and zonal statistics extracted to
160 create the mean PISR value for each rock glacier polygon. The Non-parametric data set was
161 tested for significance using Mann-Whitney U tests.

162

163

164 **4. Results**

165 In total, 89 rock glaciers were identified and mapped and these cover 14.18 km² of the study
166 area (1381.84 km²). The inventory comprises 51 active rock glaciers (covering 7.94 Km²) and 38
167 relict rock glaciers (covering 6.24 Km²). A summary of rock glacier characteristics based on the
168 classification of active and relict features is shown in Table 2. Rock glaciers occurred between
169 1412 and 2049 m.a.s.l and 89% of total rock glaciers between 1600 and 2000 m.a.s.l. (Figure 4).
170 92% of the rock glaciers identified can be classified as tongue shaped. The MAF for active (1766
171 ± 128 m.a.s.l.) and relict rock (1758 ± 133 m.a.s.l.) glaciers shows a similar distribution (see
172 Figure 6) and Chi Squared tests found there was no significant difference between the MAF of
173 active and relict rock glacier populations: (χ^2 (1, N=89) = 0.151, p=0.697).

174
175 The rock glacier spatial density is 3.2% of the study region. This compares with sites in drier
176 areas in the north in the Andes e.g. 2.2% at Valles Calchaquíes region (Falaschi et al. 2014) and
177 4% in the Andes between Santiago and Mendoza (Azócar and Brenning 2010). The spatial
178 density is more than twice that reported by Falaschi et al. (2015) (1.4%) in the Monte San
179 Lorenzo Massif 50km to the south.

180
181 The proportion of rock glaciers identified on each aspect was calculated and is summarised in
182 Figure 7 and 8. Some 80% of rock glaciers identified occurred on south, south east or south
183 west slopes (Figure 7), although only 12% of slopes are oriented to the south west and 11% to
184 the south east (Figure 8). The activity level of these populations illustrate different dominant
185 aspects with 58% of relict rock glaciers developed on south easterly slopes and 41% of active

186 rock glaciers on south westerly aspects. This suggests that in this region southerly slopes have
187 higher propensity than other aspects for the formation and persistence of rock glaciers.

188

189 The mean PISR for the study area was 150088 ± 79215 WHm² compared to 109130 ± 33836
190 WHm² and 153810 ± 38930 WHm² for active and relict rock glaciers means respectively. There
191 is a significant difference between PISR median values for active rock glaciers (92017)
192 compared to relict rock glaciers (149715) ($W=1915$, $P=0.002$) with active rock glaciers occurring
193 in areas of lower PISR (Figure 9).

194

195

196 **5. Discussion**

197 Previous work in Patagonia (Falaschi et al. 2015) confirms the presence of rock glaciers in the
198 mountains east of the current NPI in valleys draining Monte San Lorenzo and in this study we
199 extend this work to demonstrate the conditions under which they are found in the Jeinimeni
200 region, some 50 km to the north. On Cerro San Lorenzo the rock glaciers identified by Falaschi
201 et al. (2015) were smaller in size than those in Jeinimeni (active rock glaciers average 92000 m²
202 in San Lorenzo compared with 156000 m² in Jeinimeni) with similar trends in relict features
203 (36000 m² compared with 164000 m²). The reasons for this are currently unclear, but may
204 include differences in local climate or geology driving variations in debris supply.

205

206

207 In Jeinimeni 89% of rock glaciers occur between 1600 and 1900 m.a.s.l, the remainder above
208 this. It has been suggested that elevation is a function of the number of available topographic
209 and climatic niches in which rock glaciers can develop (Brenning and Trombotto 2006;
210 Kinworthy 2016), and the MAF is commonly considered a good approximation of the limit of
211 discontinuous permafrost (Scotti et al. 2013). However, as there was no significant difference
212 between the MAF elevation of active and relict rock glacier in the study region it suggests
213 additional factors control the activity level of rock glaciers in the region.

214

215

216 A climatic control is suggested by the preferential development of rock glaciers (80%) on
217 southerly aspects with low solar insolation (Krainer and Ribis 2012), despite there being a
218 relatively even distribution between northern and southern aspects within the study area and
219 thereby likely available topographical niches (Figures 7 and 8) and this is supported by our
220 analysis of PISR (Figure 9a and b). Moreover, aspect (unlike elevation) appears to control
221 whether the rock glaciers are relict or active. The majority of the relict rock glaciers are located
222 on slopes with a southeast facing aspect whereas those identified as being currently active are
223 more broadly distributed across all southward facing slopes but particularly on those with a
224 southwest aspect. Falaschi et al. (2015) also report a strong west-south-westerly orientation of
225 active rock glaciers to the south of Jeinimeni. Without further research it is hard to draw a
226 concrete conclusion from this observation though it does somewhat tantalisingly suggest that
227 the change in aspect with relict to active rock glaciers may correspond to a prior shift in
228 prevailing winds, and hence snow-drift, from the west to more northerly flow in recent times.

