

## **Glacial geomorphological mapping: A review of approaches and frameworks for best practice**

CHANDLER, Benjamin M.P., LOVELL, Howard, BOSTON, Clare M., LUKAS, Sven, BARR, Iestyn D., BENEDIKTSSON, Ivar O., BENN, Douglas I., CLARK, ChrisD., DARVILL, Christopher M., EVANS, David J.A., EWERTOWSKI, Marek W., LOIBL, David, MARGOLD, Martin, OTTO, Jan-Christoph, ROBERTS, David H., STOKES, Chris R., STORRAR, Robert <<http://orcid.org/0000-0003-4738-0082>> and STROEVEN, Arjen P.

Available from Sheffield Hallam University Research Archive (SHURA) at:

<http://shura.shu.ac.uk/22264/>

---

This document is the author deposited version. You are advised to consult the publisher's version if you wish to cite from it.

### **Published version**

CHANDLER, Benjamin M.P., LOVELL, Howard, BOSTON, Clare M., LUKAS, Sven, BARR, Iestyn D., BENEDIKTSSON, Ivar O., BENN, Douglas I., CLARK, ChrisD., DARVILL, Christopher M., EVANS, David J.A., EWERTOWSKI, Marek W., LOIBL, David, MARGOLD, Martin, OTTO, Jan-Christoph, ROBERTS, David H., STOKES, Chris R., STORRAR, Robert and STROEVEN, Arjen P. (2018). Glacial geomorphological mapping: A review of approaches and frameworks for best practice. *Earth-Science Reviews*, 185, 806-846.

---

### **Copyright and re-use policy**

See <http://shura.shu.ac.uk/information.html>

1 **Glacial geomorphological mapping:**  
2 **a review of approaches and frameworks for best practice**  
3

4 Benjamin M.P. Chandler<sup>1\*</sup>, Harold Lovell<sup>2</sup>, Clare M. Boston<sup>2</sup>, Sven Lukas<sup>3</sup>, Iestyn D. Barr<sup>4</sup>,  
5 Ívar Örn Benediktsson<sup>5</sup>, Douglas I. Benn<sup>6</sup>, Chris D. Clark<sup>7</sup>, Christopher M. Darvill<sup>8</sup>,  
6 David J.A. Evans<sup>9</sup>, Marek W. Ewertowski<sup>10</sup>, David Loibl<sup>11</sup>, Martin Margold<sup>12</sup>, Jan-Christoph Otto<sup>13</sup>,  
7 David H. Roberts<sup>9</sup>, Chris R. Stokes<sup>9</sup>, Robert D. Storrar<sup>14</sup>, Arjen P. Stroeven<sup>15, 16</sup>  
8

9 <sup>1</sup> *School of Geography, Queen Mary University of London, Mile End Road, London, E1 4NS, UK*

10 <sup>2</sup> *Department of Geography, University of Portsmouth, Portsmouth, UK*

11 <sup>3</sup> *Department of Geology, Lund University, Lund, Sweden*

12 <sup>4</sup> *School of Science and the Environment, Manchester Metropolitan University, Manchester, UK*

13 <sup>5</sup> *Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland*

14 <sup>6</sup> *Department of Geography and Sustainable Development, University of St Andrews, St Andrews, UK*

15 <sup>7</sup> *Department of Geography, University of Sheffield, Sheffield, UK*

16 <sup>8</sup> *Geography, School of Environment, Education and Development, University of Manchester, Manchester, UK*

17 <sup>9</sup> *Department of Geography, Durham University, Durham, UK*

18 <sup>10</sup> *Faculty of Geographical and Geological Sciences, Adam Mickiewicz University, Poznań, Poland*

19 <sup>11</sup> *Department of Geography, Humboldt University of Berlin, Berlin, Germany*

20 <sup>12</sup> *Department of Physical Geography and Geoecology, Charles University, Prague, Czech Republic*

21 <sup>13</sup> *Department of Geography and Geology, University of Salzburg, Salzburg, Austria*

22 <sup>14</sup> *Department of the Natural and Built Environment, Sheffield Hallam University, Sheffield, UK*

23 <sup>15</sup> *Geomorphology & Glaciology, Department of Physical Geography, Stockholm University, Stockholm, Sweden*

24 <sup>16</sup> *Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden*  
25

26 **\*Corresponding author.** Email: b.m.p.chandler@qmul.ac.uk  
27

28 **Abstract**  
29

30 Geomorphological mapping is a well-established method for examining earth surface processes  
31 and landscape evolution in a range of environmental contexts. In glacial research, it provides  
32 crucial data for a wide range of process-oriented studies and palaeoglaciological  
33 reconstructions; in the latter case providing an essential geomorphological framework for  
34 establishing glacial chronologies. In recent decades, there have been significant developments  
35 in remote sensing and Geographical Information Systems (GIS), with a plethora of high-quality  
36 remotely-sensed datasets now (often freely) available. Most recently, the emergence of  
37 unmanned aerial vehicle (UAV) technology has allowed sub-decimetre scale aerial images and  
38 Digital Elevation Models (DEMs) to be obtained. Traditional field mapping methods still have

39 an important role in glacial geomorphology, particularly in cirque glacier, valley glacier and  
40 icefield/ice-cap outlet settings. Field mapping is also used in ice sheet settings, but often takes  
41 the form of necessarily highly-selective ground-truthing of remote mapping. Given the  
42 increasing abundance of datasets and methods available for mapping, effective approaches are  
43 necessary to enable assimilation of data and ensure robustness. This paper provides a review  
44 and assessment of the various glacial geomorphological methods and datasets currently  
45 available, with a focus on their applicability in particular glacial settings. We distinguish two  
46 overarching ‘work streams’ that recognise the different approaches typically used in mapping  
47 landforms produced by ice masses of different sizes: (i) mapping of ice sheet geomorphological  
48 imprints using a combined remote sensing approach, with some field checking (where feasible);  
49 and (ii) mapping of alpine and plateau-style ice mass (cirque glacier, valley glacier, icefield and  
50 ice-cap) geomorphological imprints using remote sensing and considerable field mapping. Key  
51 challenges to accurate and robust geomorphological mapping are highlighted, often  
52 necessitating compromises and pragmatic solutions. The importance of combining multiple  
53 datasets and/or mapping approaches is emphasised, akin to multi-proxy approaches used in  
54 many Earth Science disciplines. Based on our review, we provide idealised frameworks and  
55 general recommendations to ensure best practice in future studies and aid in accuracy  
56 assessment, comparison, and integration of geomorphological data. These will be of particular  
57 value where geomorphological data are incorporated in large compilations and subsequently  
58 used for palaeoglaciological reconstructions. Finally, we stress that robust interpretations of  
59 glacial landforms and landscapes invariably requires additional chronological and/or  
60 sedimentological evidence, and that such data should ideally be collected as part of a holistic  
61 assessment of the overall glacier system.

62  
63 **Keywords:** glacial geomorphology; geomorphological mapping; GIS; remote sensing; field mapping  
64  
65  
66  
67  
68  
69  
70  
71  
72  
73  
74  
75

76 **1. Introduction**

77

78 *1.1 Background and importance*

79

80 Mapping the spatial distribution of landforms and features through remote sensing and/or field-based  
81 approaches is a well-established method in Earth Sciences to examine earth surface processes and  
82 landscape evolution (e.g. Kronberg, 1984; Hubbard and Glasser, 2005; Smith et al., 2011). Moreover,  
83 geomorphological mapping is utilised in numerous applied settings, such as natural hazard  
84 assessment, environmental planning, and civil engineering (e.g. Kienholz, 1977, Finke, 1980; Paron  
85 and Claessens, 2011; Marc and Hovius, 2015; Griffiths and Martin, 2017).

86

87 Two overarching traditions exist in geomorphological mapping: Firstly, the classical approach  
88 involves mapping all geomorphological features in multiple thematic layers (e.g. landforms, breaks of  
89 slope, slope angles, and drainage), regardless of the range of different processes responsible for  
90 forming the landscape. This approach to geomorphological mapping has been particularly widely used  
91 in mainland Europe and has resulted in the creation of national legends to record holistic  
92 geomorphological data that may be comparable across much larger areas or between studies (Demek,  
93 1972; van Dorsser and Salomé, 1973; Leser and Stäblein, 1975; Klimaszewski, 1990; Schoeneich,  
94 1993; Kneisel et al., 1998; Gustavsson et al., 2006; Rączkowska and Zwoliński, 2015). The second  
95 approach involves more detailed, thematic geomorphological mapping commensurate with particular  
96 research questions; for example, the map may have an emphasis on mass movements or glacial and  
97 periglacial landforms and processes. Such a reductionist approach is helpful in ensuring a map is not  
98 ‘cluttered’ with less relevant data that may in turn make a multi-layered map unreadable (e.g. Kuhle,  
99 1990; Robinson et al., 1995; Kraak and Ormeling, 2006). In recent years, the second approach has  
100 become much more widespread due to increasing specialisation and thus forms the basis for this  
101 review, which focuses on geomorphological mapping in glacial environments.

102

103 In glacial research, the production and analysis of geomorphological maps provide a wider context  
104 and basis for various process-oriented and palaeoglaciological studies, including:

105

- 106 (1) analysing glacial sediments and producing process-form models (e.g. Price, 1970; Benn,  
107 1994; Lukas, 2005; Benediktsson et al., 2016);
- 108 (2) quantitatively capturing the pattern and characteristics (‘metrics’) of landforms to understand  
109 their formation and evolution (e.g. Spagnolo et al., 2014; Ojala et al., 2015; Ely et al., 2016a;  
110 Principato et al., 2016; Hillier et al., 2018);

- 111 (3) devising glacial landsystem models that can be used to elucidate former glaciation styles or  
112 inform engineering geology (e.g. Eyles, 1983; Evans et al., 1999; Evans, 2017; Bickerdike et  
113 al., 2018);
- 114 (4) reconstructing the extent and dimensions of former or formerly more extensive ice masses  
115 (e.g. Dyke and Prest, 1987a; Kleman et al., 1997; Houmark-Nielsen and Kjær, 2003; Benn  
116 and Ballantyne, 2005; Glasser et al., 2008; Clark et al., 2012);
- 117 (5) elucidating glacier and ice sheet dynamics, including advance/retreat cycles, flow  
118 patterns/velocities and thermal regime (e.g. Kjær et al., 2003; Kleman et al., 2008, 2010;  
119 Evans, 2011; Boston, 2012a; Hughes et al., 2014; Darvill et al., 2017);
- 120 (6) identifying sampling locations for targeted numerical dating programmes and ensuring robust  
121 chronological frameworks (e.g. Owen et al., 2005; Barrell et al., 2011, 2013; Garcia et al.,  
122 2012; Akçar et al., 2014; Kelley et al., 2014; Stroeven et al., 2014; Gribenski et al., 2016;  
123 Blomdin et al., 2018);
- 124 (7) calculating palaeoclimatic variables for glaciated regions, namely palaeotemperature and  
125 palaeoprecipitation (e.g. Kerschner et al., 2000; Bakke et al., 2005; Stansell et al., 2007; Mills  
126 et al., 2012; Boston et al., 2015); and
- 127 (8) providing parameters to constrain and test numerical simulations of ice masses (e.g. Kleman  
128 et al., 2002; Napieralski et al., 2007a; Golledge et al., 2008; Stokes and Tarasov, 2010;  
129 Livingstone et al., 2015; Seguinot et al., 2016; Patton et al., 2017a).

130

131 Thus, accurate representation of glacial and associated landforms is crucial to producing  
132 geomorphological maps of subsequent value in a wide range of glacial research. This is exemplified  
133 in glacial geochronological investigations, where a targeted radiometric dating programme first  
134 requires a clear geomorphological (and/or stratigraphic) framework and understanding of the  
135 relationships and likely relative ages of different sediment-landform assemblages. In studies that  
136 ignore this fundamental principle, it can be challenging to reconcile any scattered or anomalous  
137 numerical ages with a realistic geomorphological interpretation, as the samples have been obtained  
138 without a clear genetic understanding of the landforms being sampled (see Boston et al. (2015) and  
139 Winkler (2018) for further discussion).

140

141 The analysis of geomorphological evidence has been employed in the study of glaciers and ice sheets  
142 for over 150 years, with the techniques used in geomorphological mapping undergoing a number of  
143 significant developments in that time. The earliest geomorphological investigations involved intensive  
144 field surveys (e.g. Close, 1867; Penck and Brückner, 1901/1909; De Geer, 1910; Trotter, 1929;  
145 Caldenius, 1932; Raistrick, 1933), before greater efficiency was achieved through the development of  
146 aerial photograph interpretation from the late 1950s onwards (e.g. Lueder, 1959; Price, 1963; Welch,  
147 1967; Howarth, 1968; Prest et al., 1968; Sugden, 1970; Sissons, 1977a; Prest, 1983; Kronberg, 1984;

148 Mollard and Janes, 1984). Satellite imagery and digital elevation models (DEMs) have been in  
149 widespread usage since their development in the late 20<sup>th</sup> Century and have, in particular, helped  
150 revolutionise our understanding of palaeo-ice sheets (e.g. Barents-Kara Ice Sheet: Winsborrow et al.,  
151 2010; British Ice Sheet: Hughes et al., 2014; Cordilleran Ice Sheet: Kleman et al., 2010;  
152 Fennoscandian Ice Sheet: Stroeve et al., 2016; Laurentide Ice Sheet: Margold et al., 2018;  
153 Patagonian Ice Sheet: Glasser et al., 2008). In recent times, increasingly higher-resolution DEMs have  
154 become available due to the adoption of Light Detection and Ranging (LiDAR) technology (e.g.  
155 Salcher et al., 2010; Jónsson et al., 2014; Miller et al., 2014; Dowling et al., 2015; Hardt et al., 2015;  
156 Putniņš and Henriksen, 2017) and Unmanned Aerial Vehicles (UAVs) (e.g. Chandler et al., 2016a;  
157 Evans et al., 2016a; Ewertowski et al., 2016; Tonkin et al., 2016; Ely et al., 2017). Aside from  
158 improvements to remote sensing technologies, the last decade has seen a revolution in data  
159 accessibility, with the proliferation of freely available imagery (e.g. Landsat data), freeware mapping  
160 platforms (e.g. *Google Earth*) and open-source Geographical Information System (GIS) packages  
161 (e.g. *QGIS*). As a result, tools for glacial geomorphological mapping are becoming increasingly  
162 accessible, both practically and financially.

163

164 Field mapping remains a key component of the geomorphological mapping process, principally in the  
165 context of manageable study areas relating to alpine- and plateau-style ice masses, i.e. cirque glaciers,  
166 valley glaciers, icefields and ice-caps (e.g. Bendle and Glasser, 2012; Boston, 2012a, b; Jónsson et al.,  
167 2014; Gribenski et al., 2016; Lardeux et al., 2016; Brook and Kirkbride, 2018; Małecki et al., 2018).  
168 This approach is also employed in ice sheet settings, but typically in the form of selective ground  
169 checking of mapping from remotely-sensed data or focused mapping of regional sectors (e.g. Stokes  
170 et al., 2013; Bendle et al., 2017a; Pearce et al., 2018). Frequently, field mapping is conducted in  
171 tandem with sedimentological investigations (see Evans and Benn, 2004, for methods), providing a  
172 means of testing preliminary interpretations and identifying problems for specific (and more detailed)  
173 studies. This integrated approach is particularly powerful and enables robust interpretations of genetic  
174 processes, glaciation styles and/or glacier dynamics (e.g. Benn and Lukas, 2006; Evans, 2010;  
175 Benediktsson et al., 2010, 2016; Gribenski et al., 2016). In this context, it is worth highlighting the  
176 frequent use of the term ‘sediment-landform assemblage’ (or ‘landform-sediment assemblage’) as  
177 opposed to ‘landform’ in glacial geomorphology, underlining the importance of studying both surface  
178 form and internal composition (e.g. Evans, 2003a, 2017; Benn and Evans, 2010; Lukas et al., 2017).

179

180 Geomorphological mapping using a combination of field mapping and remotely-sensed data  
181 interpretation (hereafter ‘remote mapping’), or a number of remote sensing methods, permits a holistic  
182 approach to mapping, wherein the advantages of each method/dataset can be combined to produce an  
183 accurate map with robust genetic interpretations (e.g. Boston, 2012a, b; Darvill et al., 2014; Storrar  
184 and Livingstone, 2017). As such, approaches are required that allow the accurate transfer and

185 assimilation of data from these various sources, particularly where data are transferred from analogue  
186 (e.g. hard-copy aerial photographs) to digital format. Apart from a few recent exceptions for specific  
187 locations (e.g. the Scottish Highlands: Boston, 2012a, b; Pearce et al., 2014), there has been limited  
188 explicit discussion of the approaches used to integrate geomorphological data in map production (i.e.  
189 the relative contributions of different methods and/or datasets and their associated uncertainties), with  
190 many contributions simply stating that the maps were produced through fieldwork and/or remote  
191 sensing (e.g. Ballantyne, 1989; Lukas, 2007a; Evans et al., 2009a; McDougall, 2013). Given the  
192 diversity of scales, data sources and research questions inherent in glacial geomorphological research,  
193 and the increasing abundance of high-quality remotely-sensed datasets, finding the most cost- and  
194 time- effective approach is difficult, especially for researchers new to the field.

195

## 196 *1.2 Aims and scope*

197

198 In this contribution, we review the wide range of approaches and datasets available to practitioners  
199 and students for geomorphological mapping in glacial environments. The main aims of this review are  
200 to (i) synthesise scale-appropriate mapping approaches that are relevant to particular glacial settings,  
201 (ii) devise frameworks that will help ensure best practice when mapping, and (iii) encourage clear  
202 communication of details on mapping methods used in glacial geomorphological studies. This will  
203 ensure transparency and aid data transferability against a background of growing demand to collate  
204 geomorphological (and chronological) data in regional compilations (e.g. the BRITICE project: Clark  
205 et al., 2004, 2018a; the DATED-1 database: Hughes et al., 2016). A further aim of this contribution is  
206 to emphasise the continued and future importance of field mapping in geomorphological research,  
207 despite the advent of very high-resolution remotely-sensed datasets in recent years.

208

209 The following two sections of this review focus on field mapping (Section 2) and remote mapping  
210 (Section 3), respectively. We consider these methods in a broadly chronological order to provide  
211 historical context and illustrate the evolution of geomorphological mapping in glacial environments.  
212 Section 4 discusses the errors associated with each mapping method, an important issue that often  
213 receives limited attention within geomorphological studies. Within this discussion, we highlight  
214 approaches that can help manage and minimise residual errors. Subsequently, we review the mapping  
215 methods used in particular glacial environments (Section 5) and synthesise frameworks to help ensure  
216 best practice when mapping (Section 6).

217

218 For the purposes of this review, we distinguish two overarching ‘work streams’: (i) mapping of  
219 palaeo-ice sheet geomorphological imprints using a combined remote sensing approach, with some  
220 field checking (where feasible); and (ii) mapping of alpine- and plateau-style ice mass  
221 geomorphological imprints using a combination of remote sensing and considerable field

222 mapping/checking. The second workstream incorporates a spatial continuum of glacier morphologies,  
223 namely cirque glaciers, valley glaciers, icefields and ice-caps (cf. Sugden and John, 1976; Benn and  
224 Evans, 2010). The rationale for this subdivision is fourfold: Firstly, the approaches are governed by  
225 the size of the (former) glacial systems and thus feasibility of using particular mapping methods in  
226 certain settings (cf. Clark, 1997; Storrar et al., 2013). Secondly, there is a greater overlap of spatial  
227 and temporal scales (i.e. more detailed records are preserved) in areas glaciated by smaller ice masses  
228 that respond more rapidly to climate change (cf. Lukas, 2005, 2012; Bradwell et al., 2013; Boston et  
229 al., 2015; Chandler et al., 2016b). Thirdly, the different mapping methodologies reflect the difficulties  
230 in identifying vertical limits, thickness distribution and surface topography of palaeo-ice sheets (i.e.  
231 emphasis often on mapping bed imprints) (cf. Stokes et al., 2015). Lastly, the overarching methods  
232 employed to map glacial landforms in alpine and plateau settings do not differ fundamentally with ice  
233 mass morphology, i.e. most studies in these environments employ a combination of field mapping and  
234 remote sensing. In Section 5.3, we also specifically consider geomorphological mapping in modern  
235 glacial environments to highlight important issues relating to the temporal resolution of remotely-  
236 sensed data and landform preservation potential. We emphasise the importance of utilising multiple  
237 datasets and/or mapping approaches in an iterative process in all glacial settings (multiple remotely-  
238 sensed datasets in the case of ice-sheet-scale geomorphology) to increase accuracy and robustness,  
239 akin to multi-proxy methodologies used in many Earth Science disciplines.

240

## 241 **2. Field mapping methods**

242

### 243 *2.1 Background and applicability of field mapping*

244

245 Traditionally, glacial geomorphological mapping has been undertaken through extensive field  
246 surveys, an approach that dates back to the late 19<sup>th</sup> Century and early 20<sup>th</sup> Century (e.g. Close, 1867;  
247 Goodchild, 1875; Partsch, 1894; Sollas, 1896; Penck and Brückner, 1901/1909; Kendall, 1902;  
248 Wright, 1912; Hollingworth, 1931; Caldenius, 1932). Field mapping involves traversing the study  
249 area and recording pertinent landforms onto (enlarged) topographic base maps (Figure 1). Typically,  
250 field mapping is conducted at cartographic scales of ~1: 10,000 (e.g. Leser and Stäblein, 1975; Rupke  
251 and De Jong, 1983; Thorp, 1986; Ballantyne, 1989; Evans, 1990; Benn et al., 1992; Mitchell and  
252 Riley, 2006; Rose and Smith, 2008; Boston, 2012a, b) or 1: 25,000 (e.g. Leser, 1983; Ballantyne,  
253 2002, 2007a, b; Benn and Ballantyne, 2005; Lukas and Lukas, 2006). Occasionally, it is conducted at  
254 even larger scales, such as 1: 1,000 to 1: 5,000, but this is most appropriate for small areas or project-  
255 specific purposes (e.g. Kienholz, 1977; Leser, 1983; Lukas et al., 2005; Coray, 2007; Graf, 2007;  
256 Reinardy et al., 2013).

257



258 With improvements in technology, the widespread availability of remotely-sensed datasets, and a  
259 concomitant ease of access to high-quality printing facilities, alternative approaches to the traditional,  
260 *purely* field mapping method have also been employed, including (i) documenting sediment-landform  
261 assemblages during extensive field campaigns both prior to and after commencing remote mapping  
262 (e.g. Dyke et al., 1992; Krüger 1994; Lukas and Lukas, 2006; Kjær et al. 2008; Boston, 2012a, b;  
263 Jónsson et al., 2014; Schomacker et al. 2014; Everest et al., 2017), (ii) mapping directly onto or  
264 annotating print-outs of imagery (e.g. aerial photographs) in the field (e.g. Lovell, 2014), (iii)  
265 recording the locations of individual landforms using a (handheld) Global Navigation Satellite System  
266 (GNSS) device (e.g. Bradwell et al., 2013; Brynjólfsson et al., 2014; Lovell, 2014; Małecki et al.,  
267 2018), or (iv) digitally mapping landforms in the field using a ruggedised tablet PC with built-in  
268 GNSS and GIS software (e.g. Finlayson et al., 2011; Pearce et al., 2014). These approaches to field  
269 mapping are particularly useful where large-scale topographic maps are unavailable or out of date.

270

271 Detailed field mapping is typically restricted to alpine- and plateau-style ice masses due to logistical  
272 and financial constraints (Clark, 1997; Storrar et al., 2013). When conducted at the ice sheet scale,  
273 field mapping is (or historically was) undertaken either as part of long-term campaigns by national  
274 geological surveys in conjunction with surficial geology mapping programmes (e.g. Barrow et al.,  
275 1913; Flint et al., 1959; Krygowski, 1963; Campbell, 1967a, b; Hodgson et al., 1984; Klassen, 1993;  
276 Priamonosov et al., 2000; Follestad and Bergstrøm, 2004) or necessarily highly-selective ground-  
277 truthing of remote mapping (e.g. Kleman et al., 1997, 2010; Golledge and Stoker, 2006; Stokes et al.,  
278 2013; Darvill et al., 2014; Stroeven et al., 2016; Pearce et al., 2018).

279

## 280 *2.2 The field mapping process*

281

282 Field mapping should ideally begin with systematic traverses of the study area – sometimes referred  
283 to as a ‘walk-over’ (e.g. Demek, 1972; Otto and Smith, 2013) – to get a sense of the scale of the study  
284 area and ensure that subtle features of importance, such as the location and orientation of ice-flow  
285 directional indicators (e.g. flutes, striae, roches moutonnées and ice-moulded bedrock), are not  
286 missed. In a palaeo-ice sheet context, mapping the location and orientation of striae in the field may  
287 be of most interest as these can provide information on multiple (local) ice flow directions, of which  
288 not all are recorded in the pattern of elongated bedforms (e.g. drumlins) mappable from remotely-  
289 sensed data (cf. Kleman, 1990; Hättestrand and Stroeven, 1996; Smith and Knight, 2011). Similarly,  
290 in a contemporary outlet glacier context, flutes are an important indicator of ice flow direction –  
291 sometimes of annual ice flow trajectories of glacier margins (cf. Chandler et al., 2016a; Evans et al.,  
292 2017) – but due to their subtlety they may only be identifiable in the field (e.g. Jónsson et al., 2014).

293

294 Traversing should ideally start from higher ground, where an overview can be gained, and proceed by  
295 crossing a valley axis (or a cirque floor, for example) many times to enable the viewing and  
296 assessment of landforms from as many perspectives, angles and directions as possible (cf. Demek,  
297 1972). In addition to systematic traverses, landform assemblages in, for example, individual  
298 valleys/basins should ideally be viewed from a high vantage point in low light (e.g. Benn, 1990).  
299 Depending on the location and orientation of landforms, it may be beneficial to see the same area  
300 either (i) early in the morning or late in the afternoon/evening due to longer shadows, or (ii) both in  
301 the morning and afternoon/evening due to the changing position of longer shadows. These procedures  
302 ensure that apparent dimensions and orientations, which are influenced by perception under different  
303 viewing angles and daylight conditions, can be taken into account in descriptions and interpretations.  
304 This approach circumvents potential complications relating to subtle features that may only be visible  
305 from one direction or certain angles.

306

307 The location of features should be recorded on field maps or imagery (e.g. aerial photograph) extracts  
308 with reference to ‘landmarks’ that are clearly identifiable both in the field and on the base  
309 maps/imagery, such as distinct changes in contour-line inflection, lakes, river bends, confluences,  
310 prominent bedrock exposures, and large ridges or mounds (Lukas and Lukas, 2006; Boston, 2012a, b).  
311 Where geomorphological features are small, background relief is low and/or conspicuous reference  
312 points are absent, a network of mapped reference points can be established by either taking a series of  
313 cross-bearings on prominent features using a compass (e.g. Benn, 1990) or by verifying locations  
314 using a handheld GNSS (e.g. Lukas and Lukas, 2006; Boston, 2012a, b; Brynjólfsson et al., 2014;  
315 Jónsson et al. 2014; Lovell, 2014; Pearce et al., 2014; van der Bilt et al., 2016). The latter is useful for  
316 recording the location of point-data such as striae, erratic or glacially-transported boulders, and  
317 sediment exposures (cf. Lukas and Lukas, 2006; Boston, 2012a, b; Pearce et al., 2014). Additional  
318 information between known reference points can then be interpolated and marked on the  
319 geomorphological map.

320

321 Establishing the size of landforms and features and plotting them on the map as accurately as possible  
322 is of crucial importance, and in addition to the inflections of contours (which may mark the location  
323 and boundaries of prominent ridges, for example), the mapper may pace out and/or estimate lengths,  
324 heights and widths. For larger landforms, or those masked by forest, walking around the perimeter of  
325 landforms and establishing a GNSS-marked ‘waypoint-trail’ is a good first approximation.

326

327 The strategy outlined above offers a broad perspective on the overall landform pattern and ensures  
328 accurate representation of landforms on field maps. To ensure accurate genetic interpretation of  
329 individual landforms, and the landscape as a whole, this field mapping strategy should ideally form  
330 part of an iterative process of observation and interpretation whilst still in the field (see Section 2.3).

331

### 332 *2.3 Interpreting glacial landforms*

333

334 In the preceding section, we focused on the technical aspects of field mapping and the means of  
335 recording glacial landforms. However, geomorphological mapping typically forms the foundation of  
336 process-oriented studies and palaeoglaciological reconstructions (see Section 1.1) and should,  
337 therefore, be embedded within a process of observation and interpretation. Definitive interpretation of  
338 glacial landforms, and glacial landscapes as a whole, can rarely be made on the basis of surface  
339 morphology alone. Additional strands of field evidence may become highly relevant, if not essential,  
340 depending on the objectives of the individual project: sedimentological data are crucial to interpreting  
341 processes of landform formation and glacier dynamics (e.g. Lukas, 2005; Benn and Lukas, 2006;  
342 Benediktsson et al., 2010, 2016; Chandler et al., 2016a; Gribenski et al., 2016), whilst chronological  
343 data are fundamental to robust palaeoglaciological reconstructions and related palaeoclimatic studies  
344 (e.g. Finlayson et al., 2011; Gribenski et al., 2016, 2018; Hughes et al., 2016; Stroeven et al., 2016;  
345 Bendle et al., 2017b; Darvill et al., 2017). Moreover, time and resources are limited and pragmatism  
346 necessary. Thus, observations must be targeted efficiently and effectively, in line with the research  
347 aims.

348

349 Much field-based research adopts an inductive approach, in which observations are collected and used  
350 to argue towards a particular conclusion. This is a valid approach at the exploratory stage of research,  
351 but deeper understanding of a landscape requires a more iterative process, in which data collection is  
352 conducted within a framework of hypothesis generation and testing. For this reason, it is useful to  
353 adopt a number of alternative working hypotheses (Chamberlin, 1897) that can be tested and  
354 gradually eliminated, following the principle of falsification (Popper, 1972). This process is best  
355 conducted in the field when it is possible to make key observations to test an interpretation, especially  
356 if the field site is remote and expensive to re-visit.

357

358 Following initial data collection, preliminary interpretations can be used to predict the outcome of  
359 new observations, which can then be used to test and refine the interpretation. Well-framed  
360 hypotheses allow an investigator to anticipate other characteristics of a glacial landscape and to test  
361 those predictions by targeted investigation of key localities (see Benn, 2006). For example, the  
362 presence of a certain group of landforms (e.g. moraines trending downslope into a side valley) can be  
363 used to formulate hypotheses (e.g. blockage of the side-valley by glacier ice, and formation of a  
364 glacial lake), which in turn can be used to predict the presence of other sediment-landform  
365 associations in a particular locality (e.g. lacustrine sediments or shoreline terraces in the side-valley).  
366 Further detailed geomorphological mapping (and sedimentological analyses) in that area would then  
367 allow testing and falsification of the alternative working hypotheses. Iterations of this process during

368 field mapping enable an increasingly detailed and robust understanding of the glacier system to be  
369 constructed. This coupled inductive-deductive approach is much more powerful than a purely  
370 inductive process: narratives that ‘explain’ a set of observations can appear very persuasive, even self-  
371 evident, but there may be other narratives that are also consistent with the same observations (cf.  
372 Popper, 1972).

373

374 Process-form models are useful tools in this inductive-deductive approach to landscape interpretation.  
375 In particular, *landsystem* or *facies models* make explicit links between landscape components and  
376 genetic processes, providing structure and context for data collection and interpretation (e.g. Eyles,  
377 1983; Brodzikowski and van Loon, 1991; Evans, 2003a; Benn and Evans, 2010). At best, process-  
378 form models are not rigid templates or preconceived categories into which observations are forced,  
379 but a flexible set of possibilities that can guide, shape and enrich investigations (Benn and Lukas,  
380 2006). For example, preliminary remote mapping may reveal features that suggest former glacier  
381 lobes may have surged (e.g. Lovell et al., 2012). Systematic study of sediment-landform assemblages,  
382 sediment exposures and other evidence, with reference to modern analogues (e.g. Evans and Rea,  
383 2003), allows this idea to be rigorously evaluated in a holistic context (e.g. Darvill et al., 2017). This  
384 can open up new avenues for research in a creative and open-ended process.

385

386 This inductive-deductive approach to interpreting glacial landscapes and events should be embedded  
387 as part of the geomorphological mapping process (see Section 6). When dealing with palaeo-ice  
388 sheets, such field-based investigations may be guided by (existing) remote mapping. In alpine and  
389 plateau-style ice mass settings, sedimentological and chronological investigations should ideally form  
390 an integral part of field surveys.

391

### 392 **3. Remote mapping methods**

393

394 In the following sections, we review the principal remote mapping approaches employed in glacial  
395 geomorphological research, with analogue (or hard-copy) remote mapping (Section 3.1) and digital  
396 remote mapping (Section 3.2) considered separately. We give an overview of a number of datasets  
397 used for digital remote (i.e. GIS-based) mapping, namely satellite imagery (see Section 3.2.2.1), aerial  
398 photographs (see Section 3.2.2.2), digital elevation models (see Section 3.2.2.3), freeware virtual  
399 globes (see Section 3.2.2.4) and UAV-captured imagery (see Section 3.2.2.5). Each individual section  
400 provides a brief outline of the historical background and development of the methods, and we discuss  
401 the individual approaches in a broadly chronological order. Section 3.3 provides an overview of  
402 image processing techniques, highlighting that pragmatic solutions are often required.

403

404 We focus principally on remotely-sensed datasets relevant to terrestrial (onshore) glacial settings in  
405 the following sections because submarine (bathymetric) datasets and mapping of submarine glacial  
406 landforms have been subject to recent reviews elsewhere (see Dowdeswell et al., 2016; Batchelor et  
407 al., 2017). Nevertheless, we acknowledge that the emergence of geophysical techniques to investigate  
408 submarine (offshore) glacial geomorphology is a major development over the last two decades.  
409 Similarly, the emergence of geophysical datasets of sub-ice geomorphology in the last decade or so  
410 has been revolutionary, particularly in relation to subglacial bedforms (see Stokes, 2018). Many of the  
411 issues we discuss in relation to mapping from DEMs are transferable to those environments.

412

### 413 *3.1 Analogue remote mapping*

414

#### 415 *3.1.1 Background and applicability of analogue remote mapping*

416 Geomorphological mapping from analogue (hard-copy) aerial photographs became a mainstream  
417 approach in glacial geomorphology in the 1960s and 1970s, with early proponents including, for  
418 example, the Geological Survey of Canada (e.g. Craig, 1961, 1964; Prest et al., 1968) and UK-based  
419 researchers examining the Quaternary geomorphology of upland Britain (e.g. Price, 1961, 1963;  
420 Sissons, 1967, 1977a, b, 1979a, b; Sugden, 1970) and contemporary glacial landsystems (e.g. Petrie  
421 and Price, 1966; Price, 1966; Welch, 1966, 1967, 1968; Howarth, 1968; Howarth and Welch, 1969a,  
422 b). The latter research on landsystems in Alaska and Iceland was particularly pioneering in that it  
423 exploited a combination of aerial photograph interpretation, surveying techniques and early  
424 photogrammetry (see Evans, 2009, for further details).

425

426 Despite continued development of remote sensing technologies and the availability of digital aerial  
427 photographs (see Section 3.2.2.2), analogue stereoscopic aerial photographs are still used for glacial  
428 geomorphological mapping (e.g. Hättestrand, 1998; Benn and Ballantyne, 2005; Lukas et al., 2005;  
429 Hättestrand et al., 2007; Boston, 2012a, b; Evans and Orton, 2015). Additionally, the availability of  
430 high-quality photogrammetric scanners means that archival, hard-copy aerial photographs can be  
431 scanned at high resolutions, processed using digital photogrammetric methods and subsequently used  
432 for on-screen vectorisation (Section 3.2; e.g. Bennett et al., 2010; Jónsson et al., 2014).

433

434 As with field mapping, the interpretation of analogue aerial photographs is primarily used for  
435 mapping alpine- and plateau-style ice mass geomorphological imprints. Historically, analogue aerial  
436 photograph interpretation was extensively used for mapping palaeo-ice sheet geomorphological  
437 imprints, particularly by the Geological Survey of Canada, who combined aerial photograph  
438 interpretation with detailed ground checking and helicopter-based surveys (e.g. Craig, 1961, 1964;  
439 Hodgson et al., 1984; Aylsworth and Shilts, 1989; Dyke et al., 1992; Klassen, 1993; Dyke and  
440 Hooper, 2001). Similarly, panchromatic and/or infrared vertical aerial photographs were used

441 extensively to map glacial landforms relating to the Fennoscandian Ice Sheet (e.g. Sollid et al., 1973;  
442 Kleman, 1992; Hättestrand, 1998; Hättestrand et al., 1999). Aerial photograph interpretation has  
443 largely been superseded by satellite imagery and DEM interpretation in palaeo-ice sheet settings (see  
444 Section 5.1) but is applied in palaeo-ice sheet contexts for more detailed mapping of selected and/or  
445 complex areas (e.g. Dyke, 1990; Hättestrand and Clark, 2006; Kleman et al., 2010; Stokes et al.,  
446 2013; Storrar et al., 2013; Darvill et al., 2014; Evans et al., 2014).

447

### 448 *3.1.2 Mapping from analogue datasets*

449 For glacial geomorphological mapping purposes, vertical panchromatic aerial photographs have  
450 traditionally been employed, with pairs of photographs (stereopairs) viewed in stereo using a  
451 stereoscope (with magnification) (e.g. Karlén, 1973; Melander, 1975; Horsfield, 1983; Krüger, 1994;  
452 Kleman et al., 1997; Hättestrand, 1998; Evans and Twigg, 2002; Jansson, 2003; Benn and Ballantyne,  
453 2005; Lukas and Lukas, 2006; Boston, 2012a, b; Chandler and Lukas, 2017). During aerial surveys,  
454 longitudinally-overlapping photographs along the flight path (endlap  $\geq 60\%$ ) are captured in a series  
455 of laterally-overlapping parallel strips (sidelap  $\geq 30\%$ ), with the two different viewing angles of the  
456 same area resulting in the stereoscopic effect (due to the principle of parallax; see Lillesand et al.,  
457 2015, for further details). This form of aerial photograph interpretation has been demonstrated to be a  
458 particularly valuable tool for determining the exact location, shape and planform of small features in  
459 glaciated terrain (e.g. Ballantyne, 1989, 2002, 2007a, b; Bickerton and Matthews, 1992, 1993; Lukas  
460 and Lukas, 2006; Boston, 2012a, b), provided the photographs are of appropriate scale, quality and  
461 tonal contrast (cf. Benn, 1990; Benn et al., 1992).

462

463 Mapping from hard-copy aerial photographs is undertaken by drawing onto acetate sheets  
464 (transparency films) whilst viewing the aerial photographs through a stereoscope, with the acetate  
465 overlain on one photograph of a stereopair (Figure 2). Ideally, mapping should be conducted using a  
466 super-fine pigment liner with a nib size of 0.05 mm to enable small features to be mapped. Even so, it  
467 may still be necessary to compromise on the level of detail mapped; for example, meltwater channels  
468 between ice-marginal moraines have been left off maps in some studies due to map scale, with the  
469 associated text describing chains of moraines interspersed with meltwater channels (e.g. Benn and  
470 Ballantyne, 2005; Lukas, 2005).

471

472 Examining stereopairs from multiple sorties ('flight missions') in parallel or in combination with  
473 digital aerial photographs may be beneficial and help alleviate issues such as localised cloud cover,  
474 snow cover, poor tonal contrast, afforestation, and anthropogenic developments (e.g. Horsfield, 1983;  
475 Bennett, 1991; McDougall, 2001). Additionally, it is advantageous to examine stereopairs multiple  
476 times – preferably before and after field mapping – to increase feature identification and improve the  
477 accuracy of genetic interpretations (Lukas and Lukas, 2006; Sahlin and Glasser, 2008). When

478 conducting mapping over a large area with multiple stereopairs, examining stereopairs from a sortie  
479 'out of sequence' (i.e. not mapping from consecutive pairs of photographs) may provide a means of  
480 internal corroboration and ensure objectivity and robustness (Bennett, 1991).

481

482 In order to reduce geometric distortion, which increases towards the edges of aerial photographs due  
483 to the central perspective (Lillesand et al., 2015), it is advisable to keep the areas mapped onto the  
484 acetate as close as possible to the centre of one aerial photograph of a stereopair (Kronberg, 1984;  
485 Lukas, 2002, 2005a; Evans and Orton, 2015). These hand-drawn overlays can subsequently be  
486 scanned at high resolutions and then georeferenced and vectorised using GIS software (see Section  
487 3.3.1).

488

### 489 *3.2 Digital remote mapping*

490

#### 491 *3.2.1 Background and applicability of digital remote mapping*

492 The development of GIS software packages (e.g. commercial: *ArcGIS*; open source: *QGIS*) and the  
493 proliferation of digital imagery, particularly freely available satellite imagery, have undoubtedly been  
494 the most significant developments in glacial geomorphological mapping in the last fifteen years or so.  
495 GIS packages have provided platforms and tools for visualising, maintaining, manipulating and  
496 analysing vast quantities of remotely-sensed and geomorphological data (cf. Gustavsson et al., 2006,  
497 2008; Napieralski et al., 2007b). Their use in combination with digital imagery allows  
498 geomorphological features to be mapped directly in GIS software (Figure 3), with individual vector  
499 layers created for each geomorphological feature. Moreover, the availability of digital imagery  
500 enables the mapper to alter the viewing scale instantaneously and switch between various  
501 datasets/types, allowing for a flexible but systematic approach.

502

503 Digital mapping (on-screen vectorisation/tracing) also provides georeferenced geomorphological data,  
504 which has two important benefits: Firstly, these data can easily be used to extract landform metrics  
505 (e.g. Hättestrand et al., 2004; Clark et al., 2009; Spagnolo et al., 2010, 2014; Storrar et al., 2014; Ojala  
506 et al., 2015; Dowling et al., 2016; Ely et al., 2016a, 2017a); and, secondly, these data can be  
507 seamlessly incorporated into wider, regional-scale GIS compilations (e.g. Bickerdike et al., 2016;  
508 Stroeven et al., 2016; Clark et al., 2018a). Additionally, digital remote mapping allows the user to  
509 record attribute data (e.g. data source) tied to individual map (vector) layers, which can be useful for  
510 large compilations of previously published mapping (e.g. Bickerdike et al., 2016; Clark et al., 2018a).  
511 Such compendia help to circumvent issues relating to the often-fragmented nature of  
512 geomorphological evidence (i.e. numerous spatially separate studies) and identify gaps in the mapping  
513 record. Once assembled across large areas, they also enable evidence-based reconstructions of entire  
514 ice sheets and regional ice sheet sectors (see Clark et al., 2004, 2018a). Indeed, the ongoing open

515 access data revolution in academia and the increasing publication/availability of mapping output (in  
516 the form of GIS files; e.g. Finlayson et al., 2011; Fu et al., 2012; Darvill et al., 2014; Bickerdike et al.,  
517 2016; Bendle et al., 2017a), means that geomorphological mapping can have wider impact beyond  
518 individual local to regional studies.

519

### 520 *3.2.2 Datasets for digital remote mapping*

521 There is now a plethora of remotely-sensed datasets covering a wide range of horizontal resolutions  
522 ( $10^{-2}$  to  $10^2$  m), enabling the application of digital mapping (in some form) to all glacial settings. We  
523 provide an overview of the principal datasets used in digital mapping below, with mapping  
524 approaches in specific glacial settings reviewed in Section 5.

525

526 *3.2.2.1 Satellite imagery.* The development of satellite-based remote sensing in the 1970s and  
527 subsequent advances in technology have revolutionised understanding of glaciated terrain, particularly  
528 with respect to palaeo-ice sheet geomorphology and dynamics (see Section 5.1; Clark, 1997; Stokes,  
529 2002; Stokes et al., 2015). The potential of satellite imagery was first demonstrated by the pioneering  
530 work of Sugden (1978), Andrews and Miller (1979) and Punkari (1980), with the availability of large-  
531 area view (185 km x 185 km) Landsat Multi-Spectral Scanner (MSS) images affording a new  
532 perspective of glaciated regions. These allowed a single analyst to systematically map ice-sheet-scale  
533 (1:45,000 to 1: 1,000,000) glacial geomorphology (e.g. Boulton and Clark, 1990a, b) in a way that  
534 previously would have required the painstaking mosaicking of thousands of aerial photographs (e.g.  
535 Prest et al., 1968).

536

537 Since the 1980s, there has been an explosion in the use of satellite imagery for glacial  
538 geomorphological mapping and there is now a profusion of datasets available (Table 1). Importantly,  
539 many of these sensors capture multispectral data, which can enhance landform detection through  
540 image processing and the use of different band combinations (see Section 3.3.2). The uptake of  
541 satellite imagery has coincided with improvements in the availability and spatial and spectral  
542 resolution of satellite datasets globally, with Landsat (multispectral: 30 m; panchromatic: 15 m),  
543 ASTER (15 m), Sentinel-2 (10 m) and SPOT (up to 1.5 m) images proving the most popular. More  
544 recently, satellite sensor advancements have enabled the capture of satellite images with resolutions  
545 comparable to aerial photographs (Figure 4; e.g. QuickBird, SPOT6-7, WorldView-2 and later). These  
546 datasets are also suitable for mapping typically smaller and/or complex glacial landforms produced by  
547 cirque glaciers, valley glaciers and icefield/ice-cap outlets (e.g. Chandler et al., 2016a; Evans et al.,  
548 2016b; Ewertowski et al., 2016; Gribenski et al., 2016; Małeckı et al., 2018).

549

550 In general, as better-resolution imagery has become more widely available at low to no cost, older,  
551 coarser-resolution datasets (e.g. Landsat MSS: 60 m) have largely become obsolete. Nevertheless,



552 Landsat data (TM, ETM+, and OLI: 15 to 30 m) are still the standard data source for ice-sheet-scale  
553 mapping, with the uptake of high-resolution commercial satellite imagery still relatively slow in such  
554 studies. This is primarily driven by the cost of purchasing high-resolution commercial datasets,  
555 making freely-available imagery such as Landsat a valuable resource. In addition, archival satellite  
556 data afford time-series of multi-spectral images that may facilitate assessments of geomorphological  
557 changes through time; for example, fluctuations in highly dynamic (surging or rapidly retreating)  
558 glacial systems (e.g. Flink et al., 2015; Jamieson et al., 2015). Conversely, for smaller research areas  
559 (e.g. for a single valley or foreland), high-resolution satellite imagery is becoming an increasingly  
560 viable option, with prices for georeferenced and orthorectified products comparable to those for  
561 digital aerial photographs (see Section 3.2.2.2). This also has the benefit of saving time on  
562 photogrammetric processing, with many vendors providing consumers with various processing  
563 options. Consequently, on-demand, high-resolution (commercial) satellite imagery will inevitably  
564 come into widespread usage, where costs are not prohibitive. Alternatively, freeware virtual globes  
565 and web mapping services (e.g. *Bing Maps*, *Google Earth*) offer valuable resources for free  
566 visualisation of such high-resolution imagery (see Section 3.2.2.4).