229

230

231 In essence, we have shown that the active and relict rock glaciers share similar elevations and if
232 the distinction between them is climatic then this pattern is difficult to explain. Falaschi et al.
233 (2015) suggested that some intact rock glaciers might exist above the 0 °C MAAT conditions
234 illustrating permafrost persisting in positive air temperatures (Gruber and Haeberli 2007). In
235 this case their preservation could be a consequence of the protective active layer and an
236 indication that they are in disequilibrium with present thermal conditions (Gruber and Haeberli
237 2007). However, rock glaciers could also achieve thermal equilibrium due to topographical
238 factors (Haeberli 1983; Falaschi et al.2015). For example, circulation of cold air from glaciers or
239 topographic shading (Brenning 2005) can influence rock glacier preservation. The evident
240 differences observed in aspect and therefore the amount of incoming solar radiation would
241 support the latter conclusion for this region.

242

243 However, we speculate that another possibility exists. It may be that our inventory has
244 captured a number of features that are currently undergoing the transition from formerly
245 debris-covered glaciers to rock glaciers. We speculate that these were formerly active glaciers,
246 most probably during the regional Little Ice Age (or perhaps earlier), but have since undergone
247 many years of negative mass balance and are now at various stages of transition from debris-
248 covered glaciers to rock glaciers (Huss and Fischer 2016; Jones et al 2018). We therefore find
249 both active and fossil rock glaciers at broadly similar elevations as they undergo this transition

250 at slightly different rates - other factors such as debris supply and availability determine where
251 each landform currently is on this transition. More work is required to test this assertion.

252

253 In the absence of a large-scale dating programme the age of the rock glaciers is difficult to
254 establish. It might be that they started to develop immediately after deglaciation of the region
255 following the regional LGM as the expanded PIS withdrew to the west from the Chacabuco and
256 Jeinimeni regions (Boex et al. 2013; Wolff et al. 2013). Alternatively, as suggested above, they
257 might have developed much later during the Holocene, perhaps in response to climatic
258 amelioration following Neoglacial times or the regional Little Ice Age at the end of the
259 nineteenth century.

260

261 If we accept the former hypothesis then the timing of ice sheet recession following the LGM is
262 important. Hubbard et al. (2005) reconstructed the dynamics and evolution of late Quaternary
263 ice sheets across the NPI using a first-order coupled climate/ice sheet model described fully in
264 Hubbard (2006), and which extends a combined empirical/modelling approach first adopted for
265 investigating the fluctuations of the Lago Rupanco and Puyehue outlet lobes in northern
266 Patagonia (Hubbard, 1997). Using dated end moraines to broadly constrain the model,
267 Hubbard et al. (2005) demonstrate that the Jeinimeni region broadly deglaciated between 14.5
268 to 13.0 ka BP. Complete retreat of the Lago General Carrera/Buenos Aires outlet glacier from
269 the area was finally accomplished by ~12.5 ka BP (Figure 10). Despite considerable recession of
270 the PIS, cool/dry glacial conditions conducive to the formation local cirque glaciers and larger
271 valley glaciers, persisted in the area for at least another ~1.5 ka, until ~11.0 ka BP when regional

272 climate ameliorated to conditions similar to today. During this post-glacial episode, the local
273 equilibrium line altitude (ELA) fluctuated between 400 m lower than present, to around 100 m
274 higher than present (for a brief 200 year period around 11.4-11.3 ka BP) and which is in general
275 agreement with the modelling further north (Hubbard, 1997). Given the predominantly arid
276 climate across the region, these ELA fluctuations equate to a mean temperature range of -3.6 to
277 +0.9°C relative to present (Hubbard et al. 2005). Such conditions would have been conducive to
278 the development of thick permafrost and formation of rock glaciers in the mountainous
279 Jeinimeni region, likely persisted for the subsequent 11000 years through to recent times.
280 Finally, between 13-8 ka BP large lakes existed to the east of the current NPI covering an area of
281 ~7400 km², around four times the current area of Lago General Carrera/Buenos Aires (Glasser
282 et al. 2016). In the Chacabuco valley delta features as high as 700 m.a.s.l. indicate the existence
283 of former lakes at this time and as these drained during the early Holocene increasing aridity
284 would likely have favoured the development of rock glaciers in the mountains to the north, and
285 at the recently deglaciated sites. Given this we could also speculate that the rock glaciers
286 developed following deglaciation and persisted on southerly slopes due to lower solar
287 insolation. Clearly, more research is required to test these hypotheses.