567

568 *3.2.2.2 Digital aerial photographs.* With improvements in technology, high-resolution (ground  
569 resolution <0.5 m per pixel) digital copies of aerial photographs have become widely available and  
570 used for glacial geomorphological mapping (e.g. Brown et al., 2011a; Bradwell et al., 2013;  
571 Brynjólfsson et al., 2014; Jónsson et al., 2014; Pearce et al., 2014; Schomacker et al., 2014; Chandler  
572 et al., 2016a; Evans et al., 2016c; Lardeux et al., 2016; Lønne, 2016; Allaart et al., 2018). Indeed,  
573 digital aerial photographs, along with scanned copies of archival aerial photographs, are now more  
574 widely used than hard-copy stereoscopic aerial photographs, particularly in modern glacial settings.  
575 Additionally, the introduction of UAV technology in recent years has allowed sub-decimetre  
576 resolution aerial photographs to be captured on demand (see Section 3.2.2.5). A further key advantage  
577 of aerial photographs in digital format is the ability to produce orthorectified aerial photograph  
578 mosaics (or ‘orthophotographs’) and DEMs with low root mean square errors (RMSEs <1 m; see  
579 Section 4.4), when combined with ground control points (GCPs) collected using surveying equipment  
580 (e.g. Kjær et al. 2008; Bennett et al., 2010; Schomacker et al., 2014; Chandler et al., 2016b; Evans et  
581 al., 2017). These photogrammetric products can then be used for on-screen vectorisation (tracing) and  
582 the generation of georeferenced geomorphological mapping (Figure 5), as outlined above.

583

584 Digital aerial photographs are commonly captured by commercial surveying companies (e.g.  
585 Loftmyndir ehf, Iceland; Getmapping, UK), meaning that they may be expensive to purchase and  
586 costs may be prohibitive for large study areas. This is in contrast to hard-copy (archival) aerial  
587 photographs that are often freely available for viewing in national collections. Additionally, digital  
588 aerial photographs are not readily viewable in stereo with a standard desktop setup, although on-

589 screen mapping in stereoscopic view is possible on workstations equipped with stereo display and  
590 software such as *BAE Systems SO CET SET* (e.g. Kjær et al., 2008; Benediktsson et al., 2009).  
591 However, this approach is not applicable to orthophotographs. An alternative approach is to visualise  
592 orthophotographs in 3D by draping them over a DEM (see Section 3.2.2.3) in GIS software such as  
593 *ESRI ArcScene* or similar (Figure 6; e.g. Benediktsson et al., 2010; Jónsson et al., 2014; Schomacker  
594 et al., 2014; van der Bilt et al., 2016). Three-dimensional assessment in *ArcScene*, parallel to mapping  
595 in *ArcMap*, may aid in landform detection, delineation and interpretation.

596  
597 *3.2.2.3 Digital Elevation Models (DEMs)*. Over the last ~15 years there has been increasing use of  
598 DEMs in glacial geomorphology, particularly for mapping at the ice sheet scale (e.g. Glasser and  
599 Jansson, 2008; Hughes et al., 2010; Ó Cofaigh et al., 2010; Evans et al., 2014, 2016d; Ojala, 2016;  
600 Principato et al., 2016; Stokes et al., 2016a; Mäkinen et al., 2017; Norris et al., 2017). DEMs are  
601 raster-based models of topography that record absolute elevation, with each grid cell in a DEM  
602 representing the average height for the area it covers (Clark, 1997; Smith et al., 2006). Terrestrial  
603 DEMs can be generated by a variety of means, including from surveyed contour data, directly from  
604 stereo imagery (aerial photographs, satellite and UAV-captured imagery), or from air- and space-  
605 borne radar and LiDAR systems (Smith and Clark, 2005). An important recent development in this  
606 regard has been the ‘Surface Extraction with TIN-based Search-space Minimization’ (SETSM)  
607 algorithm for automated extraction of DEMs from stereo satellite imagery (Noh and Howat, 2015),  
608 which has been used to generate the ArcticDEM dataset (<https://www.pgc.umn.edu/data/arcticdem/>).  
609 However, SETSM DEMs may contain systematic vertical errors that require correction (e.g. Carrivick  
610 et al., 2017; Storrar et al., 2017).

611  
612 The majority of DEMs with national- to international-scale coverage (Table 2) typically have a  
613 coarser spatial resolution than aerial photographs and satellite imagery and represent surface  
614 elevations rather than surface reflectance. As a result, it may be difficult to identify glacial landforms  
615 produced by relatively small ice masses (cirque glaciers, valley glaciers and icefield outlets),  
616 precluding detailed mapping of their planforms (cf. Smith et al., 2006; Hughes et al., 2010; Brown et  
617 al., 2011a; Boston, 2012a, b; Pearce et al., 2014). Conversely, these DEMs can be particularly  
618 valuable for mapping glacial erosional features (e.g. glacial valleys, meltwater channels), as well as  
619 major glacial depositional landforms produced by larger ice masses (e.g. Greenwood and Clark, 2008;  
620 Heyman et al., 2008; Livingstone et al., 2008; Hughes et al., 2010; Morén et al., 2011; Barr and Clark,  
621 2012; Stroeven et al., 2013; Turner et al., 2014a; Margold et al., 2015a; Blomdin et al., 2016a, b;  
622 Lindholm and Heyman, 2016; Mäkinen et al., 2017; Storrar and Livingstone, 2017). However, the  
623 recent development of UAV (see section 3.2.2.5) and LiDAR technologies have allowed the  
624 generation of very high resolution DEMs (<0.1 m), enabling the application of DEMs to map small  
625 glacial landforms (e.g. Evans et al., 2016a; Ewertowski et al., 2016; Ely et al., 2017). We anticipate

626 national-scale LiDAR DEMs becoming widely-used in the future, with a number of nations recently  
627 releasing or currently capturing/processing high horizontal resolution ( $\leq 2$  m) LiDAR data (Table 2;  
628 e.g. Dowling et al. 2013; Johnson et al. 2015).

629

630 Although the principal focus of this contribution is terrestrial/onshore glacial geomorphological  
631 mapping, it is worth highlighting here that the availability of spatially-extensive bathymetric charts,  
632 such as the General Bathymetric Chart of the Oceans (GEBCO) and International Bathymetric Chart  
633 of the Arctic Ocean (IBCAO: Jakobsson et al., 2012), and high-resolution, regional (often industry-  
634 acquired) bathymetric data has been an important development in submarine/offshore glacial  
635 geomorphological mapping. This has enabled the gridding of DEMs to map submarine glacial  
636 geomorphological imprints (see Dowdeswell et al., 2016), markedly enhancing understanding of  
637 palaeo-ice sheets in marine sectors (e.g. Ottesen et al., 2005, 2008a, 2016; Bradwell et al., 2008;  
638 Winsborrow et al., 2010, 2012; Livingstone et al., 2012; Ó Cofaigh et al., 2013; Hodgson et al., 2014;  
639 Stokes et al., 2014; Margold et al., 2015a, b; Greenwood et al., 2017) and modern tidewater (often  
640 surging) glaciers (e.g. Ottesen and Dowdeswell, 2006; Ottesen et al., 2008b, 2017; Robinson and  
641 Dowdeswell, 2011; Dowdeswell and Vazquez, 2013; Flink et al., 2015; Streuff et al., 2015; Allaart et  
642 al., 2018). In addition, recent years have seen the production of DEMs of sub-ice topography from  
643 geophysical datasets (radar and seismics) at spatial resolutions suitable for identifying and mapping  
644 bedforms (see King et al., 2007, 2009, 2016a; Smith et al., 2007; Smith and Murray, 2009). This work  
645 has advanced understanding of the evolution of bedforms beneath Antarctic ice streams, providing  
646 important genetic links between the formation of landforms beneath modern ice sheets and those left-  
647 behind by palaeo-ice masses (Stokes, 2018). The interested reader is directed to recent reviews for  
648 further discussion on the importance of geophysical evidence for understanding ice sheet extent and  
649 dynamics (Livingstone et al., 2012; Ó Cofaigh, 2012; Stokes et al., 2015; Dowdeswell et al., 2016;  
650 Batchelor and Dowdeswell, 2017; Stokes, 2018).

651

652 *3.2.2.4 Freeware virtual globes.* The advent of freeware virtual globes (e.g. *Google Earth*, *NASA*  
653 *Worldwind*) and web mapping services (e.g. *Bing Maps*, *Google Earth Engine*, *Google Maps*) has  
654 provided platforms for free visualisation of imagery from various sources and low-cost mapping  
655 resources. A key benefit of virtual globes is the ability to visualise imagery and terrain in 3D and from  
656 multiple viewing angles, which may aid landform detection when used in conjunction with other  
657 datasets and software (e.g. Heyman et al., 2008; Bendle et al., 2017a). Moreover, a number of virtual  
658 globes and web mapping services have the ability to link with other freeware and open-source  
659 programmes; for example, free plugins are available to import *Google Earth* and *Bing Maps* imagery  
660 into the open-source GIS software package *QGIS*. Thus, a mapper can combine freely available, often  
661 high-resolution (e.g. QuickBird, SPOT6-7, WorldView-2 and later), imagery and the capabilities of

662 GIS technology without the expense associated with commercial imagery and software (see Sections  
663 3.2.2.1 and 3.2.2.2).

664

665 The most widely-used virtual globe is *Google Earth*, with a ‘professional’ version (*Google Earth Pro*)  
666 freely available since 2015 (see Mather et al., 2015, for a review). An increasing number of glacial  
667 geomorphological studies are noting the use of *Google Earth* (but not necessarily the imagery type) as  
668 a mapping tool (see Table 1), principally to cross-check mapping conducted from other imagery.  
669 However, some studies have also utilised the built-in vectorising tools for mapping (e.g. Margold and  
670 Jansson, 2011; Margold et al., 2011; Fu et al., 2012). There is a compromise on the functionality of  
671 freeware virtual globes and vectorisation tools are often not as flexible and/or user-friendly, but these  
672 can be overcome by importing imagery into GIS software. In the case of *Google Earth*, it is also  
673 possible to export Keyhole Markup Language (KML) files that can be used for subsequent analyses  
674 and map production in GIS software (following file conversion). Open access remotely-sensed  
675 datasets are also available through commercial GIS software, with high resolution satellite imagery  
676 (e.g. GeoEye-1, SPOT-5, WorldView) available for mapping through the in-built ‘World Imagery’  
677 service in *ESRI ArcGIS* (e.g. Bendle et al., 2017a).

678

679 Despite the benefits, some caution is necessary when using freeware virtual globes as there may be  
680 substantial errors in georeferencing of imagery, which users cannot account for and/or correct.  
681 Moreover, dating of imagery is not necessarily clear or accurate (Mather et al., 2015; Wyshnytzky,  
682 2017). The latter may not be a concern if mapping in a palaeoglaciological setting, whilst any  
683 georeferencing errors may not be as significant if mapping broad patterns at the ice sheet scale.  
684 Conversely, errors associated with freeware mapping may be significant when comparing imagery  
685 from different times and/or when mapping in highly dynamic, contemporary glacial environments.  
686 Aside from these potential issues, limitations are imposed by pre-processing of imagery, with no  
687 option to, for example, modify band combinations to enhance landform detection (see Section 3.3.2).

688

689 *3.2.2.5 UAV-captured imagery.* The recent emergence of UAV technology provides an alternative  
690 method for the acquisition of very high-resolution (<0.1 m per pixel) geospatial data that circumvents  
691 some of the issues associated with more established approaches, particularly in relation to temporal  
692 resolution and the high-cost of acquiring commercial remotely-sensed data (see also Smith et al.,  
693 2016a). Following the initial acquisition of the UAV and associated software, this method provides a  
694 rapid, flexible and relatively inexpensive means of acquiring up-to-date imagery at an unprecedented  
695 spatial resolution and it is becoming increasingly employed in glacial research (Figure 7; Rippin et al.,  
696 2015; Ryan et al., 2015; Chandler et al., 2016b; Ewertowski et al., 2016; Tonkin et al., 2016; Westoby  
697 et al., 2016; Ely et al., 2017; Allaart et al., 2018). UAV-captured images are processed using  
698 Structure-from-Motion (SfM) photogrammetry techniques, with *Agisoft Photoscan* being the most

699 common software in use at present (e.g. Chandler et al., 2016b; Evans et al., 2016a; Ely et al., 2017;  
700 Allaart et al., 2018). This methodology has enabled the production of sub-decimetre resolution  
701 orthophotographs and DEMs with centimetre-scale error values (RMSEs <0.1 m; see Section 4.4) for  
702 glacial geomorphological mapping (e.g. Evans et al., 2016a; Ely et al., 2017). Although surveying of  
703 GCPs is still preferable for processing UAV-captured imagery, a direct georeferencing workflow (see  
704 Turner et al., 2014b, for further details) is capable of producing reliable geospatial datasets from  
705 imagery captured using consumer-grade UAVs and cameras, without the need for expensive survey  
706 equipment (see Carbonneau and Dietrich, 2017).

707

708 The use of UAVs will be valuable in future glacial geomorphological research due to their flexibility  
709 and low-cost. In particular, UAVs open up the exciting possibility of undertaking repeat surveys at  
710 high temporal (sub-annual to annual) resolutions in modern glacial settings (Immerzeel et al., 2014;  
711 Chandler et al., 2016b; Ely et al., 2017). Multi-temporal UAV imagery will enable innovative  
712 geomorphological studies on issues such as (i) the modification and preservation potential of  
713 landforms over short timescales (Ely et al., 2017), (ii) the frequency of ice-marginal landform  
714 formation, particularly debates on sub-annual to annual landform formation (Chandler et al., 2016b),  
715 and (iii) changes in process-form regimes at contemporary ice-margins (Evans et al., 2016a).

716

717 Using UAVs to capture aerial imagery is not without challenges, particularly in relation to the  
718 challenge of intersecting suitable weather conditions in modern glacial environments: many UAVs are  
719 unable to fly in high windspeeds, whilst rain can infiltrate electrical components and create hazy  
720 imagery (Ely et al., 2017). Flight times and areal coverage are also limited by battery life, with some  
721 battery packs permitting as little as 10 minutes per flight. There are also legal considerations, with the  
722 use of UAVs prohibited in some localities/countries or requiring licenses/permits. Moreover, there  
723 may be restrictions on flying heights and UAVs may need to be flown in visual line of sight, further  
724 limiting areal coverage. Nevertheless, we envisage UAV technology becoming more widespread and  
725 a key tool in high-resolution glacial geomorphological investigations, especially if future  
726 technological developments can increase the range of conditions in which UAVs can be flown. In  
727 future, it is likely that UAV technology will be primarily used for investigating short-term changes  
728 across relatively small areas.

729

### 730 *3.3 Image processing for mapping*

731

732 An important part of geomorphological mapping is processing remotely-sensed datasets in preparation  
733 for mapping, but this is often given limited prominence in glacial geomorphological studies.  
734 Crucially, processing of remotely-sensed data aids the identification of glacial landforms and ensures  
735 accurate transfer of geomorphological data from the imagery. In the sections below, we provide a

736 brief overview of image processing solutions for aerial photographs (Section 3.3.1), satellite imagery  
737 (Section 3.3.2) and DEMs (Section 3.3.3). Reference is made to common processing techniques used  
738 to remove distortion and displacement evident in aerially-captured imagery (see Campbell and Wynne  
739 (2011) and Lillesand et al. (2015) for further details), but these are not discussed in detail for reasons  
740 of brevity and clarity. However, a detailed workflow diagram outlining the potential procedures for a  
741 range of scenarios (depending on data, resources and time) is available as Supplementary Material.  
742 We emphasise that compromises and pragmatic solutions are necessary, particularly in the case of  
743 aerial photographs, as the ‘idealised’ scenario is frequently not an option due to data limitations or  
744 logistical constraints.

745

### 746 3.3.1 Aerial photograph processing

747 Aerial photographs contain varying degrees of distortion and displacement owing to their central (or  
748 perspective) projection. Geometric distortion is related to radial lens distortion and refraction of light  
749 rays in the atmosphere. Additional displacement occurs as a result of the deviation of the camera from  
750 a vertical position (caused by roll, pitch and yaw of the aircraft), and the relief and curvature of the  
751 Earth. Non-corrected aerial photographs are therefore characterised by relief displacement and scale  
752 variations, which increase towards the edges of the photograph (see Campbell and Wynne (2011) and  
753 Lillesand et al. (2015) for further details). Thus, it is necessary to apply geometric corrections to aerial  
754 photographs before geomorphological mapping.

755

756 Ideally, aerial photographs should be corrected using stereoscopic (or conventional) photogrammetric  
757 processing in software packages such as *Imagine Photogrammetry* (formerly *Leica Photogrammetry*  
758 *Suite*, or *LPS*). This approach involves the extraction of quantitative elevation data from stereoscopic  
759 (overlapping) imagery to generate DEMs and orthorectified imagery (see also Section 3.2). Internal  
760 and external parameters, along with the location of GCPs, are used to establish the relationship  
761 between the position of the images and a ground coordinate system (e.g. Kjær et al., 2008; Bennett et  
762 al., 2010). However, this approach may be impractical and unsuitable in many glacial settings. For  
763 example, it is unrealistic to collect GCPs using (heavy) survey equipment (e.g. RTK-GPS) in former  
764 plateau icefield and ice-cap settings due to their location (remote, upland environments) and the size  
765 of the study area (and thus quantity of aerial photographs and GCPs required). Moreover, camera  
766 calibration data (focal length, fiducial marks, principal point coordinates and lens distortion) are  
767 frequently unavailable or incomplete for archive datasets, and the process is not applicable to acetate  
768 overlays. Thus, orthorectification of imagery – three-dimensional correction of geometric distortions –  
769 is typically precluded over larger areas, although it may be possible to employ this approach for  
770 individual cirque basins, valleys, and glacier forelands (e.g. Wilson, 2005; Bennett et al., 2010;  
771 Chandler et al., 2016a). Consequently, pragmatic solutions are required for georectification of  
772 imagery, i.e. the process of transforming and projecting imagery to a (local) planar coordinate system.

773 Several approaches have been used to overcome this and we briefly outline these below in relation to  
774 analogue aerial photographs (Section 3.3.1.1) and digital aerial photographs (Section 3.3.1.2).

775

776 *3.3.1.1 Analogue aerial photograph processing.* A pragmatic solution to correcting analogue (hard-  
777 copy) aerial photographs is to georeference scanned copies of acetate overlays or the original aerial  
778 photographs to reference points on other forms of (coarser) georeferenced digital imagery (if  
779 available; e.g. DEMs, orthorectified radar images, satellite images). The scanned images can then be  
780 georectified and resampled using the georeferencing functions within GIS and remote sensing  
781 programmes such as *ArcGIS* or *Erdas Imagine* (cf. Boston, 2012a, for further details). This approach  
782 is particularly useful when hard-copy aerial photographs are used in combination with (coarser)  
783 digital imagery. Using this procedure, georeferenced acetate overlays of Quaternary features in the  
784 Scottish Highlands have been produced with RMSE values ranging between 2.71 m and 7.82 m  
785 (Boston, 2012a), comparable to archival aerial photographs that have been processed using  
786 stereoscopic photogrammetric techniques (e.g. Bennett et al., 2010).

787

788 The above georectification method works best if relatively small areas are mapped on one acetate.  
789 This is because radial distortion increases towards the edges of aerial photographs, which presents a  
790 significant problem for matching reference points when large areas have been mapped. From our  
791 experience, we estimate the maximum effective area that can be corrected without the danger of  
792 mismatches is ~6 km<sup>2</sup>. However, this figure depends on the terrain conditions and would have to be  
793 smaller in high mountain areas where relief distortion is increased due to greater differences between  
794 valleys and adjacent peaks (Lillesand et al., 2015). The mapped area could, conversely, be somewhat  
795 larger in low-relief terrain because objects are roughly equally as far away from the camera lens over  
796 larger areas and thus subject to less distortion (Kronberg, 1984; Lillesand et al., 2015). The  
797 aforementioned constraints might seem to make georectification from hard-copy aerial photographs a  
798 laborious process, but this is counterbalanced by being able to record small landforms in great detail  
799 due to the high-resolution 3D visualisation allowed by stereopairs.

800

801 *3.3.1.2 Digital aerial photograph processing.* Digital aerial photographs can be georeferenced within  
802 GIS and remote sensing software following a similar process to that outlined in Section 3.3.1.1, i.e.  
803 digital aerial photographs can be georeferenced to other forms of (coarser) georeferenced imagery.  
804 Alternatively, SfM photogrammetry can be used to produce orthophotographs and DEMs from digital  
805 aerial photographs, which partly circumvents issues relating to incomplete or absent camera  
806 calibration data (e.g. Chandler et al., 2016a; Evans et al., 2016e, 2017; Tonkin et al., 2016; Mertes et  
807 al., 2017; Midgley and Tonkin, 2017). SfM photogrammetry functions under the same basic principles  
808 as stereoscopic photogrammetry, but there are some fundamental differences: the geometry of the  
809 ‘scene’, camera positions and orientation are solved automatically in an arbitrary ‘image-space’

810 coordinate system without the need to specify either the 3D location of the camera or a network of  
811 GCPs with known ‘object-space’ coordinates (cf. Westoby et al., 2012; Carrivick et al., 2016; Smith  
812 et al., 2016a, for further details). However, positional data (GCPs) are still required to process the  
813 digital photographs for geomorphological mapping, i.e. to assign the SfM models to an ‘object-space’  
814 coordinate system. Ideally, this should be conducted through ground control surveys (see above), but  
815 a potential pragmatic solution is to utilise coordinate data from freeware virtual globes such as *Bing*  
816 *Maps* (see also Supplementary Material). Position information (‘object-space’ coordinates) is  
817 introduced after model production, with the benefit that errors in GCPs will not propagate in the  
818 DEM.

819

### 820 *3.3.2 Satellite imagery processing*

821 Satellite imagery products are typically available in georectified form as standard and therefore do not  
822 require geometric correction prior to geomorphological mapping. With respect to high-resolution,  
823 commercial satellite imagery (e.g. WorldView-4 captured imagery; 0.31 m Ground Sampled  
824 Distance), these products are often available for purchase as either georeferenced and orthorectified  
825 products (with consumers able to define the processing technique used) at comparable prices to  
826 commercial aerial photographs, thereby removing the need for photogrammetric processing.  
827 Alternatively, it is possible to purchase less expensive ‘ortho-ready’ imagery and perform  
828 orthorectification (where DEM or GCP data are available), thus providing greater end-user control on  
829 image processing (e.g. Chandler et al., 2016a; Ewertowski et al., 2016).

830

831 Although satellite imagery does not typically require geometric correction for mapping, it is important  
832 to consider the choice of band combinations when using multispectral satellite imagery (e.g. Landsat,  
833 ASTER; Table 1). Since the detection of glacial landforms from optical satellite imagery relies on the  
834 interaction of reflected radiation with topography, different combinations of spectral bands can be  
835 employed to optimise landform identification (see Jansson and Glasser, 2005). Manipulating the order  
836 of bands with different spectral wavelengths allows the generation of various visualisations, or false-  
837 colour composites, of the terrain. For example, specific band combinations may be particularly useful  
838 for detecting moraine ridges (7, 5, 2 and 5, 4, 2), mega-scale glacial lineations (4, 5, 6) and meltwater  
839 channels (4, 3, 2) from Landsat TM and ETM+ imagery (Jansson and Glasser, 2005; Heyman et al.,  
840 2008; Lovell et al., 2011; Morén et al., 2011). This is principally due to the change in surface  
841 vegetation characteristics (e.g. type, density, and degree of development) between different  
842 landforms, and between landforms and the surrounding terrain. For example, moraine ridges or the  
843 crests of glacial lineations are typically better drained and therefore less densely vegetated than  
844 intervening low-relief areas. In contrast, former meltwater channels typically appear as overly-wide  
845 corridors (relative to any modern drainage) of lush green vegetation and stand out clearly as bright red  
846 when using a near-infrared false-colour composites (bands 4, 3, 2: Landsat TM and ETM+), since the



847 chlorophyll content of surface vegetation is strongly reflected in near-infrared bands (band 4: Landsat  
848 TM and ETM+). In addition to the manipulation of band combinations during the mapping process, it  
849 can also be beneficial to use satellite image derivatives based on ratios of band combinations, such as  
850 vegetation indices (see Walker et al., 1995) and semi-automated image classification techniques (e.g.  
851 Smith et al., 2000, 2016b).

852

853 Aside from manipulating spectral band combinations, it may also be beneficial to use the higher-  
854 resolution panchromatic band as a semi-transparent layer alongside the multispectral bands to aid  
855 landform detection (e.g. Morén et al., 2011; Stroeven et al., 2013; Lindholm and Heyman, 2016), or to  
856 merge the pixel resolutions of a higher resolution panchromatic band with lower resolution  
857 multispectral bands through ‘pan-sharpening’ techniques (e.g. Glasser and Jansson, 2008; Greenwood  
858 and Clark, 2008; Storrar et al., 2014; Chandler et al., 2016a; Ewertowski et al., 2016). Pan-sharpening  
859 can be particularly valuable when it is desirable to have both multispectral capabilities (e.g. different  
860 band combinations to differentiate between features with varying surface characteristics) and higher-  
861 spatial resolutions to help determine the extent and morphology of individual landforms.

862

### 863 *3.3.3 Digital Elevation Model processing*

864 Various processing techniques are available that can be beneficial when identifying and mapping  
865 glacial landforms from DEMs (Bolch and Loibl, 2017). DEM data are typically converted into  
866 ‘hillshaded relief models’ (Figure 8), whereby different solar illumination angles and azimuths are  
867 simulated within GIS software to produce the shaded DEMs. This rendition provides a visually  
868 realistic representation of the land surface, with shadows improving detection of surface features.  
869 Ideally, hillshaded relief models should be generated using a variety of illumination azimuths  
870 (direction of light source) and angles (elevation of light source) to alleviate the issue of ‘azimuth  
871 bias’, the notion that some linear landforms are less visible when shaded from certain azimuths (see  
872 Lidmar-Bergström et al., 1991; Smith and Clark, 2005). An illumination angle of 30° and azimuths  
873 set at orthogonal positions of 45° and 315° have been suggested as optimal settings for visualisation  
874 (Smith and Clark, 2005; Hughes et al., 2010). Vertical exaggeration of these products (e.g. three to  
875 four times) can also aid landform identification (e.g. Hughes et al., 2010). Semi-transparent DEMs  
876 can be draped over shaded-relief images to accentuate topographic contrasts (Figure 9), or a semi-  
877 transparent satellite image can be draped over a DEM to achieve both a multispectral and topographic  
878 assessment of a landscape (e.g. Jansson and Glasser, 2005). First- and second-order DEM-derivatives,  
879 including surface gradient (slope) and curvature, have also been found to be useful for mapping (e.g.  
880 Smith and Clark, 2005; Evans, 2012; Storrar and Livingstone, 2017).

881

## 882 **4. Assessment of mapping errors and uncertainties**

883

884 In this section, we provide an overview of the main sources of error and uncertainty associated with  
885 the various geomorphological mapping methods introduced in the preceding sections. Consideration  
886 and management of mapping errors should be an important part of glacial geomorphological mapping  
887 studies because any errors/uncertainties incorporated in the geomorphological map may propagate  
888 into subsequent palaeoglaciological and palaeoclimatic reconstructions. This is of most relevance to  
889 small ice masses (cirque glaciers, valley glaciers, outlet glaciers), e.g. metre-scale geolocation errors  
890 would have significant implications for studies aiming to establish ice-margin retreat rates at the order  
891 of tens of metres (e.g. Krüger, 1995; Lukas and Benn, 2006; Lukas, 2012; Bradwell et al., 2013;  
892 Chandler et al., 2016b). Conversely, any mapping errors might be negligible in the context of  
893 continental-scale ice sheet reconstructions (e.g. Hughes et al., 2016; Stroeven et al., 2016; Margold et  
894 al., 2018).

895

896 The overall ‘quality’ of a geomorphological map is a function of three interlinked factors: mapping  
897 resolution, accuracy, and precision. It is important to highlight that, irrespective of the mapping  
898 method employed (field or remote-based), the accuracy and precision of the mapping reflects two  
899 related factors: (i) the skill, philosophy, and experience of the mapper; and (ii) the detectability of the  
900 landforms (Smith and Wise, 2007; Otto and Smith, 2013; Hillier et al., 2015). Mapper philosophy  
901 concerns issues such as how landforms are mapped (e.g. generalised mapping vs. mapping the  
902 intricate details of individual landforms) and interpreted (e.g. differences in terminology and landform  
903 classification), which will partly vary with study objectives and mapper background and training. The  
904 significance of the skill, philosophy and experience in mapping is exemplified by the stark differences  
905 across boundaries of British Geological Survey (BGS) map sheets that have been mapped by different  
906 surveyors (cf. Clark et al., 2004).

907

908 A key determinant of landform detectability is resolution, generally defined as the finest element that  
909 can be distinguished during survey/observation (Lam and Quattrochi, 1992). In geomorphological  
910 mapping it may be, for example, the smallest distinguishable landform that is visible from remotely-  
911 sensed data or that can be drawn on a field map. The accuracy of geomorphological mapping relates  
912 to positional accuracy (i.e. difference between ‘true’ and mapped location of the landform), geometric  
913 accuracy (i.e. difference between ‘true’ and mapped shape of the landform), and attribute accuracy  
914 (i.e. deviation between ‘true’ and mapped landform types) (Smith et al., 2006). For spatial data, it is  
915 usually not possible to obtain absolute ‘true’ data, due to limitations such as the ‘resolution’ of  
916 remotely-sensed data and the accuracy of instruments/surveying equipment. Precision is often used to  
917 express the reproducibility of surveys, which is controlled by random errors. These are errors that are  
918 innate in the survey/observation process and cannot be removed (Butler et al., 1998). We now outline  
919 the specific uncertainties associated with field mapping (Section 4.1), analogue remote mapping  
920 (Section 4.2) and digital remote mapping (Section 4.3).

921

922 *4.1 Field mapping errors and uncertainty*

923

924 The correct positioning, orientation and scale of individual geomorphological features on field maps  
925 is dependent on the skill of the mapper and the ability to correctly interpret and record landforms. If a  
926 handheld GNSS device is used to locate landforms in the field, the positional accuracy is usually  
927 restricted to several metres and related to three factors: (i) the quality of the device (e.g. antenna,  
928 number of channels, ability to use more than one GNSS); (ii) the position of satellites; and (iii) the  
929 characteristics of the surrounding landscapes and space weather (solar activity can affect signal  
930 quality). Higher accuracy (cm- or even mm-scale) can only be achieved when supplemented by  
931 measurements using additional surveying (e.g. differential Global Positioning Systems (dGPS), real  
932 time kinematic (RTK-) GPS or total station). Alongside positioning errors, the horizontal resolution  
933 (and, consequently, accuracy) of the field map is related to line thickness on the field map (Knight et  
934 al., 2011; Boston, 2012a, b; Otto and Smith, 2013). A pencil line has a thickness of between 0.20 and  
935 0.50 mm on a field map; therefore, individual lines represent a thickness of between 2 and 5 m on  
936 1: 10,000 scale maps, rendering the maps accurate to this level at best (Raisz, 1962; Robinson et al.,  
937 1995; Boston, 2012a). This necessitates some element of selection during field mapping of relatively  
938 small landforms formed by alpine- and plateau-style ice masses, as not all the information that can be  
939 seen in the field can be mapped, even at a large scale such as 1: 10,000. In terms of the vertical  
940 accuracy of field maps, it should be recognised that the mapping is only as accurate as the resolution  
941 of the source elevation data: if the topographic base map has contours at 10 m intervals, the mapping  
942 has a vertical resolution, and thus accuracy, of 10 m at best, irrespective of the (perceived) skill of the  
943 cartographer. As with positional accuracy, higher vertical accuracy necessitates the use of geodetic-  
944 grade surveying equipment.

945

946 *4.2 Analogue remote mapping errors and uncertainty*

947

948 Accurate detection and mapping of individual landforms from analogue (hard-copy) aerial  
949 photographs is influenced by factors such as the scale or resolution of the photographs, shadow length  
950 (shadows may obscure the 'true' planform or landforms altogether), the presence/absence of  
951 vegetation, cloud cover, and tonal contrast (photographs may appear 'flat', thus limiting landform  
952 detection). The resolution of analogue remotely-sensed datasets is associated with scale, which results  
953 from the altitude of the plane, camera lens focal length, and the optical resolution of the lens and  
954 sensor (Wolf et al., 2013). The accuracy of the (non-rectified) mapping, as with field mapping, is also  
955 limited by the thickness of the pen used for drawing on the acetate sheets. Super-fine pens typically  
956 have a nib size of 0.05–0.20 mm; thus, lines on an acetate overlay typically represent thicknesses  
957 between ~1.25 m and 5.00 m at a common aerial photograph average scale of 1: 25,000. Despite

958 being particularly useful for detailed mapping of small features and complex landform patterns, the  
959 level of accuracy achievable using this method is therefore ~1.25 m at best. However, further errors  
960 will be introduced to the geomorphological mapping once the raw, non-rectified acetates are  
961 georectified (see Section 3.3.1).

962

#### 963 4.3 Digital remote mapping errors and uncertainty

964

965 A key influence on landform detectability from digital remotely-sensed data is the scale of the feature  
966 relative to the resolution of the digital dataset, with a particular challenge being the mapping of  
967 features with a scale close to or smaller than the resolution of the imagery. Conversely, mapping  
968 exceptionally large ('mega-scale') glacial landforms can be challenging, depending on the remotely-  
969 sensed dataset employed (e.g. Greenwood and Kleman, 2010). Unlike analogue mapping (both in the  
970 field and remotely), the thickness of digital lines is not typically a problem for digital mapping, so  
971 landform detection and recording are fundamentally linked to spatial resolution. Spatial resolution of  
972 digital remotely-sensed data refers to the capability to distinguish between two objects, typically  
973 expressed as either (i) pixel size or grid cell size or (ii) ground sampled distance. Pixel/grid size refers  
974 to the projected ground dimension of the smallest element of the digital image (Figure 10), whilst  
975 ground sampled distance (GSD) refers to the ground distance between two measurements made by the  
976 detector (the value of measurement is subsequently assigned to a pixel) (Figure 10; Duveiller and  
977 Defourny, 2010). In practice, the spatial resolution of digital imagery is lower than the pixel size  
978 (Figure 10).

979

980 Landform detectability from raster images (i.e. remotely-sensed data) can be considered with  
981 reference to the Nyquist-Shannon sampling theorem, since they comprise discrete sampled values.  
982 According to this theorem, the *intrinsic resolution* is twice the sampling distance of the measured  
983 values, whereas the *nominal resolution* is twice the pixel/grid size (cf. Pipaud et al., 2015, and  
984 references therein). The *effective resolution* and, consequently, the minimum landform  
985 footprint/planform that can be unambiguously sampled are defined by the smaller of these two values  
986 (cf. Pike, 1988). Where the Nyquist-Shannon criterion is not satisfied for either the intrinsic or  
987 nominal resolution, landforms with footprints below the critical value may be visible but are rendered  
988 ambiguously in digital imagery, i.e. their boundaries are not clearly definable and mappable (cf.  
989 Cumming and Wong, 2005). Further factors that influence landform identification from digital  
990 imagery include the strength of the landform signal relative to background terrain, and the azimuth  
991 bias introduced by differences in the orientation of linear features and the illumination angle of the  
992 sun (Smith and Wise, 2007), along with localised issues such as cloud cover, snow cover, areas in  
993 shadow, and vegetation. The timing of data collection is also a key factor, particularly in the case of  
994 modern glacial environments (see Section 5.3).

995

996 Aside from the factors outlined above, (raw) remotely-sensed data will contain distortion and/or  
997 geometric artefacts of varying degrees. Distortions inherent in raw aerial photographs can be partially  
998 or almost fully removed during georeferencing of acetate sheets or photogrammetric processing of  
999 aerial photographs (see Section 3.3.1). Raw satellite imagery will contain biases related to attitude,  
1000 ephemeris and drift errors, as well as displacements related to the relief, which, similarly to aerial  
1001 photographs, is more visible in mountainous areas than in lowland settings (Grodecki and Dial, 2003;  
1002 Shean et al., 2016). With respect to DEMs, some datasets captured using air- and space-borne radar  
1003 approaches may contain a number of artefacts (Clark, 1997; Figure 11), with geometric artefacts  
1004 particularly significant in upland settings. Geometric artefacts, such as foreshortening and layover, are  
1005 corrected during image processing by stretching high terrain into the correct position, which can result  
1006 in a smoothed region on steep slopes (Figure 12). In other parts of upland terrain, information will be  
1007 lost on the leeside of slopes, away from the sensor, where high ground prevents the radar beam from  
1008 reaching the lower ground beneath it (Figure 11). Such issues can be alleviated, at least partly, by  
1009 examining multiple complementary remotely-sensed datasets and mapping at a variety of scales.

1010

#### 1011 *4.4. Assessment and mitigation of uncertainties*

1012

1013 Due to the subjective nature of geomorphological mapping, assessing mapping precision is not an  
1014 easy task. One possible approach is to compare results of mapping using different datasets/methods  
1015 with a dataset perceived to be more ‘truthful’ (i.e. field-based survey) (Smith et al., 2006). The  
1016 number, size and shape of mapped landforms in comparison with a ‘true’ dataset can be used as an  
1017 approximation of mapping reliability. Precision and accuracy of the produced geomorphological map  
1018 can also be estimated based on the quality of the source data. Most of the datasets are delivered with  
1019 at least some assessment of uncertainties, often expressed as accuracy, e.g. the SRTM DEM has a  
1020 horizontal accuracy of  $\pm 20$  m and a vertical accuracy of  $\pm 16$  m (Rabus et al., 2003). Alternatively,  
1021 some remotely-sensed datasets have an associated *total root mean square error* (RMSE), which  
1022 indicates displacement between ‘true’ control points and corresponding points on the remotely-sensed  
1023 data (Wolf et al., 2013). However, both are measures of the overall (‘global’) quality of the dataset.  
1024 Thus, these errors may be deceptive because such ‘global’ measures ignore spatial patterns of errors  
1025 and local terrain characteristics (cf. Lane et al., 2005; James et al., 2017). For example, DEM errors  
1026 will typically be more pronounced on steep slopes, where even a small horizontal shift will incur large  
1027 differences in elevation.

1028

1029 Ideally, remotely-sensed datasets should be evaluated independently by the mapper to establish their  
1030 geolocation accuracy (accuracy of  $x$ ,  $y$  and  $z$  coordinates). If feasible, surveys of GCPs should be  
1031 conducted using geodetic-grade surveying equipment (e.g. RTK-GPS, total station). A sub-sample of

1032 this GCP dataset can be used for photogrammetric processing and allow RMSEs to be calculated.  
1033 Subsequently, the remaining GCPs (i.e. those not used for photogrammetric processing) can be used  
1034 to perform a further quality check, by quantifying deviations from the coordinates of the GCPs and  
1035 the corresponding points on the generated DEM (e.g. Carrivick et al., 2017). An additional approach,  
1036 in geomorphologically stable areas, is to compare the location of individual data points from the DEM  
1037 (or raw point cloud) being used for mapping with those on a reference DEM (or raw point cloud) (e.g.  
1038 King et al., 2016b; Carrivick et al., 2017; James et al., 2017; Mertes et al., 2017; Midgley and Tonkin,  
1039 2017). Parameters such as the mean deviation, standard deviation and relative standard deviation  
1040 between the two datasets can then be calculated to perform a quantitative assessment of quality and  
1041 accuracy of the DEM (e.g. King et al., 2016b; Mertes et al., 2017). Performing these assessments may  
1042 then facilitate correction of the processed datasets (e.g. Nuth and Kääb, 2011; Carrivick et al., 2017;  
1043 King et al., 2017).

1044

1045 To some extent, residual uncertainties relating to the skill, philosophy and experience of the mapper  
1046 may be reduced by developing a set of clear criteria for identifying and mapping particular landforms  
1047 (e.g. Barrell et al., 2011; Darvill et al., 2014; Bendle et al., 2017a; Lovell and Boston, 2017). That  
1048 said, there are currently no ‘agreed’ genetic classification schemes for interpreting glacial sediment-  
1049 landform assemblages, despite the development of facies and landsystem models for particular glacial  
1050 environments (e.g. Eyles, 1983; Brodzikowski and van Loon, 1991; Evans, 2003a; Benn and Evans,  
1051 2010). Indeed, terminologies are inconsistently used in glacial geomorphological research, as different  
1052 ‘schools’ or traditions still exist. Thus, it is probably most appropriate to select a scheme that has been  
1053 in frequent use in a given area (to enable ready comparison) or to develop one suited for a particular  
1054 area or problem. Notwithstanding potential discrepancies relating to genetic classification or  
1055 terminology, this will at least ensure transparency in future use and analysis of the geomorphological  
1056 mapping.

1057

1058 Given the influence of the individual mapper on accuracy and precision, it may be beneficial and  
1059 desirable for multiple mappers to complete (initially) independent field surveys and examination of  
1060 remotely-sensed datasets to enhance reliability and reproducibility (cf. Hillier et al., 2015; Ewertowski  
1061 et al., 2017). However, this approach would only be applicable in collaborative efforts and may be  
1062 impractical due to various factors (e.g. study area size, data access restrictions). The level of detection  
1063 of individual landforms might be improved by employing multiple methods to enhance landform  
1064 detectability, whilst the genetic interpretation of landforms (landform classification) can be tested by  
1065 detailed sedimentological investigations (see Section 2.3). Some uncertainties associated with the  
1066 quality of the data source (e.g. shadows, artefacts) can be alleviated, at least partly, by examining  
1067 multiple complementary remotely-sensed datasets and mapping at a variety of scales.

1068

## 1069 **5. Scale-appropriate mapping approaches**

1070

1071 The following sections place the presented geomorphological mapping methods (see Sections 2 and 3)  
1072 in the spatial and temporal context of the glacial settings in which they are commonly used,  
1073 demonstrating that particular methods are employed depending on factors such as the size of the study  
1074 area, former glacial system, and landform assemblages (Table 3). We focus on three broad glacial  
1075 settings for the purposes of this discussion: palaeo-ice sheets (Section 5.1), alpine- and plateau-style  
1076 ice masses (Section 5.2), and the forelands of modern cirque, valley and outlet glaciers (Section 5.3).  
1077 Although geomorphological mapping in modern glacial settings follows the same general procedures  
1078 as in former alpine and plateau-style ice mass settings (see Section 6.2), specific consideration of  
1079 contemporary glacier forelands is warranted due to important issues relating to the temporal resolution  
1080 of remotely-sensed data and landform preservation potential, which are not as significant in  
1081 palaeoglaciological settings.

1082

### 1083 *5.1 Palaeo-ice sheet settings*

1084

1085 The continental-scale of palaeo-ice sheets typically necessitates a mapping approach that enables  
1086 systematic mapping of a large area in a time- and cost-effective manner while still allowing accurate  
1087 identification of landform assemblages at a variety of scales. The nature of the approach will differ  
1088 depending on the aim of the investigation, as this fundamentally determines *what* needs to be mapped  
1089 and *how* it should be mapped. Palaeo-ice sheet reconstructions have been produced at a range of  
1090 scales, from entire ice sheets (e.g. Dyke and Prest, 1987a, b, c; Kleman et al., 1997, 2010; Boulton et  
1091 al., 2001; Glasser et al., 2008; Clark et al., 2012; Livingstone et al., 2015; Stroeven et al., 2016) to  
1092 regional/local sectors (e.g. Hättestrand, 1998; Jansson et al., 2003; Stokes and Clark, 2003; Ó Cofaigh  
1093 et al., 2010; Astakhov et al., 2016; Darvill et al., 2017). Depending on the aim of the study, some  
1094 investigations may focus specifically on mapping particular landforms. For example, studies of ice-  
1095 sheet flow patterns frequently focus on mapping subglacial bedforms, such as drumlins (e.g. Boulton  
1096 and Clark, 1990a, b; Kleman et al., 1997, 2010; Stokes and Clark, 2003; Hughes et al., 2010).  
1097 Nonetheless, cartographic reduction is often still required to manage the volume of information,  
1098 resulting in the grouping of similarly-orientated bedforms into flow-sets (occasionally termed fans or  
1099 swarms) (e.g. Jansson et al., 2002, 2003; De Angelis and Kleman, 2007; Greenwood and Clark,  
1100 2009a, b; Stokes et al., 2009; Hughes et al., 2014; Atkinson et al., 2016).

1101

1102 In many cases, studies attempt to incorporate all or most of the common landform types across ice  
1103 sheet scales to derive palaeoglaciological reconstructions (e.g. Kleman et al., 1997, 2010; Stroeven et  
1104 al., 2016). The rationale for this is that glaciation styles and processes (e.g. ice-marginal, subglacial)  
1105 can be inferred from particular combinations of landforms in landform assemblages (e.g. Clayton et

1106 al., 1985; Stokes and Clark, 1999; Evans, 2003b; Kleman et al., 2006; Evans et al., 2008, 2014;  
1107 Darvill et al., 2017; Norris et al., 2018). Establishing relationships between landforms is therefore  
1108 valuable, not only in understanding glaciation styles, but also in helping decipher the relative  
1109 sequence of formation (e.g. Clark, 1993; Kleman and Borgström, 1996) that may lay the foundations  
1110 for absolute dating. Typically, ice sheet investigations are focused on the spatial and temporal  
1111 evolution of these various aspects, requiring the robust integration of geomorphological mapping with  
1112 absolute dating techniques (see Stokes et al., 2015). For example, following pioneering  
1113 palaeoglaciological studies of the Fennoscandian ice sheet (e.g. Kleman, 1990, 1992; Kleman and  
1114 Stroeven, 1997; Kleman et al., 1997), cosmogenic nuclide exposure dating offered a means to  
1115 quantify dates and rates (e.g. Fabel et al., 2002, 2006; Stroeven et al., 2002a, b, 2006; Harbor et al.,  
1116 2006). Such data are crucial to tune and validate numerical models used to reconstruct evolving ice  
1117 sheet limits, flow configurations and subglacial processes (e.g. Boulton and Clark, 1990a, b; Näslund  
1118 et al., 2003; Evans et al., 2009b; Hubbard et al., 2009; Stokes and Tarasov, 2010; Kirchner et al.,  
1119 2011; Livingstone et al., 2015; Stokes et al., 2016b; Patton et al., 2017a, b).

1120

#### 1121 *5.1.1 Manual mapping of palaeo-ice sheet geomorphological imprints*

1122 Satellite imagery and DEMs are the prevailing remotely-sensed datasets used for mapping ice-sheet-  
1123 scale landforms, and these datasets have been at the forefront of key developments in the  
1124 understanding of palaeo-ice sheets (cf. Stokes, 2002; Stokes et al., 2015). Notably, the use of satellite  
1125 imagery resulted in the identification of hitherto-unrecognised mega-scale glacial lineations (MSGLs;  
1126 Boulton and Clark, 1990a, b; Clark, 1993), which are now recognised as diagnostic geomorphological  
1127 evidence of ice streams within palaeo-ice sheets (see Stokes and Clark, 1999, 2001, and references  
1128 therein). This has allowed tangible links to be made between the behaviours of former Quaternary ice  
1129 sheets and present-day ice sheets (e.g. King et al., 2009; Stokes and Tarasov, 2010; Stokes et al.,  
1130 2016b). Aerial photograph interpretation and field mapping are also used in some studies (e.g.  
1131 Hättestrand and Clark, 2006; Kleman et al., 2010; Darvill et al., 2014), but satellite imagery and  
1132 DEMs are in wider usage for practical reasons (see also Section 3.2). In recent years, the development  
1133 of LiDAR datasets has led to their increasing application for high resolution mapping of landforms  
1134 formed by palaeo-ice sheets, particularly in Scandinavia (e.g. Dowling et al., 2015; Greenwood et al.,  
1135 2015; Ojala et al., 2015; Ojala, 2016; Mäkinen et al., 2017; Peterson et al., 2017). We expect this to be  
1136 a major area of growth in future mapping studies of former ice sheets.