288

289

290

291 **6. Conclusions**

292

293

294 We have produced a preliminary rock glacier inventory for the mountains in the Jeinimeni
295 region of central Patagonia and have demonstrated that active and relict rock glaciers are
296 widely developed in the mountains between 1412 and 2049 m.a.s.l to the east of the present-
297 day North Patagonian Icefield. In total 89 rock glaciers were identified and mapped and they
298 cover 14.18 km² of the study area. The inventory comprises 51 active rock glaciers (covering
299 7.94 km²) and 38 relict rock glaciers (covering 6.24 km²). We show that they are preferentially
300 developed on slopes with a south-facing orientation and active rock glaciers are preserved in
301 areas of lower PISR indicating strong solar radiation control.

302

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305 the Research Council of Norway through its Centres of Excellence (grant 223259).

306

307

308

309

310 **Figure captions**

311

312 Figure 1. Location map illustrating the steep precipitation gradient west to east across
313 Patagonia. Top left: location of rock glaciers. Image data: Aster GDEM product of
314 NASA and METI (2009). Top right and bottom right: mean annual precipitation rates
315 using WorldClim (<http://worldclim.org>) 0.5°resolution data for 1970 - 2000. The
316 Jeinimeni Region study area is identified located east of the North Patagonian Icefield.

317

318 Figure 2. Annotated example of characteristics extracted for each of the rock glacier measured.
319 Other characteristics recorded were: surface area, average elevation as well as the maximum,
320 minimum and average slope angle along the central flow line (46°58'30.86"S 72°00'13.94"W).
321 Image data: Google Earth Imagery (version 7.1.7.2606, Google Inc., California, USA),
322 CNES/Airbus 2018; imagery date: 16 March 2016.

323
324 Figure 3. Annotated examples of rock glaciers: (a) Active rock glacier(46°58'30.86"S,
325 72°00'13.94"W). Image data: Google Earth Imagery (version 7.1.7.2606, Google Inc., California,
326 USA), CNES/Airbus 2018; imagery date: 16 March 2016; and (b) Relict rock glacier
327 (47°01'08.34"S, 72°00'47.17"W). Image data: Google Earth Imagery (version 7.1.7.2606, Google
328 Inc., California, USA), CNES/Airbus 2018; imagery date: 29 February 2016.

329
330 Figure 4. Distribution of rock glaciers by elevation. Variations of density through elevation
331 bands.

332
333 Figure 5. Permafrost Zone Index (PZI) from Gruber (2012) indicating all rock glaciers occur
334 within the likely permafrost zone. There appears to be no strong relationship between active
335 and relict rock glaciers and strength of permafrost zone. Image data: Aster GDEM product of
336 NASA and METI (2009).

337
338 Figure 6. Box plot showing similarity in elevation of MAF between active and relict rock glaciers.
339 51 active rock glaciers and 38 relict rock glaciers are shown along with 2 outliers.

340
341
342 Figure 7. Rock glacier size and slope orientation. There is no evident pattern of orientation and
343 rock glacier size. Two large outliers occur on south east aspects.

344

345 Figure 8. Spatial density of slope orientation plotted against rock glacier distribution. Active
346 rock glaciers predominantly occur on south westerly slopes whilst relict rock glaciers occur on
347 south easterly slopes.

348
349 Figure 9. Potential Incoming Solar Radiation (PISR) for sites with active and relict and active rock
350 glaciers illustrating mean values. Active rock glacier sites had significantly lower PISR median
351 values, 92017 and 149715 respectively ($W=1915$, $P=0.002$) than sites with relict features.
352 (Image data: Aster GDEM product of NASA and METI (2009))

353
354
355 Figure 10. Model snapshot of the retreat of the Patagonian ice sheet (PIS) at c. 13.5 ka BP (from
356 Hubbard et al. 2005). The Jeinimeni study area (red box) is bounded by two major outlet
357 glaciers, the Lago General Carrera/Buenos Aires lobe to the north and the Lago Cochrane lobe
358 to the south, both of which had fully retreated westward of the study area by 12.5 ka BP.
359 Climatic and permafrost conditions conducive to local rock glacier formation would have
360 proceeded with the onset of regional deglaciation.

361 362 **Disclosure Statement**

363 No potential conflict of interest was reported by the authors

364 365 **Notes on Contributors**

366 **Heather Selley** is undertaking a PhD research project at Leeds University using high resolution altimetry
367 data to investigate the mass balance Greenland and Antarctica.

368
369 **Stephan Harrison** is at Exeter University and works on the impacts of climate change in mountain
370 systems. He has worked for many years in Patagonia, and also in the tropical Andes and the Himalaya.

371
372 **Neil Glasser** is at Aberystwyth University and studies the evolution and behaviour of glaciers and ice
373 sheets, mainly in Patagonia, the Himalayas and Antarctica.

374

375 **Olaf Wünderich** is a surveyor and mountain guide working in the mountains of Patagonia.

376

377 **Daniel Colson** is a remote sensing and GIS specialist.

378

379 **Alun Hubbard** is a glaciologist at Aberystwyth University and the Arctic University of Norway in Tromsø.

380 His research is focuses on climate, ocean and ice sheet interactions in Polar and Alpine regions.

381

382

383 **References**

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