1137

1138 Mapping glacial landforms from remotely-sensed data typically involves manual on-screen  
1139 vectorisation (tracing) using one of two main approaches: (i) creating polylines along the crestline or  
1140 thalweg of landforms or (ii) digitally tracing polygons that delineate the breaks of slope around  
1141 landform margins (i.e. vectorising the planform). The approach employed will depend on the  
1142 requirements of the study; for example, flow-parallel bedforms (e.g. drumlins and MSGLs) have



1143 variously been mapped as polylines (e.g. Kleman et al., 1997, 2010; Stokes and Clark, 2003; De  
1144 Angelis and Kleman, 2007; Storrar and Stokes, 2007; Livingstone et al., 2008; Brown et al., 2011b)  
1145 and polygons (e.g. Hättestrand and Stroeven, 2002; Hättestrand et al., 2004; Hughes et al., 2010;  
1146 Spagnolo et al., 2010, 2014; Stokes et al., 2013; Ely et al., 2016a; Bendle et al., 2017a) (Figure 13).  
1147 The rationale behind mapping flow-parallel bedforms as linear features is that dominant orientations  
1148 of a population provide sufficient information when investigating ice-sheet-scale flow patterns and  
1149 organisation, although image resolution may also be a determining factor. Mapping polygons allows  
1150 the extraction of individual landform metrics (e.g. elongation ratios) that can provide insights into  
1151 subglacial processes (e.g. Ely et al., 2016a) and regional variations in ice sheet flow dynamics (e.g.  
1152 Stokes and Clark, 2002, 2003; Hättestrand et al., 2004; Spagnolo et al., 2014), but it is far more time-  
1153 consuming than vectorising linear features. Increasingly, it is being recognised that the population  
1154 metrics and spectral characteristics of the subglacial bedform ‘field’ as a whole are most important for  
1155 quantifying bedforms and deciphering subglacial processes and conditions (see Hillier et al., 2013,  
1156 2016; Spagnolo et al., 2017; Clark et al., 2018b; Ely et al., 2018; Stokes, 2018).

1157

#### 1158 *5.1.2 Automated mapping of palaeo-ice sheet geomorphological imprints*

1159

1160 Comprehensive mapping of palaeo-ice sheet geomorphological imprints, and particularly of  
1161 bedforms, typically entails the identification and mapping of large numbers (in some cases >10,000)  
1162 of the same, or very similar, types of features (e.g. Hättestrand et al., 2004; Clark et al., 2009; Kleman  
1163 et al., 2010; Storrar et al., 2013). The manual vectorisation of such large numbers of landforms is a  
1164 time-consuming process. Consequently, semi-automated and automated mapping techniques are  
1165 increasingly being applied to glacial geomorphology (e.g. Napieralski et al., 2007b; Saha et al., 2011;  
1166 Maclachlan and Eyles, 2013; Eisank et al., 2014; Robb et al., 2015; Yu et al., 2015; Jorge and  
1167 Brennand, 2017a, b), particularly given that features of a single landform type (e.g. drumlins or  
1168 MSGs) will have fairly uniform characteristics (orientation, dimensions, and morphology).  
1169 Automated and semi-automated mapping techniques typically use either a pixel- or an object-based  
1170 approach (see Robb et al., 2015, and references therein). Thus far, automated and semi-automated  
1171 approaches have primarily focused on mapping drumlins or MSGs from medium- to high-resolution  
1172 DEMs. Several methods have been used, including multi-resolution segmentation (MRS) algorithms  
1173 (Eisank et al., 2014), a Curvature Based Relief Separation (CBRS) technique (Yu et al., 2015), Object  
1174 Based Image Analysis (OBIA) (Saha et al., 2011; Robb et al., 2015), and clustering algorithms (Smith  
1175 et al., 2016b).

1176

1177 Most recently, 2D discrete Fourier transformations have been applied to automatically quantify the  
1178 characteristics of MSGs (see Spagnolo et al., 2017). In contrast to traditional mapping approaches,  
1179 this new method analyses all of the topography (rather than simply focusing on the landforms) to

1180 identify the wavelength and amplitude of periodic features (i.e. waves or ripples across the  
1181 topography) without the need to manually vectorise (trace) them. This automated approach is in its  
1182 infancy but is likely to provide quantitative data that are useful for (i) testing and parameterising  
1183 models of subglacial processes and landforms (e.g. Barchyn et al., 2016; Stokes, 2018) and (ii)  
1184 facilitating comparison between subglacial bedforms and other bedforms (e.g. Fourrière et al., 2010;  
1185 Kocurek et al., 2010; Murray et al., 2014).

1186

## 1187 *5.2 Alpine and plateau glacial settings*

1188

1189 Mapping the geomorphological imprints of former alpine- and plateau-style ice masses (cirque  
1190 glaciers, valley glaciers, icefields and ice-caps) is particularly important because the  
1191 geomorphological imprints of these discrete ice masses can facilitate reconstructions of their three-  
1192 dimensional form (extent, morphology, and thickness). By contrast, establishing the vertical limits,  
1193 thickness distribution, and surface topography of palaeo-ice sheets is challenging (cf. Stokes et al.,  
1194 2015). Importantly, three-dimensional glacier reconstructions permit the calculation of palaeoclimatic  
1195 boundary conditions for glaciated regions (e.g. Kerschner et al., 2000; Bakke et al., 2005; Stansell et  
1196 al., 2007; Mills et al., 2012; Boston et al., 2015), data that cannot be obtained from point-source  
1197 palaeoenvironmental records in distal settings (e.g. lacustrine archives). Empirical palaeoclimatic data  
1198 derived from glacier reconstructions are important for three reasons. Firstly, these data facilitate  
1199 analyses of wind patterns across loci of former glaciers and, in a wider context, regional precipitation  
1200 gradients and atmospheric circulation patterns (e.g. Ballantyne, 2007a, b). Secondly, the data allow  
1201 glaciodynamic conditions reconstructed from sediment-landform assemblages (e.g. moraines) to be  
1202 directly linked to climatic regimes, thereby providing insights into glacier-climate interactions at long-  
1203 term timescales (e.g. Benn and Lukas, 2006; Lukas, 2007a). Finally, independent, empirical  
1204 information on climatic boundary conditions is fundamental to parameterising and testing numerical  
1205 models used to simulate past glacier-climate interactions (e.g. Golledge et al., 2008). Thus, the  
1206 geomorphological records of alpine and plateau-style ice masses are powerful proxies for  
1207 understanding the interactions of such ice masses with climate.

1208

1209 Alpine- and plateau-style ice masses encompass a broad spatial spectrum of glacier morphologies (cf.  
1210 Sugden and John, 1976; Benn and Evans, 2010), but geomorphological mapping of glacial landforms  
1211 in alpine and plateau settings generally follows a similar approach that combines remote sensing and  
1212 considerable field mapping/checking (Figure 14; e.g. Federici et al., 2003, 2017; Bakke et al., 2005;  
1213 Lukas and Lukas, 2006; Reuther et al., 2007; Hyatt, 2010; Bendle and Glasser, 2012; Pearce et al.,  
1214 2014; Blomdin et al., 2016a; Gribenski et al., 2016; Borsellino et al., 2017). Hence, alpine- and  
1215 plateau-style ice masses are considered collectively here. The similarities in mapping approaches  
1216 across a wider range of spatial scales partly reflect the fact that, in both alpine and plateau settings, the

1217 majority of (preserved) glacial landforms are confined to spatially- and/or topographically-restricted  
1218 areas (e.g. cirques, glaciated valleys), i.e. glacial landforms relating to plateau-style ice masses  
1219 (plateau icefields, ice-caps) are dominantly formed by outlet glaciers. Conversely, an important  
1220 component of mapping in upland environments is often assessing any glacial geomorphological  
1221 evidence for connections between supposed valley glaciers and plateau surfaces/rounded summits, i.e.  
1222 alpine vs. plateau styles of glaciation (e.g. McDougall, 2001; Boston et al., 2015). The recognition of  
1223 any plateau-based ice has significant implications for studies aiming to assess glacier dynamics and  
1224 regional palaeoclimate (see Rea et al., 1999; Boston, 2012a, and references therein). Consequently, it  
1225 is important to deploy a versatile mapping approach in alpine and plateau settings that allows mapping  
1226 of glacial landforms at a wide range of spatial scales and potentially across very large areas (>500  
1227 km<sup>2</sup>), whilst also providing sufficiently high resolution imagery to map planforms of individual, small  
1228 landforms (e.g. moraines).

1229

### 1230 *5.2.1 Remote mapping of alpine and plateau settings*

1231

1232 Glacial geomorphological mapping from remotely-sensed data in alpine and plateau ice mass settings  
1233 typically involves interpretation of either analogue or digital aerial photographs (see Sections 3.1 and  
1234 3.2.2.2; e.g. Bickerton and Matthews, 1993; Boston, 2012a; Finlayson et al., 2011; Lukas, 2012;  
1235 Izagirre et al., 2018). This reflects the superior resolution required to map in detail the frequently  
1236 smaller glacial landforms produced by alpine and plateau-style ice masses, by contrast to the coarser  
1237 resolution satellite imagery and DEMs predominantly used in ice sheet settings (see Section 5.1). The  
1238 use of analogue (hard-copy) and digital aerial photographs varies in alpine and plateau settings,  
1239 depending on data availability and the preference of individual mappers. For example, hard-copy,  
1240 panchromatic aerial photographs have been widely used in conjunction with stereoscopes (see Section  
1241 3.1) for mapping Younger Dryas glacial landforms in Scotland, owing to their excellent tonal contrast  
1242 (e.g. Benn and Ballantyne, 2005; Lukas and Lukas, 2006; Boston, 2012a, b). Indeed, depending on the  
1243 environment and quality/resolution of available remotely-sensed imagery, panchromatic, stereoscopic  
1244 aerial photographs can provide the most accurate approach (in terms of landform identification), with  
1245 photographs of this format having superior tonal contrast than their digital (colour) counterparts.  
1246 Digital colour aerial photographs may appear ‘flat’ (i.e. shadows are absent or less pronounced)  
1247 making it more difficult to pick out subtle features, particularly in the absence of *SOCET SET* stereo  
1248 display software and equipment (see Section 3.2.2.2). Nevertheless, mapping from digital aerial  
1249 photographs has the advantage of providing georeferenced data and avoiding the duplication of effort,  
1250 with hand-drawing on acetate overlays necessitating subsequent vectorisation (see Sections 3.1 and  
1251 3.2). Although panchromatic aerial photographs are invariably older, temporality usually presents no  
1252 issue in palaeoglaciological (non-glacierised) settings, with the critical factor being image quality.

1253

1254 Irrespective of the type of aerial photographs used for geomorphological mapping, georectification is  
1255 required to ensure accurate depiction of glacial landforms on the final maps (Section 3.3). This is  
1256 important for minimising potential geospatial errors that will propagate into any subsequent glacier  
1257 reconstructions and analyses of glacier-climate interactions. Ideally, georectification would involve  
1258 stereoscopic photogrammetry, as discussed in Section 3.3, but this approach is impractical for larger  
1259 ice masses (i.e. plateau icefields and plateau ice-caps). Thus, it is necessary to apply the pragmatic  
1260 solutions described in Section 3.3.1.1, namely georectifying the aerial photographs or acetate overlays  
1261 to other (coarser) georeferenced digital imagery or topographic data. Conversely, geomorphological  
1262 studies at the scale of individual cirque basins, valley glaciers or glacier forelands would be  
1263 appropriate for topographic surveys and hence stereoscopic photogrammetry, provided (i) the  
1264 accessibility of the study area permits the use of surveying equipment and (ii) camera calibration data  
1265 are available (see Section 3.3).

1266

1267 In some locations, coarse to medium resolution satellite imagery may be the only source of imagery  
1268 available, yet sufficiently detailed to map the geomorphological imprint of former or formerly more  
1269 extensive valley glaciers, icefields and ice-caps (Figure 15; e.g. Glasser et al., 2005; Heyman et al.,  
1270 2008; Barr and Clark, 2009, 2012; Morén et al., 2011; Hochreuther et al., 2015; Loibl et al., 2015;  
1271 Blomdin et al., 2016a, b; Gribenski et al., 2016, 2018). However, these coarse remotely-sensed  
1272 datasets may only allow for mapping of broad landform arrangements and patterns, rather than the  
1273 intricate details of individual landforms, and preclude mapping of small features (cf. Barr and Clark,  
1274 2012; Fu et al., 2012; Stroeven et al., 2013; Blomdin et al., 2016b). The emergence of high-resolution  
1275 (commercial) satellite imagery may result in more widespread use of satellite imagery for mapping in  
1276 alpine and plateau settings, although the benefits of increased resolution may be counteracted by  
1277 prohibitive costs for large study areas (see Section 3.2.2.1).

1278

### 1279 *5.2.2 Field mapping in alpine and plateau settings*

1280

1281 Detailed field mapping, following the procedures outlined in Section 2.2, has been widely applied as  
1282 part of geomorphological studies focused on alpine- and plateau-style ice masses (e.g. Benn, 1992;  
1283 Federici et al., 2003, 2017; Lukas, 2007a; Reuther et al., 2007; Boston, 2012a; Małeckı et al., 2018;  
1284 Brook and Kirkbride, 2018). Although field mapping is widely used in such settings, many studies do  
1285 not explicitly report whether this entails field mapping *sensu stricto* (i.e. the procedure outlined in  
1286 Section 2.2), or verification of landforms mapped from remotely-sensed data by direct ground  
1287 observations ('ground truthing'). We reaffirm the points raised in Sections 2.2 and 2.3 that, whenever  
1288 possible, field mapping should be combined with remote mapping in cirque glacier, valley glacier,  
1289 icefield and ice-cap settings in order to identify subtle glacial landforms and test interpretations of  
1290 ambiguous features. While we advocate the application of detailed field mapping, we recognise that

1291 logistical and/or financial issues may preclude this and that it may only be possible to ‘ground truth’  
1292 selected areas. Nevertheless, some form of field survey is important in alpine and plateau settings to  
1293 (i) circumvent potential issues with the quality/resolution of remotely-sensed data (e.g. poor tonal  
1294 contrast) and (ii) arrive at definitive interpretations of glacial landforms and landscapes (see also  
1295 Section 2.3)

1296

### 1297 *5.3 Modern glacial settings*

1298

1299 Many contemporary glacier forelands are rapidly evolving and new landscapes are emerging. This is  
1300 largely due to changes resulting from the current retreat of ice masses and exposure of previously-  
1301 glacierised terrain, leading to destabilisation of some landforms (e.g. Krüger and Kjær, 2000; Kjær  
1302 and Krüger, 2001; Lukas et al., 2005; Lukas, 2011), erosion by changing meltwater routes, and  
1303 remoulding or complete obliteration of extant landforms in areas following a glacier re-advance or  
1304 surge (e.g. Evans et al., 1999; Evans and Twigg, 2002; Evans, 2003b; Evans and Rea, 2003;  
1305 Benediktsson et al., 2008). Glaciofluvial processes on active temperate glacier forelands (e.g. Iceland)  
1306 often make these environments unfavourable for preservation of (small) landforms (e.g. Evans and  
1307 Twigg, 2002; Evans, 2003b, Kirkbride and Winkler, 2012; Evans and Orton, 2015; Evans et al.,  
1308 2016a). In addition, de-icing and sediment re-working processes prevalent in many modern glacial  
1309 environments (e.g. Iceland, Svalbard) typically result in substantial ice-marginal landscape  
1310 modification and topographic inversion (e.g. Etzelmüller et al., 1996; Krüger and Kjær, 2000; Kjær  
1311 and Krüger, 2001; Lukas et al., 2005; Schomacker, 2008; Bennett and Evans, 2012; Ewertowski and  
1312 Tomczyk, 2015). Anthropogenic activity can also have considerable implications for glacial systems  
1313 (Jamieson et al., 2015; Evans et al., 2016b). The rapidity, ubiquity, and efficacy of these censoring  
1314 processes (cf. Kirkbride and Winkler, 2012, for further details) in contemporary glacial environments  
1315 should be key considerations in geomorphological mapping studies; in particular, the recognition that  
1316 ice-cored features mapped at a given interval in time are not the ‘final’ geomorphological products  
1317 (cf. Krüger and Kjær, 2000; Kjær and Krüger, 2001; Everest and Bradwell, 2003; Lukas et al., 2005,  
1318 2007; Lukas, 2007b).

1319

1320 In addition to landform preservation potential, spatial and temporal scales will be key determinants in  
1321 the approaches used in mapping of ice-marginal landscapes, with studies in such settings often  
1322 focused on the formation of small features (<3 m in height) on recent, short timescales (0–30 years)  
1323 (e.g. Beedle et al., 2009; Lukas, 2012; Bradwell et al., 2013; Reinardy et al., 2013; Chandler et al.,  
1324 2016b) and/or evolution of the glacier foreland over a given time period (e.g. Bennett et al., 2010;  
1325 Bennett and Evans, 2012; Ewertowski, 2014; Jamieson et al., 2015; Chandler et al., 2016a, b; Evans et  
1326 al., 2016a). Thus, the approach to geomorphological mapping discussed in Section 5.2 requires some  
1327 modification, as discussed below. It is also worth noting that geomorphological mapping usually

1328 forms part of process-oriented studies in modern glacial settings (Figure 16), often with the intention  
1329 of providing modern analogues for palaeo-ice masses and their geomorphological imprints (e.g. Evans  
1330 et al., 1999; Evans, 2011; Schomacker et al., 2014; Benediktsson et al., 2016).

1331

1332 Geophysical surveying methods can also strengthen links between modern and ancient landform  
1333 records through surveying of the internal architecture of landforms that can be directly linked to  
1334 depositional processes, as well as glaciological and climatic conditions (e.g. Bennett et al., 2004;  
1335 Benediktsson et al., 2009, 2010; Lukas and Sass, 2011; Midgley et al., 2013, 2018). Recent advances  
1336 in geophysical imaging of sub-ice geomorphology have also allowed links to be made between  
1337 modern and palaeo-ice sheets (see Section 3.2.2.3), and we expect this to be a growth area going  
1338 forward (see also Stokes, 2018). More broadly, geophysical methods can be used to identify the extent  
1339 of buried ice, allowing an assessment of the geomorphological stability of contemporary glacier  
1340 forelands (e.g. Everest and Bradwell, 2003).

1341

#### 1342 *5.3.1 Remote mapping of modern glacial settings*

1343 The spatial resolution of remotely-sensed data is of critical importance in modern glacial settings:  
1344 spatial resolutions commensurate with the size of the landforms being mapped and the scope of the  
1345 research are required. Typically, aerial photographs or satellite imagery with GSDs of <0.5 m are used  
1346 in modern glacial settings to enable mapping of small features (e.g. Benediktsson et al., 2010; Lukas,  
1347 2012; Bradwell et al., 2013; Brynjólfsson et al., 2014; Lovell, 2014; Schomacker et al., 2014;  
1348 Chandler et al., 2016a; Ewertowski et al., 2016; Lovell et al., 2018). LiDAR or UAV-derived DEMs  
1349 are also becoming increasingly used for mapping in modern glacial environments (e.g. Brynjólfsson et  
1350 al., 2014, 2016; Jónsson et al. 2014, 2016; Benediktsson et al., 2016; Chandler et al., 2016a;  
1351 Ewertowski et al., 2016; Everest et al., 2017; Allaart et al., 2018; Lovell et al., 2018). Despite the  
1352 high-resolution of the imagery, some compromise on the level of detail may be necessary, such as  
1353 deciding on a maximum mapping scale (e.g. 1:500–1:1000; Schomacker et al., 2014) to prevent too  
1354 detailed mapping or by simplifying the mapping of certain features. In studies of low-amplitude  
1355 (annual) moraines, the crestlines rather than the planforms are typically mapped, reflecting a  
1356 combination of image resolution and data requirements: annual moraine sequences are often used to  
1357 calculate ice-margin retreat rates and the position of crestlines offers sufficient detail for this purpose  
1358 (Figure 17; Krüger, 1995; Beedle et al., 2009; Lukas, 2012; Bradwell et al., 2013; Chandler et al.,  
1359 2016a, b). Moreover, this approach can actually ‘normalise’ the data for subsequent analyses,  
1360 removing the variability of, for example, moraine-base widths that result from gravitational processes  
1361 during or after moraine formation.

1362

1363 The temporality (both month and year) of imagery takes on greater significance in modern glacial  
1364 environments. Depending on the purpose of the research, either the most recent high-resolution

1365 remotely-sensed dataset available or a series of images from a number of intervals during a given time  
1366 period are commonly required (e.g. Benediktsson et al., 2010; Bennett et al., 2010; Bradwell et al.,  
1367 2013; Reinardy et al., 2013; Chandler et al., 2016a; Evans et al., 2016b; Ewertowski et al., 2016). In  
1368 exceptional circumstances, the research may require an annual temporal resolution; for example,  
1369 aerial photographs are commonly captured annually at the beginning and end of the ablation season in  
1370 many forelands of the European Alps (cf. Lukas, 2012; Zemp et al., 2015). The increasing use of  
1371 UAVs provides very high-resolution imagery (<0.1 m GSD) of contemporary glacier forelands and  
1372 the option to capture up-to-date imagery during every visit to the site, circumventing issues relating to  
1373 temporal resolution. This approach is likely to come into greater usage for studies examining short-  
1374 term ice-marginal landscape evolution and preservation potential.

1375  
1376 Photogrammetric image processing (see Section 3.3) is arguably of most importance in contemporary  
1377 glacial environments, particularly where the purpose of the mapping is to investigate small variations  
1378 of the order of metres to tens of metres at short (0–30 years) timescales (cf. Evans, 2009). However,  
1379 such constraints are not necessarily applicable where broader landsystem mapping is conducted (e.g.  
1380 Evans, 2009; Evans and Orton, 2015; Evans et al., 2016a). Ideally, digital aerial photographs should  
1381 be processed using stereoscopic photogrammetry techniques using GCPs collected during topographic  
1382 surveys to enable the production of DEMs and orthorectified imagery with low error values (RMSEs  
1383 <2 m; see Section 3.3). It is preferable to survey GCPs and capture imagery contemporaneously, with  
1384 surveyed GCPs appearing in the captured aerial imagery (e.g. Evans and Twigg, 2002; Evans et al.,  
1385 2006, 2012; Schomacker et al., 2014), but imagery often pre-dates the geomorphological  
1386 investigations and topographic surveys (e.g. Bennett et al., 2010; Bradwell et al., 2013; Chandler et  
1387 al., 2016b). Alternatively, the digital aerial photographs could be processed using SfM  
1388 photogrammetry methods (see Section 3.3.1.2).

1389  
1390 *5.3.2 Field mapping in modern glacial settings*

1391 The rapidly-changing nature of modern glacier forelands presents a number of challenges when using  
1392 topographic base maps (see Section 2). Firstly, in relation to spatial limitations, topographic maps  
1393 available in many settings (typically at scales of 1: 25,000 or 1: 50,000) may offer insufficient spatial  
1394 resolution for mapping due to two factors: (i) the relief of the small geomorphological features  
1395 ubiquitous in contemporary glacial environments is often less than the contour intervals depicted on  
1396 the maps; and (ii) many forelands, such as those of southeast Iceland, have limited elevation changes  
1397 across the foreland (cf. Evans and Twigg, 2002; Evans et al., 2016a).

1398  
1399 Publicly-available topographic maps are rarely updated frequently enough to be useful for mapping  
1400 the often rapid (annual to decadal-scale) changes taking place at modern glacier margins and in  
1401 proglacial landscapes. Instead, it is desirable to undertake geodetic-grade surveying (i.e. using an

1402 RTK-GPS) of landforms and measurement of high-resolution topographic profiles, where conditions  
1403 allow a safe approach towards the glacier margin (e.g. Benediktsson et al., 2008; Bradwell et al.,  
1404 2013). Indeed, conducting detailed surveying with geodetic-grade equipment is essential for  
1405 quantifying small changes in ice-marginal/proglacial landscapes (e.g. Schomacker and Kjær, 2008;  
1406 Ewertowski and Tomczyk, 2015; Korsgaard et al., 2015) and obtaining metre-scale ice-margin retreat  
1407 rates from the geomorphological record (e.g. Bradwell et al., 2013; Chandler et al., 2016a). This level  
1408 of detail and accuracy may be unnecessary for some glacial geomorphological studies (e.g. those  
1409 focused on the overall glacial landsystem), and annotation of aerial photograph extracts may be  
1410 sufficient. There remain potential temporal limitations with these approaches, namely (i) limitations  
1411 imposed by the date/year of image capture when mapping on print-outs and (ii) difficulties with  
1412 correlating survey data with imagery, depending on the time difference and rapidity of landscape  
1413 changes. In localities where (parts of) the ice-marginal/proglacial landscape cannot be satisfactorily or  
1414 safely traversed, imagery and elevation control from remotely-sensed sources will be necessary (e.g.  
1415 Evans et al., 2016e).

1416

## 1417 **6. Frameworks for best practice**

1418

1419 Based on our review of the various mapping approaches, we here synthesise *idealised* frameworks for  
1420 mapping palaeo-ice sheet geomorphological imprints (Section 6.1) and alpine and plateau-style ice  
1421 mass (cirque glaciers, valley glaciers, ice-fields and ice-caps) geomorphological imprints (Section  
1422 6.2). The aim is to provide frameworks for best practice in glacial geomorphological mapping,  
1423 ensuring robust and systematic geomorphological mapping programmes. The templates outlined can  
1424 be modified as necessary, depending on the study area size and project scope, along with the datasets,  
1425 software and time available.

1426

1427 Before outlining the idealised frameworks, we offer four general recommendations for undertaking  
1428 and reporting glacial geomorphological mapping that are applicable at all scales of investigation:

1429

1430 (1) The methods, datasets and equipment employed in mapping should be clearly stated,  
1431 including the resolution and format of remotely-sensed data.

1432 (2) Any processing methods and imagery rectification errors (RMSEs) should be reported, as  
1433 well as mapping uncertainties (both in terms of the location of the landforms and their  
1434 identification/classification). Where remotely-sensed datasets are obtained as pre-processed,  
1435 georeferenced products, this should also be stated.

1436 (3) Establishing and reporting criteria for identifying and mapping different landforms is  
1437 desirable. As a minimum, this could take the form of a brief definition of the mapped  
1438 landform.



1439 (4) GIS software (e.g. *ArcGIS*, *QGIS*) should be used for geomorphological mapping and  
1440 vectorisation to provide georeferenced geomorphological data that is also readily transferable  
1441 for data sharing or community use.

1442  
1443 Following the above general recommendations will provide transparency about how the mapping was  
1444 compiled and what considerations were made during the process, aiding accuracy assessment,  
1445 comparison and integration of geomorphological data. This is particularly valuable for the  
1446 incorporation of the geomorphological mapping in large compilations (Bickerdike et al., 2016;  
1447 Stroeven et al., 2016; Clark et al., 2018a) and any subsequent use of the data for palaeoglaciological  
1448 reconstructions and/or testing numerical ice sheet models (Stokes et al., 2015; Margold et al., 2018).

1449  
1450 In relation to software (recommendation 4), some practitioners may prefer to use graphics software  
1451 packages (e.g. *Adobe Illustrator*, *Canvas X*, *CorelDRAW*) for the production of final glacial  
1452 geomorphological maps (e.g. Brynjólfsson et al., 2014; Darvill et al., 2014; Blomdin et al., 2016a;  
1453 Chandler et al., 2016a; Bendle et al., 2017a; Norris et al., 2017). Such graphics software can provide  
1454 greater functionality than current GIS packages for fine adjustments of the final cartographic design.  
1455 However, any modification in graphics software should be kept to a minimum in order to avoid  
1456 compromising the transferability of the data for other users (e.g. as shapefiles), with the focus instead  
1457 on adjustments to the map symbology and ensuring optimal map presentation.

1458  
1459 *6.1 Palaeo-ice sheet geomorphological imprints*

1460  
1461 For mapping of palaeo-ice sheet geomorphological imprints we recommend the use of multiple  
1462 remotely-sensed datasets in a synergistic and systematic process, subject to data availability and  
1463 coverage (Figure 18). As a minimum, remote sensing investigations should involve reconnaissance-  
1464 level mapping using multiple remotely-sensed datasets to establish the most suitable dataset (e.g.  
1465 Stokes et al., 2016a). However, mapping often benefits from utilising a range of imagery types and  
1466 resolutions, enabling the advantages of each respective method/dataset to be integrated to produce an  
1467 accurate geomorphological map (see below). At the outset of the mapping, a decision should be made  
1468 on the level of mapping detail required for particular landforms (i.e. polyline or polygon mapping), in  
1469 line with the aims and requirements of the study (see Section 5.1.1).

1470  
1471 Initially, mapping should involve an assessment of the study area using remotely-sensed data in  
1472 conjunction with existing maps and literature to identify gaps in the mapping record and localities for  
1473 focused mapping. Following this reconnaissance stage, the mapper may proceed with mapping from  
1474 both DEMs and satellite imagery, adding increasing levels of detail with increasingly higher  
1475 resolution datasets. Recommended techniques for processing the satellite images and DEMs are

1476 outlined in Sections 3.3.2 and 3.3.3, including the generation of false-colour composites with different  
1477 spectral band combinations to aid landform identification (e.g. Jansson and Glasser, 2005; Lovell et  
1478 al., 2011; Storrar and Livingstone, 2017).

1479  
1480 DEMs may provide a superior source of imagery as they directly record the shape of landforms, rather  
1481 than the interaction of reflected radiation and topography, and therefore allow for more accurate and  
1482 intuitive mapping. For example, DEMs are often particularly useful for identifying and mapping  
1483 meltwater channels (e.g. Greenwood et al., 2007; Storrar and Livingstone, 2017). Specific features  
1484 may also only be identifiable on satellite imagery, such as low-relief corridors of glaciofluvial  
1485 deposits, due to their distinctive spectral signatures (e.g. Storrar and Livingstone, 2017). Moreover,  
1486 the typically superior resolution of satellite imagery may enhance landform detectability and allow for  
1487 more detailed mapping. Many glacial landforms are also clearly distinguishable in one or more sets of  
1488 remotely-sensed data (or through using a combination of datasets).

1489  
1490 To ensure that all landforms are mapped from remotely-sensed data, the datasets should be viewed at  
1491 a variety of scales and mapping conducted through multiple passes of the area, enabling the addition  
1492 of increasing levels of detail to and/or refinement of initial mapping with each pass (Norris et al.,  
1493 2017). It may be advantageous to perform a final check at a small cartographic scale (e.g. 1:500,000)  
1494 to ensure there are no errors in the mapping, such as duplication of landforms at image overlaps (e.g.  
1495 De Angelis, 2007). The mapping should be iterative, with repeated consultations of various remotely-  
1496 sensed datasets throughout the process recommended.

1497  
1498 In this contribution, we have focused on the use of satellite imagery and DEMs for mapping palaeo-  
1499 ice sheet geomorphological imprints, since these are the most widely used for practical reasons.  
1500 However, aerial photograph interpretation and fieldwork should not be abandoned altogether in  
1501 palaeo-ice sheet settings. Aerial photographs, where available, can be used to add further detail and  
1502 refine the mapping, whilst fieldwork enables ground-truthing of remote mapping (e.g. Hättestrand and  
1503 Clark, 2006; Kleman et al., 2010; Darvill et al., 2014; Evans et al., 2014). Furthermore, mapping from  
1504 satellite imagery and DEMs can direct fieldwork, highlighting areas for sedimentological and  
1505 stratigraphic investigations. Such studies can provide invaluable data on landform genesis, subglacial  
1506 processes, and ice dynamics (e.g. Livingstone et al., 2010; Evans et al., 2015; Spagnolo et al., 2016;  
1507 Phillips et al., 2017; Norris et al., 2018). Remote mapping of palaeo-ice sheet geomorphology also  
1508 guides targeted dating for chronological investigations and should be an essential first phase in such  
1509 studies (e.g. Stroeve et al., 2011; Darvill et al., 2014, 2015).

1510

1511 *6.2 Alpine and plateau-style ice mass geomorphological imprints*

1512

1513 Our idealised framework for mapping alpine and plateau-style ice mass geomorphological imprints is  
1514 an iterative process involving several consultations of remotely-sensed data and field mapping  
1515 (Figures 19 and 20). This methodology provides a robust approach to mapping that has been broadly  
1516 used in previous studies (e.g. Benn and Ballantyne, 2005; Lukas and Lukas, 2006; Kjær et al., 2008;  
1517 Boston, 2012a, b; Brynjólfsson et al., 2014; Jónsson et al., 2014; Pearce et al., 2014; Schomacker et  
1518 al., 2014; Chandler et al., 2016a; Chandler and Lukas, 2017). This framework is also applicable to  
1519 modern glacial settings as the overarching methods do not differ fundamentally, but practitioners  
1520 should be aware of issues relating to the temporal resolution of remotely-sensed data (see Section  
1521 5.3).

1522  
1523 In the initial preparatory stage, the mapper should consult topographic, geological and extant  
1524 geomorphological maps (where available), and ideally undertake mapping of the study area using  
1525 remotely-sensed data, at least at a reconnaissance level. This essential phase familiarises the mapper  
1526 with the study area prior to fieldwork and enables the identification of significant areas for targeted,  
1527 detailed field mapping (or ground verification) and sedimentological investigations of specific  
1528 landforms. Conversely, the reconnaissance investigations may also clarify which areas are less  
1529 important for a field visit and aid route planning. Importantly, this enables a systematic approach to  
1530 mapping, and is particularly important in previously-unmapped areas (e.g. Boston, 2012a, b). During  
1531 the initial stage, it may also be desirable to establish a legend/mapping system in readiness for  
1532 subsequent field mapping (Otto and Smith, 2013).

1533  
1534 Following the preparatory/reconnaissance stage, detailed field mapping, or at a minimum some  
1535 ground verification, should ideally be conducted to avoid overlooking (subtle) landforms and  
1536 misinterpreting others. Depending on the nature of the project and accessibility limitations, ground  
1537 verification may be done during a single (and relatively short) field visit (e.g. Lukas, 2012; Chandler  
1538 et al., 2016a), whilst detailed field mapping would usually require longer field visits or even repeated,  
1539 long-term field campaigns (e.g. Kjær et al. 2008; Boston, 2012a, b; Schomacker et al., 2014; Evans et  
1540 al., 2016a). During field surveys, consultation of initial remote mapping helps to ensure accurate  
1541 representation of landforms on field maps and allows verification of all features identified remotely  
1542 (e.g. Boston, 2012a, b; Pearce et al., 2014).

1543  
1544 Following field mapping, which may be an intermittent and ongoing process in the case of large study  
1545 areas and long-term research projects, it is ideal to finalise the geomorphological mapping using high-  
1546 resolution imagery (i.e. aerial photographs, satellite imagery, LiDAR DEMs, UAV-derived imagery).  
1547 This allows complex patterns of landforms, such as British ‘hummocky moraine’ (e.g. Lukas and  
1548 Lukas, 2006; Boston, 2012b), crevasse-squeeze ridges (e.g. Kjær et al., 2008), drumlin fields (e.g.  
1549 Benediktsson et al., 2016), and sawtooth ‘annual’ moraines (e.g. Chandler et al., 2016a; Evans et al.,

1550 2016a), to be mapped with high spatial accuracy, following landform identification and interpretation  
1551 in the field. Again, during this stage, previous mapping from DEMs and field maps should be  
1552 consulted. As highlighted in the scale-appropriate examples, the procurement of remotely-sensed data  
1553 with appropriate spatial and temporal resolution is important (see Sections 5.2 and 5.3).

1554

1555 Depending on the type of imagery used (hard-copy or digital), the rectification of imagery/overlays  
1556 may precede or follow aerial photograph mapping: where digital format aerial photographs are used,  
1557 rectification will be undertaken before mapping (Figure 19), whilst acetate overlays will be corrected  
1558 after mapping from hard-copy aerial photographs (Figure 20) (see also Supplementary Material).  
1559 Subsequently, acetate overlays can be checked against digital imagery (if available) before being  
1560 vectorised (digitally traced) in a GIS software package (e.g. *ArcMap*, *QGIS*).

1561

1562 In our view, geomorphological mapping in cirque glacier, valley glacier, icefield and ice-cap settings  
1563 should not be reliant solely on the morphological characteristics of features and should ideally be  
1564 combined with detailed sedimentological investigations of available exposures as part of an inductive-  
1565 deductive process, using standard procedures (cf. Evans and Benn, 2004; Lukas et al., 2013, and  
1566 references therein). This reflects the fact that these glacier systems occupy more manageable study  
1567 areas and, as such, sedimentological analyses can be more readily applied. By combining  
1568 geomorphological mapping and sedimentology, issues relating to equifinality (Chorley, 1962; Möller  
1569 and Dowling, 2018) will be avoided, which is important when attempting to establish the wider  
1570 palaeoglaciological and palaeoclimatic significance of the geomorphological evidence (cf. Benn and  
1571 Lukas, 2006). This multi-proxy, process-form approach ensures accurate genetic interpretations on  
1572 geomorphological maps.

1573

## 1574 **7. Conclusions**

1575

1576 Geomorphological mapping forms the basis of a wide range of process-oriented, glacial chronological  
1577 and palaeoglaciological studies. Thus, it is imperative that effective approaches are used to ensure  
1578 robust assimilation of data and that errors and uncertainties are explicitly reported. This is particularly  
1579 the case where field mapping and analogue data are transferred to digital format and combined with  
1580 digital remotely-sensed data.

1581

1582 In general, specific methods and datasets are often applied to particular glacial settings: (i) a mixture  
1583 of satellite imagery (e.g. Landsat) and DEMs (e.g. ASTER GDEM, SRTM) are typically used for  
1584 mapping in palaeo-ice sheet settings; and (ii) a combination of aerial photographs and field mapping  
1585 are widely employed for mapping alpine and plateau-style ice mass geomorphological imprints.  
1586 Increasingly, UAV-captured aerial imagery and high resolution DEMs (derived from UAV-captured

1587 imagery and LiDAR) are being utilised for mapping of modern glacial environments and are likely to  
1588 be a growth area in future geomorphological mapping studies, enabling high resolution, multi-  
1589 temporal remotely-sensed datasets to be obtained at relatively low cost. The use of particular methods  
1590 reflects the spatial and temporal resolution of remotely-sensed datasets, along with the practicality of  
1591 their application (both in terms of time and finance).

1592

1593 In this contribution, we have highlighted that compromises and pragmatic solutions are often  
1594 necessary in glacial geomorphological mapping, particularly with respect to processing techniques  
1595 and the level of mapping detail. For example, detailed GNSS surveys using geodetic-grade equipment  
1596 are desirable for photogrammetric processing of aerial photographs, but this is impractical for the  
1597 large areas covered by icefields, ice-caps and ice sheets. Thus, pragmatic approaches may be used,  
1598 such as georeferencing analogue-derived mapping to existing (coarser) georeferenced datasets (e.g.  
1599 satellite imagery, DEMs or orthophotographs). In relation to the level of mapping detail, it is often  
1600 necessary to map particular landforms as linear features (e.g. subglacial bedforms, moraines) or define  
1601 a maximum scale during mapping, due to image resolution and/or study requirements.

1602

1603 We have outlined idealised frameworks and general recommendations to ensure best practice in future  
1604 studies. In particular, we emphasise the importance of utilising multiple datasets or mapping  
1605 approaches in synergy, akin to multi-proxy/-method approaches used in many Earth Science  
1606 disciplines; multiple remotely-sensed datasets in the case of ice-sheet-scale geomorphology and a  
1607 combination of remote sensing and field mapping for cirque glaciers to ice-caps. Further key  
1608 recommendations are the clear reporting of (i) the methods, datasets and equipment employed in  
1609 mapping, (ii) any processing methods employed and imagery rectification errors (RMSEs) associated  
1610 with imagery, along with mapping uncertainties, and (iii) the criteria for identifying and mapping  
1611 different landforms. We also recommend that mapping is conducted in GIS software to provide  
1612 georeferenced geomorphological data that is easily transferable between users. Finally, we advocate  
1613 sedimentological investigations of available exposures as part of an inductive-deductive process  
1614 during fieldwork to ensure accurate genetic interpretations of the geomorphological record as part of a  
1615 holistic approach. Following these recommendations will aid in comparison, integration, and accuracy  
1616 assessment of geomorphological data, particularly where geomorphological data are incorporated in  
1617 large compilations and subsequently used for palaeoglaciological reconstruction.

1618

## 1619 **Acknowledgements**

1620

1621 We are grateful to numerous colleagues for informal discussions that have directly or indirectly  
1622 helped shape this paper. Alex Clayton is thanked for kindly supplying the UAV imagery and DEM for  
1623 the Skálafellsjökull foreland, whilst Jon Merritt is thanked for providing CMB and SL with access to

1624 aerial photographs at the British Geological Survey in Edinburgh. We are also grateful to Jacob  
1625 Bendle, Natacha Gribenski and Sophie Norris for kindly providing figures for inclusion in this  
1626 contribution. The NEXTMap Great Britain™ data for Ben More Coigach was licensed to BMPC by  
1627 the NERC Earth Observation Data Centre under a Demonstration Use License Agreement. CMB and  
1628 HL obtained access to aerial photographs and NEXTMap Great Britain™ data through NERC Earth  
1629 Observation Data Centre whilst in receipt of NERC Algorithm studentships NE/G52368X/1 (CMB)  
1630 and NE/I528050/1 (HL). This contribution was written whilst BMPC was in receipt of a Queen Mary  
1631 Natural and Environmental Science Studentship, which is gratefully acknowledged. We thank Richard  
1632 Waller and an anonymous reviewer for constructive comments that helped improve the clarity of this  
1633 contribution, along with Ian Candy for editorial handling.

1634

## 1635 **References**

1636

- 1637 Akçar, N., Yavuz, V., Ivy-Ochs, S., Reber, R., Kubik, P.W., Zahno, C., Schlüchter, C., 2014. Glacier  
1638 response to the change in atmospheric circulation in the eastern Mediterranean during the Last  
1639 Glacial Maximum. *Quat. Geochronol.* 19, 27–41.
- 1640 Alexanderson, H., Adrielsson, L., Hjort, C., Möller, P., Antonov, O., Eriksson, S., Pavlov, M., 2002.  
1641 Depositional history of the North Taymyr ice-marginal zone, Siberia—a landsystem  
1642 approach. *J. Quat. Sci.* 17(4), 361–382.
- 1643 Allaart, L., Friis, N., Ingólfsson, Ó., Håkansson, L., Noormets, R., Farnsworth, W.R., Mertes, J.,  
1644 Schomacker, A., 2018. Drumlins in the Nordenskiöldbreen forefield, Svalbard. *GFF* 140,  
1645 170–188.
- 1646 Andrews, J.T., Miller, G.H., 1979. Glacial erosion and ice sheet divides, northeastern Laurentide Ice  
1647 Sheet, on the basis of the distribution of limestone erratics. *Geology* 7(12), 592–596.
- 1648 Astakhov, V., Shkatova, V., Zastrozhnov, A., Chuyko, M., 2016. Glaciomorphological Map of the  
1649 Russian Federation. *Quat. Int.* 420, 4–14.
- 1650 Atkinson, N., Pawley, S., Utting, D.J., 2016. Flow-pattern evolution of the Laurentide and Cordilleran  
1651 ice sheets across west-central Alberta, Canada: implications for ice sheet growth, retreat and  
1652 dynamics during the last glacial cycle. *J. Quat. Sci.* 31(7), 753–768.
- 1653 Aylsworth, J.M., Shilts, W.W., 1989. Glacial features around the Keewatin Ice Divide: Districts of  
1654 Mackenzie and Keewatin. Geological Survey of Canada paper 88-24.
- 1655 Bakke, J., Dahl, S.O., Paasche, Ø., Løvlie, R., Nesje, A., 2005. Glacier fluctuations, equilibrium-line  
1656 altitudes and palaeoclimate in Lyngen, northern Norway, during the Lateglacial and  
1657 Holocene. *The Holocene* 15, 518–540.
- 1658 Ballantyne, C.K., 1989. The Loch Lomond Readvance on the Isle of Skye, Scotland: glacier  
1659 reconstruction and palaeoclimatic implications. *J. Quat. Sci.* 4, 95–108.
- 1660 Ballantyne, C.K., 2002. The Loch Lomond Readvance on the Isle of Mull, Scotland: glacier  
1661 reconstruction and palaeoclimatic implications. *J. Quat. Sci.* 17, 759–771.
- 1662 Ballantyne, C.K., 2007a. The Loch Lomond Readvance on north Arran, Scotland: glacier  
1663 reconstruction and palaeoclimatic implications. *J. Quat. Sci.* 22, 343–359.
- 1664 Ballantyne, C.K., 2007b. Loch Lomond Stadial glacier on North Harris, Outer Hebrides, North-West  
1665 Scotland: glacier reconstruction and palaeoclimatic implications. *Quat. Sci. Rev.* 26, 3134–  
1666 3149.
- 1667 Barchyn, T.E., Dowling, T.P.F., Stokes, C.R., Hugenholtz, C.H., 2016. Subglacial bed form  
1668 morphology controlled by ice speed and sediment thickness. *Geophys. Res. Lett.* 43, 7572–  
1669 7580.
- 1670 Barr, I.D., Clark, C.D., 2009. Distribution and pattern of moraines in Far NE Russia reveal former  
1671 glacial extent. *J. Maps* 5, 186–193.

- 1672 Barr, I.D., Clark, C.D., 2012. An updated moraine map of Far NE Russia. *J. Maps* 8, 431–436.
- 1673 Barrell, D.J.A., Andersen, B.G., Denton, G.H. and Lyttle, B.S., 2011. Glacial geomorphology of the  
1674 central South Island, New Zealand. GNS Science Monograph 27. GNS Science, Lower Hutt,  
1675 81 pp + map (5 sheets).
- 1676 Barrell, D.J.A., Andersen, B.G., Denton, G.H. and Lyttle, B.S., 2013. Glacial geomorphology of the  
1677 central South Island, New Zealand – digital data. GNS Science Monograph 27a. GNS  
1678 Science, 17 pp (GIS digital data files + explanatory notes).
- 1679 Barrow, G., Hinxman, L.W., Cunningham Craig, E.H., 1913. The Geology of Upper Strathspey,  
1680 Gaick, and the Forest of Atholl (Explanation of Sheet 64). Memoirs of the Geological Survey,  
1681 HMSO, Edinburgh, Scotland.
- 1682 Batchelor, C., Dowdeswell, J.A., Ottesen, D., 2017. Submarine Glacial Landforms. In: Micallef, A.,  
1683 Krastel, S., Savini, A. (Eds.), *Submarine Geomorphology*. Springer, Cham, Switzerland: pp.  
1684 207–234.
- 1685 Beedle, M.J., Menounos, B., Luckman, B.H., Wheate, R., 2009. Annual push moraines as climate  
1686 proxy. *Geophys. Res. Lett.* 36, L20501.
- 1687 Bendle, J.M., Glasser, N.F., 2012. Palaeoclimatic reconstruction from Lateglacial (Younger Dryas  
1688 Chronozone) cirque glaciers in Snowdonia, North Wales. *Proceedings of the Geologists'*  
1689 *Association* 123, 130–145.
- 1690 Bendle, J.M., Thorndycraft, V.R., Palmer, A.P., 2017a. The glacial geomorphology of the Lago  
1691 Buenos Aires and Lago Pueyrredón ice lobes of central Patagonia. *J. Maps* 13, 654–673.
- 1692 Bendle, J.M., Palmer, A.P., Thorndycraft, V.R., Matthews, I.P., 2017b. High-resolution chronology  
1693 for deglaciation of the Patagonian Ice Sheet at Lago Buenos Aires (46.5° S) revealed through  
1694 varve chronology and Bayesian age modelling. *Quat. Sci. Rev.* 177, 314–339.
- 1695 Benediktsson, Í.Ö., Möller, P., Ingólfsson, Ó., van der Meer, J.J.M., Kjær, K.H., Krüger, J., 2008.  
1696 Instantaneous end moraine and sediment wedge formation during the 1890 glacier surge of  
1697 Brúarjökull, Iceland. *Quat. Sci. Rev.* 27, 209–234.
- 1698 Benediktsson, Í.Ö., Ingólfsson, Ó., Schomacker, A., Kjaer, K.H., 2009. Formation of submarginal and  
1699 proglacial end moraines: implications of ice-flow mechanism during the 1963–64 surge of  
1700 Brúarjökull, Iceland. *Boreas* 38, 440–457.
- 1701 Benediktsson, Í.Ö., Schomacker, A., Lokrantz, H., Ingólfsson, Ó., 2010. The 1890 surge end moraine  
1702 at Eyjabakkajökull, Iceland: a re-assessment of a classic glaciotectonic locality. *Quat. Sci.*  
1703 *Rev.* 29, 484–506.
- 1704 Benediktsson, Í.Ö., Schomacker, A., Johnson, M.D., Geiger, A.J., Ingólfsson, Ó., Guðmundsdóttir,  
1705 E.R. 2015. Architecture and structural evolution of an early Little Ice Age terminal moraine at  
1706 the surge-type glacier Múlajökull, Iceland. *J. Geophys. Res.: Earth Surf.* 120, 1895–1910.
- 1707 Benediktsson, Í.Ö., Jónsson, S.A., Schomacker, A., Johnson, M.D., Ingólfsson, Ó., Zoet, L., Iverson,  
1708 N.R., Stötter, J., 2016. Progressive formation of modern drumlins at Múlajökull, Iceland:  
1709 stratigraphical and morphological evidence. *Boreas*, 45, 567–583.
- 1710 Benn, D.I., 1990. Scottish Lateglacial moraines: debris supply, genesis and significance. Unpublished  
1711 PhD thesis, University of St Andrews.
- 1712 Benn, D.I., 1994. Fluted moraine formation and till genesis below a temperate valley glacier:  
1713 Slettmarkbreen, Jotunheimen, southern Norway. *Sedimentology* 41, 279–292.
- 1714 Benn, D.I. 2006. Interpreting glacial sediments. In: Knight, P. (Ed.) *Glacier Science and*  
1715 *Environmental Change*. Oxford, Blackwell, pp. 434–439.
- 1716 Benn, D.I., Ballantyne, C.K., 2005. Palaeoclimatic reconstruction from Loch Lomond Readvance  
1717 glaciers in the West Drumochter Hills, Scotland. *J. Quat. Sci.* 20, 577–592.
- 1718 Benn, D.I., Evans, D.J.A., 2010. *Glaciers and Glaciation* (2<sup>nd</sup> Edition). Hodder Education, London,  
1719 802 pp.
- 1720 Benn, D.I., Lukas, S., 2006. Younger Dryas glacial landsystems in North West Scotland: an  
1721 assessment of modern analogues and palaeoclimatic implications. *Quat. Sci. Rev.* 25, 2390–  
1722 2408.
- 1723 Benn, D.I., Lowe, J.J., Walker, M.J.C., 1992. Glacier response to climatic change during the Loch  
1724 Lomond Stadial and early Flandrian: geomorphological and palynological evidence from the  
1725 Isle of Skye, Scotland. *J. Quat. Sci.* 7, 125–144.

- 1726 Bennett, G.L., Evans, D.J.A., 2012. Glacier retreat and landform production on an overdeepened  
1727 glacier foreland: the debris-charged glacial landsystem at Kvíárjökull, Iceland. *Earth Surf.*  
1728 *Process. Land.* 37, 1584–1602.
- 1729 Bennett, G.L., Evans, D.J.A., Carbonneau, P., Twigg, D.R., 2010. Evolution of a debris-charged  
1730 glacier landsystem, Kvíárjökull, Iceland. *J. Maps* 6, 40–67.
- 1731 Bennett, M.R., 1991. Scottish "hummocky moraine": its implications for the deglaciation of the North  
1732 West Highlands during the Younger Dryas or Loch Lomond Stadial. University of Edinburgh,  
1733 Unpublished PhD thesis, 362 pp.
- 1734 Bennett, M.R., Huddart, D., Waller, R.I., Cassidy, N., Tomio, A., Zukowskyj, P., Midgley, N.G.,  
1735 Cook, S.J., Gonzalez, S., Glasser, N.F., 2004. Sedimentary and tectonic architecture of a large  
1736 push moraine: a case study from Hagafellsjökull-Eystri, Iceland. *Sedi. Geol.* 172, 269–292.
- 1737 Bickerdike, H.L., Evans, D.J.A., Ó Cofaigh, C., Stokes, C.R., 2016. The glacial geomorphology of the  
1738 Loch Lomond Stadial in Britain: a map and geographic information system resource of  
1739 published evidence. *J. Maps* 12(5), 1178–1186.
- 1740 Bickerdike, H.L., Ó Cofaigh, C., Evans, D.J.A., Stokes, C.R., 2018. Glacial landsystems, retreat  
1741 dynamics and controls on Loch Lomond Stadial (Younger Dryas) glaciation in Britain.  
1742 *Boreas* 47, 202–224.
- 1743 Bickerton, R.W., Matthews, J.A., 1992. On the accuracy of lichenometric dates: an assessment based  
1744 on the 'Little Ice Age' moraine sequence of Nigardsbreen, southern Norway. *The Holocene* 2,  
1745 227–237.
- 1746 Bickerton, R.W., Matthews, J.A., 1993. 'Little ice age' variations of outlet glaciers from the  
1747 jostedalsbreen ice-cap, Southern Norway: A regional lichenometric-dating study of ice-  
1748 marginal moraine sequences and their climatic significance. *J. Quat. Sci.* 8, 45–66.
- 1749 Blomdin, R., Heyman, J., Stroeven, A.P., Hättestrand, C., Harbor, J.M., Gribenski, N., Jansson, K.N.,  
1750 Petrakov, D.A., Ivanov, M.N., Alexander, O., Rudoy, A.N., Walther, M., 2016a. Glacial  
1751 geomorphology of the Altai and Western Sayan Mountains, Central Asia. *J. Maps* 12(1), 123–  
1752 136.
- 1753 Blomdin, R., Stroeven, A.P., Harbor, J.M., Lifton, N.A., Heyman, J., Gribenski, N., Petrakov, D.A.,  
1754 Caffee, M.W., Ivanov, M.N., Hättestrand, C., Rogozhina, I., Usabaliev, R., 2016b. Evaluating  
1755 the timing of former glacier expansions in the Tian Shan: A key step towards robust spatial  
1756 correlations. *Quat. Sci. Rev.* 153, 78–96.
- 1757 Blomdin, R., Stroeven, A.P., Harbor, J.M., Gribenski, N., Caffee, M.W., Heyman, J., Rogozhina, I.,  
1758 Ivanov, M.N., Petrakov, D.A., Walther, M., Rudoy, A.N., Zhang, W., Orkhonselenge, A.,  
1759 Hättestrand, C., Lifton, N.A., Jansson, K.N., 2018. Timing and dynamics of glaciation in the  
1760 Ikh Turgen Mountains, Altai region, High Asia. *Quat. Geochron.* 47, 54–71.
- 1761 Bolch, T., Loibl, D., 2017. GIS for Glaciers and Glacial Landforms. Reference Module in Earth  
1762 Systems and Environmental Sciences.
- 1763 Borsellino, R., Shulmeister, J., Winkler, S., 2017. Glacial geomorphology of the Barbizon & Butler  
1764 Downs, Rangitata Valley, South Island, New Zealand. *J. Maps* 13, 502–510.
- 1765 Boston, C.M., 2012a. A Lateglacial plateau icefield in the Monadhliath Mountains, Scotland:  
1766 reconstruction, dynamics and palaeoclimatic implications. Unpublished PhD thesis, Queen  
1767 Mary University of London, 295 pp.
- 1768 Boston, C.M., 2012b. A glacial geomorphological map of the Monadhliath Mountains, Central  
1769 Scottish Highlands. *J. Maps* 8(4), 437–444.
- 1770 Boston, C.M., Lukas, S., Carr, S.J. 2015. A Younger Dryas plateau icefield in the Monadhliath,  
1771 Scotland, and implications for regional palaeoclimate. *Quat. Sci. Rev.* 108, 139–162.
- 1772 Boulton, G.S., Clark, C.D., 1990a. A highly mobile Laurentide ice sheet revealed by satellite images  
1773 of glacial lineations. *Nature* 346(6287), 813–817.
- 1774 Boulton, G.S., Clark, C.D., 1990b. The Laurentide ice sheet through the last glacial cycle: the  
1775 topology of drift lineations as a key to the dynamic behaviour of former ice sheets. *Earth*  
1776 *Environ. Sci. Trans. R. Soc. Edinb.* 81(4), 327–347.
- 1777 Boulton, G.S., Dongelmans, P., Punkari, M., Broadgate, M., 2001. Palaeoglaciology of an ice sheet  
1778 through a glacial cycle: the European ice sheet through the Weichselian. *Quat. Sci. Rev.*  
1779 20(4), 591–625.



- 1780 Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long, D., Everest, J.D.,  
1781 Hestvik, O.B., Stevenson, A.G., Hubbard, A.L., Finlayson, A.G., Mathers, H.E., 2008. The  
1782 northern sector of the last British Ice Sheet: maximum extent and demise. *Earth-Sci. Rev.* 88,  
1783 207–226.
- 1784 Bradwell, T., Sigurðsson, O., Everest, J., 2013. Recent, very rapid retreat of a temperate glacier in SE  
1785 Iceland. *Boreas* 42, 959–973.
- 1786 Brodzikowski, K., van Loon, A.J., 1991. *Glacigenic Sediments*. Elsevier, Amsterdam, 674 pp.
- 1787 Brook, M.S., Kirkbride, M.P., 2018. Reconstruction and paleoclimatic significance of late Quaternary  
1788 glaciers in the Tararua Range, North Island, New Zealand. *Quat. Int.* 470(A), 53–66.
- 1789 Brown, V.H., Evans, D.J.A., Evans, I.S., 2011a. The Glacial Geomorphology and Surficial Geology  
1790 of the South-West English Lake District. *J. Maps* 7(1), 221–243.
- 1791 Brown, V.H., Stokes, C.R., Ó Cofaigh, C., 2011b. The Glacial Geomorphology of the North-West  
1792 sector of the Laurentide Ice Sheet. *J. Maps* 7, 409–428.
- 1793 Brynjólfsson, S., Schomacker, A., Ingólfsson, Ó., 2014. Geomorphology and the Little Ice Age extent  
1794 of the Drangajökull ice cap, NW Iceland, with focus on its three surge-type outlets.  
1795 *Geomorphology* 213, 292–304.
- 1796 Brynjólfsson, S., Schomacker, A., Korsgaard, N.J., Ingólfsson, Ó. 2016. Surges of outlet glacier from  
1797 the Drangajökull ice cap, northwest Iceland. *Earth Planet. Sci. Lett.* 450, 140–151.
- 1798 Butler, J., Lane, S., Chandler, J., 1998. Assessment of DEM quality for characterizing surface  
1799 roughness using close range digital photogrammetry. *The Photogramm. Rec.* 16(92), 271–  
1800 291.
- 1801 Caldenius, C.C., 1932. Las glaciaciones cuaternarias en la Patagonia y Tierra del Fuego. *Geogr. Ann.*  
1802 14, 1–164.
- 1803 Campbell, J.B., Wynne, R.H., 2011. *Introduction to remote sensing (5<sup>th</sup> Edition)*. Taylor and Francis,  
1804 London, 667 pp.
- 1805 Campbell, R.B., 1967a. Geology of Glenlyon map-area, Yukon Territory. Geological Survey of  
1806 Canada, Memoir 352, 92 pp.
- 1807 Campbell, R.B., 1967b. Surficial Geology, Glenlyon, Yukon Territory. Geological Survey of Canada,  
1808 "A" Series Map 1222A, 1: 253,440.
- 1809 Carbonneau, P.E., Dietrich, J.T., 2017. Cost-effective non-metric photogrammetry from consumer-  
1810 grade sUAS: implications for direct georeferencing of structure from motion  
1811 photogrammetry. *Earth Surf. Proc. Land.* 42, 473–486.
- 1812 Carrivick, J.L., Smith, M.W., Quincey, D.J., 2016. *Structure from Motion in the Geosciences*. New  
1813 Analytical Methods in Earth and Environmental Science Series. John Wiley & Sons,  
1814 Chichester, UK, 208 pp.
- 1815 Carrivick, J.L., Yde, J., Russell, A.J., Quincey, D.J., Ingeman-Nielsen, T., Mallalieu, J., 2017. Ice-  
1816 margin and meltwater dynamics during the mid-Holocene in the Kangerlussuaq area of west  
1817 Greenland. *Boreas* 46, 369–387.
- 1818 Chamberlin, T.C., 1897/1965. The method of multiple working hypotheses. *Science* 148, 745–759.
- 1819 Chandler, B.M.P., Lukas, S., 2017. Reconstruction of Loch Lomond Stadial (Younger Dryas) glaciers  
1820 on Ben More Coigach, NW Scotland, and implications for reconstructing palaeoclimate using  
1821 small ice masses. *J. Quat. Sci.* 32(4), 475–492.
- 1822 Chandler, B.M.P., Evans, D.J.A., Roberts, D.H., Ewertowski, M.W., Clayton, A.I., 2016a. Glacial  
1823 geomorphology of the Skálafellsjökull foreland, Iceland: A case study of ‘annual’ moraines.  
1824 *J. Maps* 12(5), 904–916.
- 1825 Chandler, B.M.P., Evans, D.J.A., Roberts, D.H., 2016b. Characteristics of recessional moraines at a  
1826 temperate glacier in SE Iceland: Insights into patterns, rates and drivers of glacier retreat.  
1827 *Quat. Sci. Rev.* 135, 171–205.
- 1828 Chorley, R.J., 1962. *Geomorphology and General Systems Theory*. United States Geological Survey,  
1829 Professional Paper 500B.
- 1830 Clark, C.D., 1993. Mega-scale glacial lineations and cross-cutting ice-flow landforms. *Earth Surf.*  
1831 *Proc. Land.* 18(1), 1–29.
- 1832 Clark, C.D. 1997. Reconstructing the evolutionary dynamics of former ice sheets using multi-  
1833 temporal evidence, remote sensing and GIS. *Quat. Sci. Rev.* 16, 1067–1092.

- 1834 Clark, C.D., Stokes, C.R., 2001. Extent and basal characteristics of the M'Clintock Channel Ice  
1835 Stream. *Quat. Int.* 86, 81–101.
- 1836 Clark, C.D., Knight, J.K., Gray, J.T., 2000. Geomorphological reconstruction of the Labrador sector  
1837 of the Laurentide Ice Sheet. *Quat. Sci. Rev.* 19(13), 1343–1366.
- 1838 Clark, C.D., Evans, D.J.A., Khatwa, A., Bradwell, T., Jordan, C.J., Marsh, S.H., Mitchell, W.A.,  
1839 Bateman, M.D., 2004. Map and GIS database of glacial landforms and features related to the  
1840 last British Ice Sheet. *Boreas* 33, 359–375.
- 1841 Clark, C.D., Hughes, A.L.C., Greenwood, S.L., Spagnolo, M., Ng, F.S.L., 2009. Size and shape  
1842 characteristics of drumlins, derived from a large sample, and associated scaling laws. *Quat.*  
1843 *Sci. Rev.* 28, 677–692.
- 1844 Clark, C.D., Hughes, A.L.C., Greenwood, S.L., Jordan, C., Sejrup, H.P., 2012. Pattern and timing of  
1845 retreat of the last British-Irish Ice Sheet. *Quat. Sci. Rev.* 44, 112–146.
- 1846 Clark, C.D., Ely, J.C., Greenwood, S.L., Hughes, A.L.C., Meehan, R., Barr, I.D., Bateman, M.D.,  
1847 Bradwell, T., Doole, J., Evans, D.J.A., Jordan, C.J., Monteys, X., Pellicer, X.M., Sheehy, M.,  
1848 2018a. BRITICE Glacial Map, version 2: a map and GIS database of glacial landforms of the  
1849 last British–Irish Ice Sheet. *Boreas*, 47, 11–27.
- 1850 Clark, C.D., Ely, J.C., Spagnolo, M., Hahn, U., Hughes, A.L.C., Stokes, C.R., 2018b. Spatial  
1851 organization of drumlins. *Earth Surf. Proc. Land.*, 43, 499–513.
- 1852 Clayton, L., Teller, J.T., Attig, J.W., 1985. Surging of the southwestern part of the Laurentide Ice  
1853 Sheet. *Boreas* 14(3), 235–241.
- 1854 Close, M.H. 1867. Notes on the general glaciation of Ireland. *J. R. Geogr. Soc. Lond. Dublin* 1, 207–  
1855 242.
- 1856 Coray, S., 2007. Glazialsedimentologische Untersuchungen an Flutes im Vorfeld des  
1857 Findelengletschers. Unpublished MSc Thesis, Universität Bern, 116 pp.
- 1858 Coronato, A., Seppälä, M., Ponce, J.F., Rabassa, J., 2009. Glacial geomorphology of the Pleistocene  
1859 lake Fagnano ice lobe, Tierra del Fuego, southern South America. *Geomorphology* 112(1),  
1860 67–81.
- 1861 Craig, B.G., 1961. Surficial geology of northern District of Keewatin, Northwest Territories.  
1862 Geological Survey of Canada, Map 7-1961, Scale 1: 1,013,760.
- 1863 Craig, B.G., 1964. Surficial geology of east-central District of Mackenzie. Geological Survey of  
1864 Canada, Bulletin, 99.
- 1865 Cumming, I.G., Wong, F.H., 2005. Digital Processing of Synthetic Aperture Radar Data: Algorithms  
1866 and Implementation. Artech House, Boston.
- 1867 da Rosa, K.K., Vieira, R., Fernandez, G.B., Simoes, F.L., Simoes, J.C., 2011. Formas glaciales y  
1868 procesos glaciológicos del glaciar templado Wanda, Shetland del Sur. *Investig. Geogr.* 43, 3–  
1869 16.
- 1870 da Rosa, K.K., 2013a. The landforms and pattern of deglaciation of the Dragon glacier, King George  
1871 Island, South Shetlands, Antarctica. *Rev. Geogr. (Recife)* 30(2), 1–16.
- 1872 da Rosa, K.K., Vieira, R., Júnior, C.W.M., de Souza Júnior, E., Simões, J.C., 2013b. Compilation of  
1873 geomorphological map for reconstructing the deglaciation of ice-free areas in the Martel Inlet,  
1874 King George Island, Antarctica. *Rev. Bras. Geomorfol.* 14(2), 181–187.
- 1875 Darvill, C.M., Stokes, C.R., Bentley, M.R., Lovell, H., 2014. A glacial geomorphological map of the  
1876 southernmost ice lobes of Patagonia: the Bahía Inútil – San Sebastián, Magellan, Otway,  
1877 Skyring and Río Gallegos lobes. *J. Maps* 10(3), 500–520.
- 1878 Darvill, C.M., Bentley, M.J., Stokes, C.R., Hein, A.S., Rodés, Á., 2015. Extensive MIS 3 glaciation in  
1879 southernmost Patagonia revealed by cosmogenic nuclide dating of outwash sediments. *Earth*  
1880 *Planet. Sci. Lett.* 429, 157–169.
- 1881 Darvill, C.M., Stokes, C.R., Bentley, M.J., Evans, D.J.A., Lovell, H., 2017. Dynamics of former ice  
1882 lobes of the southernmost Patagonian Ice Sheet based on a glacial landsystems approach. *J.*  
1883 *Quat. Sci.* 32, 857–876.
- 1884 De Angelis, H., 2007. Glacial geomorphology of the east-central Canadian Arctic. *J. Maps* 3, 323–  
1885 341.
- 1886 De Angelis, H., Kleman, J., 2007. Palaeo-ice streams in the Foxe/Baffin sector of the Laurentide Ice  
1887 Sheet. *Quat. Sci. Rev.* 26(9), 1313–1331.

- 1888 De Geer, G. 1910. Den svenska Setsbergsexkursionen 1910 för deltagare i den 11:te internationella  
1889 geologkonferensen i Stockholm. *Ymer* 30, 305-310.
- 1890 Demek, J., 1972. Manual of detailed geomorphological mapping. IUG, Prague, 344 pp.
- 1891 Dowdeswell, J.A., Vásquez, M., 2013. Submarine landforms in the fjords of southern Chile:  
1892 implications for glacial processes and sedimentation in a mild glacier-influenced  
1893 environment. *Quat. Sci. Rev.* 64, 1–19.
- 1894 Dowdeswell, J.A., Canals, M., Jakobsson, M., Todd, B. J., Dowdeswell, E.K., Hogan, K.A., 2016.  
1895 Atlas of Submarine Glacial landforms: Modern, Quaternary and Ancient. Geological Society,  
1896 London, Memoirs, No. 46.
- 1897 Dowling, T.P.F., Alexanderson, H., Möller, P., 2013. The new high-resolution LiDAR digital height  
1898 model ('Ny Nationell Höjdmodell') and its application to Swedish Quaternary  
1899 geomorphology. *GFF* 135(2), 145–151.
- 1900 Dowling, T.P.F., Spagnolo, M., Möller, P., 2015. Morphometry and core type of streamlined  
1901 bedforms in southern Sweden from high resolution LiDAR. *Geomorphology* 236, 54–63.
- 1902 Dowling, T.P.F., Möller, P., Spagnolo, M., 2016. Rapid subglacial streamlined bedform formation at a  
1903 calving bay margin. *J. Quat. Sci.* 31, 879–892.
- 1904 Dunstone, R.B., 2014. Testing the groove-ploughing theory for mega-scale glacial lineation (MSGL)  
1905 formation, using a large dataset of their morphology. Unpublished MSc thesis, University of  
1906 Durham, 127 pp. [Available at Durham e-theses: <http://etheses.dur.ac.uk/9457/>]
- 1907 Duveiller, G., Defourny, P., 2010. A conceptual framework to define the spatial resolution  
1908 requirements for agricultural monitoring using remote sensing. *Remote Sens. Environ.*  
1909 114(11), 2637-2650.
- 1910 Dyke, A.S. 1990. Quaternary geology of the Frances Lake map area, Yukon and Northwest  
1911 Territories. Geological Survey of Canada, Memoir 426.
- 1912 Dyke, A.S., Hooper, J.M.G., 2001. Deglaciation of northwest Baffin Island, Nunavut. Geological  
1913 Survey of Canada Map 1999A, Scale 1: 500,000.
- 1914 Dyke, A.S., Prest, V.K., 1987a. Late Wisconsinan and Holocene History of the Laurentide Ice Sheet.  
1915 *Géogr. Phys. Quat.* 41, 237–263.
- 1916 Dyke, A.S., Prest, V.K., 1987b. Late Wisconsinan and Holocene retreat of the Laurentide Ice Sheet,  
1917 Map 1702A. Geological Survey of Canada, Ottawa.
- 1918 Dyke, A.S., Prest, V.K., 1987c. Paleogeography of northern North America, 18 000 - 5 000 years ago,  
1919 Map 1703A. Geological Survey of Canada, Ottawa.
- 1920 Dyke, A.S., Morris, T.F., Green, D.E.C., England, J., 1992. Quaternary geology of Prince of Wales  
1921 Island, arctic Canada. Geological Survey of Canada Memoir 433.
- 1922 Eisank, C., Smith, M., Hillier, J., 2014. Assessment of multiresolution segmentation for delimiting  
1923 drumlins in digital elevation models. *Geomorphology* 214, 452–464.
- 1924 Ely, J.C., Clark, C.D., Spagnolo, M., Stokes, C.R., Greenwood, S.L., Hughes, A.L.C., Dunlop, P.,  
1925 Hess, D., 2016a. Do subglacial bedforms comprise a size and shape continuum?  
1926 *Geomorphology* 257, 108–119.
- 1927 Ely, J.C., Gribble, E.A., Clark, C.D., 2016b. The glacial geomorphology of the western cordilleran ice  
1928 sheet and Ahklun ice cap, Southern Alaska. *J. Maps* 12(Sup. 1), 415–424.
- 1929 Ely, J.C., Graham, C., Barr, I.D., Rea, B.R., Spagnolo, M., Evans, J., 2017. Using UAV acquired  
1930 photography and structure from motion techniques for studying glacier landforms: application  
1931 to the glacial flutes at Isfallsglaciären. *Earth Surf. Proc. Land.* 42(6), 877–888.
- 1932 Ely, J.C., Clark, C.D., Spagnolo, M., Hughes, A.L., Stokes, C.R., 2018. Using the size and position of  
1933 drumlins to understand how they grow, interact and evolve. *Earth Surf. Proc. Land.* 43(5),  
1934 1073–1087.
- 1935 Ercolano, B., Coronato, A., Tiberi, P., Corbella, H., Marderwald, G., 2016. Glacial geomorphology of  
1936 the tableland east of the Andes between the Coyle and Gallegos river valleys, Patagonia,  
1937 Argentina. *J. Maps* 12(1), 304–313.
- 1938 Espinoza, J.M., Glacial geomorphology and paleoglacial behaviour estimation in the Sierra Baguales  
1939 (50°S): Paleoclimatic factors that controlled glacier variations within the Pleistocene –  
1940 Holocene regional context. Unpublished PhD thesis, Universidad de Chile.

- 1941 Etzelmüller, B., Hagen, J.O., Vatne, G., Ødegård, R.S., Sollid, J.L., 1996. Glacier debris accumulation  
1942 and sediment deformation influenced by permafrost: examples from Svalbard. *Ann. Glaciol.*  
1943 22, 53–62.
- 1944 Evans, D.J.A. (Ed.), 2003a. *Glacial Landystems*. Arnold, London, 532 pp.
- 1945 Evans, D.J.A., 2003b. Ice-Marginal Terrestrial Landystems: Active Temperate Glacier Margins. In:  
1946 Evans, D.J.A. (Ed.), *Glacial Landystems*. Arnold, London, pp. 12–43.
- 1947 Evans, D.J.A., 2009. Glacial Geomorphology at Glasgow. *Scottish Geographical Journal* 125, 285–  
1948 320.
- 1949 Evans, D.J.A., 2010. Controlled moraine development and debris transport pathways in polythermal  
1950 plateau icefields: examples from Tungnafellsjökull, Iceland. *Earth Surf. Proc. Land.* 35,  
1951 1430–1444.
- 1952 Evans, D.J.A., 2011. Glacial landystems of Satujökull, Iceland: A modern analogue for glacial  
1953 landystem overprinting by mountain icecaps. *Geomorphology* 129, 225–237.
- 1954 Evans, D.J.A., 2017. Chapter 4 – Conceptual glacial ground models: British and Irish case studies. In:  
1955 Griffiths, J.S., Martin, C.J. (Eds.), *Engineering Geology and Geomorphology of Glaciated  
1956 and Periglaciated Terrains: Engineering Group Working Party Report*. Engineering Geology  
1957 Special Publication 28. The Geological Society, London, pp. 369–500.
- 1958 Evans, D.J.A., Benn, D.I. (Eds.), 2004. *A Practical Guide to the Study of Glacial Sediments*. Arnold,  
1959 London, 266 pp.
- 1960 Evans, D.J.A., Orton, C., 2015. Heinabergsjökull and Skalafellsjökull, Iceland: Active Temperate  
1961 Piedmont Lobe and Outwash Head Glacial Landystem. *J. Maps* 11(3), 415–431.
- 1962 Evans, D.J.A., Rea, B.R., 2003. Surging Glacier Landystem. In: Evans, D.J.A. (Ed.), *Glacial  
1963 Landystems*. Arnold, London, pp. 259–288.
- 1964 Evans, D.J.A., Twigg, D.R., 2002. The active temperate glacial landystem: a model based on  
1965 Breiðamerkurjökull and Fjallsjökull, Iceland. *Quat. Sci. Rev.* 21, 2143–2177.
- 1966 Evans, D.J.A., Lemmen, D.S., Rea, B.R., 1999. Glacial landystems of the southwest Laurentide Ice  
1967 Sheet: modern Icelandic analogues. *J. Quat. Sci.* 14, 673–691.
- 1968 Evans, D.J.A., Twigg, D.R., Shand, M., 2006. Surficial geology and geomorphology of the þórisjökull  
1969 plateau icefield, west-central Iceland. *J. Maps* 2, 17–29.
- 1970 Evans, D.J.A., Clark, C.D., Rea B.R., 2008. Landform and sediment imprints of fast glacier flow in  
1971 the southwest Laurentide Ice Sheet. *J. Quat. Sci.* 23(3), 249–272.
- 1972 Evans, D.J.A., Twigg, D.R., Rea, B.R., Orton, C., 2009a. Surging glacier landystem of  
1973 Tungnaárjökull, Iceland. *J. Maps* 5, 134–151.
- 1974 Evans, D.J.A., Livingstone, S.J., Vieli, A., Ó Cofaigh, C., 2009b. The palaeoglaciology of the central  
1975 sector of the British and Irish Ice Sheet: reconciling glacial geomorphology and preliminary  
1976 ice sheet modelling. *Quat. Sci. Rev.* 28, 739–757.
- 1977 Evans, D.J.A., Strzelecki, M., Milledge, D.G., Orton, C., 2012. Hørbyebreen polythermal glacial  
1978 landystem, Svalbard. *J. Maps* 8, 146–156.
- 1979 Evans, D.J.A., Young, N.J.P., Ó Cofaigh, C., 2014. Glacial geomorphology of terrestrial-terminating  
1980 fast flow lobes/ice stream margins in the southwest Laurentide Ice Sheet. *Geomorphology*  
1981 204, 86–113.
- 1982 Evans, D.J.A., Roberts, D.H., Cofaigh, C.Ó., 2015. Drumlin sedimentology in a hard-bed, lowland  
1983 setting, Connemara, western Ireland: implications for subglacial bedform generation in areas  
1984 of sparse till cover. *J. Quat. Sci.* 30, 537–557.
- 1985 Evans, D.J.A., Ewertowski, M., Orton, C., 2016a. Fláajökull (north lobe), Iceland: active temperate  
1986 piedmont lobe glacial landystem. *J. Maps* 12(5), 777–789.
- 1987 Evans, D.J.A., Ewertowski, M., Jamieson, S.S.R., Orton, C., 2016b. Surficial geology and  
1988 geomorphology of the Kumtor Gold Mine, Kyrgyzstan: human impacts on mountain glacier  
1989 landystems. *J. Maps* 12(5), 757–769.
- 1990 Evans, D.J.A., Ewertowski, M., Orton, C., 2016c. Eiríksjökull plateau icefield landystem, Iceland. *J.*  
1991 *Maps* 12(5), 747–756.
- 1992 Evans, D.J.A., Storrar, R.D., Rea, B.R., 2016d. Crevasse-squeeze ridge corridors: Diagnostic features  
1993 of late-stage palaeo-ice stream activity. *Geomorphology* 258, 40–50.
- 1994 Evans, D.J.A., Ewertowski, M., Orton, C., Harris, C., Guðmundsson, S., 2016e. Snæfellsjökull  
1995 volcano-centred ice cap landystem, West Iceland. *J. Maps* 12(5) 1128–1137.

- 1996 Evans, D.J.A., Ewertowski, M., Orton, C., 2017. Skaftafellsjökull, Iceland: glacial geomorphology  
1997 recording glacier recession since the Little Ice Age. *J. Maps* 13, 358–368.
- 1998 Evans, I.S., 1990. Cartographic techniques in geomorphology. In: Goudie, A.S. (Ed.),  
1999 *Geomorphological techniques (2<sup>nd</sup> Edition)*. Routledge, London, pp. 97–108.
- 2000 Evans I.S., 2012, *Geomorphometry and landform mapping: What is a landform?* *Geomorphology* 137,  
2001 94–106.
- 2002 Everest, J.D., Bradwell, T., 2003. Buried glacier ice in southern Iceland and its wider significance.  
2003 *Geomorphology* 52, 347–358.
- 2004 Everest, J., Bradwell, T., Jones, L., Hughes, L., 2017. The geomorphology of Svínafellsjökull and  
2005 Virkisjökull-Falljökull glacier forelands, southeast Iceland. *J. Maps* 13, 936–945.
- 2006 Ewertowski, M.W., 2014. Recent transformations in the high-Arctic glacier landsystem, Ragnarbreen,  
2007 Svalbard. *Geogr. Ann.* 96A(3), 265–285.
- 2008 Ewertowski, M.W., Tomczyk, A.M., 2015. Quantification of the ice-cored moraines' short-term  
2009 dynamics in the high-Arctic glaciers Ebbabreen and Ragnarbreen, Petuniabukta, Svalbard.  
2010 *Geomorphology* 234, 211–227.
- 2011 Ewertowski, M.W., Evans, D.J.A., Roberts, D.H., Tomczyk, A.M., 2016. Glacial geomorphology of  
2012 the terrestrial margins of the tidewater glacier, Nordenskiöldbreen, Svalbard. *J. Maps* 12(Sup.  
2013 1), 476–487.
- 2014 Ewertowski M.W., Kijowski A., Szuman I., Tomczyk A.M., Kasprzak L., 2017. Low-altitude remote  
2015 sensing and GIS-based analysis of cropmarks: classification of past thermal-contraction-crack  
2016 polygons in central western Poland. *Geomorphology* 293B, 418–432.
- 2017 Eyles, N. (Ed.), 1983. *Glacial Geology: An Introduction for Engineers and Earth Scientists*.  
2018 Permagon, Oxford, 409 pp.
- 2019 Fabel, D., Stroeven, A.P., Harbor, J., Kleman, J., Elmore, D., Fink, D., 2002. Landscape preservation  
2020 under Fennoscandian ice sheets determined from in situ produced <sup>10</sup>Be and <sup>26</sup>Al. *Earth*  
2021 *Planet. Sci. Lett.* 201, 397–406.
- 2022 Fabel, D., Fink, D., Fredin, O., Harbor, J., Land, M., Stroeven, A.P., 2006. Exposure ages from relict  
2023 lateral moraines overridden by the Fennoscandian ice sheet. *Quat. Res.* 65, 136–146.
- 2024 Federici, P.R., Pappalardo, M., Ribolini, A., 2003. *Geomorphological Map of the Maritime Alps*  
2025 *Natural Park and surroundings (Argentera Massif, Italy)*, 1: 25000 scale. Selca, Florence.
- 2026 Federici, P.R., Ribolini, A., Spagnolo, M., 2017. Glacial history of the Maritime Alps from the Last  
2027 Glacial Maximum to the Little Ice Age. *Geological Society, London, Special Publications*  
2028 433(1), 137–159.
- 2029 Finke, L., 1980. Anforderungen aus der Planungspraxis an ein geomorphologisches Kartenwerk. In:  
2030 Barsch, D., Liedtke, H. (Eds.), *Methoden und Anwendbarkeit geomorphologischer*  
2031 *Detailkarten*. Freie Universität Berlin, Berlin; pp. 75–81.
- 2032 Finlayson, A., Merritt, J., Browne, M., Merritt, J., McMillan, A., Whitbread, K., 2010. Ice sheet  
2033 advance, dynamics, and decay configurations: evidence from west central Scotland. *Quat. Sci.*  
2034 *Rev.* 29, 969–988.
- 2035 Finlayson, A.G., Gолledge, N., Bradwell, T., Fabel, D., 2011. Evolution of a Lateglacial mountain  
2036 icecap in northern Scotland. *Boreas* 40, 536–554.
- 2037 Flink, A.E., Noormets, R., Kirchner, N., Benn, D.I., Luckman, A., Lovell, H., 2015. The evolution of  
2038 a submarine landform record following recent and multiple surges of Tunabreen glacier,  
2039 Svalbard. *Quat. Sci. Rev.* 108, 37–50.
- 2040 Flint, R.F., Colton, R.B., Goldthwait, R.P., Willman, H.B., 1959. *Glacial map of the United States*  
2041 *east of the Rocky Mountains*. Geological Society of America.
- 2042 Follestad, B., Bergström, B., 2004. *Otta 1718-IV. Quaternary geology map with description*.  
2043 *Norwegian Geological Survey*. 1:50,000.
- 2044 Fourrière, A., Claudin, P., Andreotti, B., 2010. Bedforms in a turbulent stream: Formation of ripples  
2045 by primary linear instability and of dunes by nonlinear pattern coarsening. *J. Fluid Mech.* 649,  
2046 287–328.
- 2047 Fu, P., Heyman, J., Hättestrand, C., Stroeven, A.P., Harbor, J.M., 2012. Glacial geomorphology of the  
2048 Shaluli Shan area, southeastern Tibetan Plateau. *J. Maps* 8, 48–55.

- 2049 Garcia, J.L., Kaplan, M.R., Hall, B.L., Schaefer, J.M., Vega, R.M., Schwartz, R., Finkel, R., 2012  
 2050 Glacier expansion in southern Patagonia throughout the Antarctic cold reversal. *Geology* 40,  
 2051 859–862
- 2052 Glasser, N.F., Jansson, K.N., 2005. Fast-flowing outlet glaciers of the last glacial maximum  
 2053 Patagonian Icefield. *Quat. Res.* 63(2), 206–211.
- 2054 Glasser, N., Jansson, K., 2008. The Glacial Map of southern South America. *J. Maps* 4, 175–196.
- 2055 Glasser, N.F., Jansson, K.N., Harrison, S., Rivera, A., 2005. Geomorphological evidence for  
 2056 variations of the North Patagonian Icefield during the Holocene. *Geomorphology* 71(3-4),  
 2057 263–277.
- 2058 Glasser, N.F., Jansson, K.N., Harrison, S., Kleman, J., 2008. The glacial geomorphology and  
 2059 Pleistocene history of South America between 38 S and 56 S. *Quat. Sci. Rev.* 27(3), 365–390.
- 2060 Golledge, N.R., Stoker, M.S., 2006. A palaeo-ice-stream of the British Ice Sheet in eastern Scotland.  
 2061 *Boreas* 35, 231–243.
- 2062 Golledge, N.R., Hubbard, A., Sugden, D.E., 2008. High-resolution numerical simulation of Younger  
 2063 Dryas glaciation in Scotland. *Quat. Sci. Rev.* 27, 888–904.
- 2064 Goodchild, J.G., 1875. The glacial phenomena of the Eden Valley and the western part of the  
 2065 Yorkshire-dale District. *Quart. J. Geol. Soc. Lond.* 31, 55–99.
- 2066 Graf, A., 2007. Genese alpiner Seitenmoränen am Beispiel des Findelengletschers bei Zermatt (VS).  
 2067 Unpublished MSc Thesis, Universität Bern, 126 pp.
- 2068 Greenwood, S.L., Clark, C.D., 2008. Subglacial bedforms of the Irish Ice Sheet. *J. Maps* 4, 332–357.
- 2069 Greenwood, S.L., Clark, C.D., 2009a. Reconstructing the last Irish Ice Sheet 1: changing flow  
 2070 geometries and ice flow dynamics deciphered from the glacial landform record. *Quat. Sci.*  
 2071 *Rev.* 28, 3085–3100.
- 2072 Greenwood, S.L., Clark, C.D., 2009b. Reconstructing the last Irish Ice Sheet 2: a geomorphologically-  
 2073 driven model of ice sheet growth, retreat and dynamics. *Quat. Sci. Rev.* 28(27), 3101–3123.
- 2074 Greenwood, S.L., Kleman, J., 2010. Glacial landforms of extreme size in the Keewatin sector of the  
 2075 Laurentide Ice Sheet. *Quat. Sci. Rev.* 29(15), 1894–1910.
- 2076 Greenwood, S.L., Clark, C.D., Hughes, A.L.C., 2007. Formalising an inversion methodology for  
 2077 reconstructing ice-sheet retreat patterns from meltwater channels: application to the British  
 2078 Ice Sheet. *J. Quat. Sci.* 22, 637–645.
- 2079 Greenwood, S.L., Clason, C.C., Mikko, H., Nyberg, J., Peterson, G., Smith, C.A., 2015. Integrated  
 2080 use of lidar and multibeam bathymetry reveals onset of ice streaming in the northern Bothnian  
 2081 Sea. *GFF* 137, 284–292
- 2082 Greenwood, S.L., Clason, C.C., Nyberg, J., Jakobsson, M., Holmlund, P., 2017. The Bothnian Sea ice  
 2083 stream: early Holocene retreat dynamics of the south-central Fennoscandian Ice Sheet. *Boreas*  
 2084 46, 346–362.
- 2085 Gribenski, N., Jansson, K.N., Lukas, S., Stroeven, A.P., Harbor, J.M., Blomdin, R., Ivanov, M.N.,  
 2086 Heyman, J., Petrakov, D.A., Rudoy, A., Clifton, T., Lifton, N.A., Caffee, M.W., 2016.  
 2087 Complex patterns of glacier advances during the late glacial in the Chagan Uzun Valley,  
 2088 Russian Altai. *Quat. Sci. Rev.* 149, 288–305.
- 2089 Gribenski, N., Jansson, K.N., Preusser, F., Harbor, J.M., Stroeven, A.P., Trauerstein, M., Blomdin, R.,  
 2090 Heyman, J., Caffee, M.W., Lifton, N.A., Zhang, W., 2018. Re-evaluation of MIS 3 glaciation  
 2091 using cosmogenic radionuclide and single grain luminescence ages, Kanas Valley, Chinese  
 2092 Altai. *J. Quat. Sci.* 33, 55–67.
- 2093 Griffiths, J.S., Martin, C.J. (Eds.), 2017. *Engineering Geology and Geomorphology of Glaciated and*  
 2094 *Periglaciated Terrains: Engineering Group Working Party Report. Engineering Geology*  
 2095 *Special Publication 28. The Geological Society, London, 953 pp.*
- 2096 Grodecki, J., Dial, G., 2003. Block Adjustment of High-Resolution Satellite Images Described by  
 2097 Rational Polynomials. *Photogramm. Eng. Remote Sens.* 69(1), 59–68.
- 2098 Gustavsson, M., Kolstrup, E., Sejmonsbergen, A.C., 2006. A new symbol-and-GIS based detailed  
 2099 geomorphological mapping system: Renewal of a scientific discipline for understanding  
 2100 landscape development. *Geomorphology* 77(1–2), 90–111.
- 2101 Gustavsson, M., Sejmonsbergen, A.C., Kolstrup, E., 2008. Structure and contents of a new  
 2102 geomorphological GIS database linked to a geomorphological map – With an example from  
 2103 Liden, central Sweden. *Geomorphology* 95, 335–349.

- 2104 Harbor, J., Stroeven, A.P., Fabel, D., Clarhäll, A., Kleman, J., Li, Y.K., Elmore, D., Fink, D., 2006.  
 2105 Cosmogenic nuclide evidence for minimal erosion across two subglacial sliding boundaries of  
 2106 the late glacial Fennoscandian ice sheet. *Geomorphology* 75, 90–99.
- 2107 Hardt, J., Hebenstreit, R., Lüthgens, C., Böse, M., 2015. High-resolution mapping of ice-marginal  
 2108 landforms in the Barnim region, northeast Germany. *Geomorphology* 250, 41–52.
- 2109 Hättestrand, C., 1998. The glacial geomorphology of central and northern Sweden. *Sver. Geol.*  
 2110 *Unders. Ca* 85, 1–47.
- 2111 Hättestrand, C., Clark, C.D., 2006. The glacial geomorphology of Kola Peninsula and adjacent areas  
 2112 in the Murmansk Region, Russia. *J. Maps* 2, 30–42.
- 2113 Hättestrand, C., Stroeven, A.P., 1996. Field evidence for wet-based ice sheet erosion from the south-  
 2114 central Queen Elizabeth Islands, Northwest Territories, Canada. *Arct. Alp. Res.* 28, 466–474.
- 2115 Hättestrand, C., Stroeven, A.P., 2002. A relict landscape in the centre of Fennoscandian glaciation:  
 2116 Geomorphological evidence of minimal Quaternary glacial erosion. *Geomorphology* 44(1),  
 2117 127–143.
- 2118 Hättestrand, C., Goodwillie, D., Kleman, J., 1999. Size distribution of two cross-cutting drumlin  
 2119 systems in northern Sweden: a measure of selective erosion and formation time length. *Ann.*  
 2120 *Glaciol.* 28, 146–152.
- 2121 Hättestrand, C., Kosche, S., Näslund, J.-O., Fabel, D., Stroeven, A.P., 2004. Drumlin formation time -  
 2122 evidence from northern and central Sweden. *Geogr. Ann.* 86A, 155–167.
- 2123 Hättestrand, C., Kolka, V., Stroeven, A.P., 2007. The Keiva ice marginal zone on the Kola Peninsula,  
 2124 northwest Russia: a key component for reconstructing the palaeoglaciology of the  
 2125 northeastern Fennoscandian Ice Sheet. *Boreas* 36, 352–370.
- 2126 Heiser, P.A., Roush, J.J., 2001. Pleistocene glaciations in Chukotka, Russia: moraine mapping using  
 2127 satellite synthetic aperture radar (SAR) imagery. *Quat. Sci. Rev.* 20(1), 393–404.
- 2128 Hess, D.P., Briner, J.P., 2009. Geospatial analysis of controls on subglacial bedform morphometry in  
 2129 the New York Drumlin Field – implications for Laurentide Ice Sheet dynamics. *Earth Surf.*  
 2130 *Proc. Land.* 34, 1126–1135.
- 2131 Heyman, J., Hättestrand, C., Stroeven, A.P., 2008. Glacial geomorphology of the Bayan Har sector of  
 2132 the NE Tibetan Plateau. *J. Maps* 4(1), 42–62.
- 2133 Hillier, J.K., Smith, M.J., Clark, C.D., Stokes, C.R., Spagnolo, M., 2013. Subglacial bedforms reveal  
 2134 an exponential size–frequency distribution. *Geomorphology* 190, 82–91.
- 2135 Hillier, J.K., Smith, M.J., Armugam, R., Barr, I., Boston, C.M., Clark, C.D., Ely, J., Frankl, A.,  
 2136 Greenwood, S.L., Gosselin, L., Hättestrand, C., Hogan, K., Hughes, A.L.C., Livingstone, S.J.,  
 2137 Lovell, H., McHenry, M., Munoz, Y., Pellicer, X.M., Pellitero, R., Robb, C., Roberson, S.,  
 2138 Ruther, D., Spagnolo, M., Standell, M., Stokes, C.R., Storrar, R., Tate, N.J., Wooldridge, K.,  
 2139 2015. Manual mapping of drumlins in synthetic landscapes to assess operator effectiveness. *J.*  
 2140 *Maps* 11, 719–729.
- 2141 Hillier, J.K., Kougioumtzoglou, I.A., Stokes, C.R., Smith, M.J., Clark, C.D., Spagnolo, M.S., 2016.  
 2142 Exploring Explanations of Subglacial Bedform Sizes Using Statistical Models. *PLoS One* 11,  
 2143 e0159489.
- 2144 Hillier, J.K., Benediktsson, Í.Ö., Dowling, T.P.F., Schomacker, A., 2018. Production and preservation  
 2145 of the smallest drumlins. *GFF* 140(2), 136–152.
- 2146 Hochreuther, P., Loibl, D., Wernicke, J., Zhu, H., Griebinger, J., Bräuning, A., 2015. Ages of major  
 2147 Little Ice Age glacier fluctuations on the southeast Tibetan Plateau derived from tree-ring-  
 2148 based moraine dating. *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 422, 1–10.
- 2149 Hodgson, D.A., Vincent, J.S., Fyles, J.G., 1984. Quaternary geology of central Melville Island,  
 2150 Northwest Territories. Geological Survey of Canada paper 83-16.
- 2151 Hodgson, D.A., Graham, A.G.C., Griffiths, H.J., Roberts, S.J., Ó Cofaigh, C., Bentley, M.J., Evans,  
 2152 D.J.A., 2014. Glacial history of sub-Antarctic South Georgia based on the submarine  
 2153 geomorphology of its fjords. *Quat. Sci. Rev.* 89, 129–147.
- 2154 Hollingworth, S.E., 1931. The glaciation of western Edenside and adjoining areas and the drumlins of  
 2155 Edenside and the Solway Basin. *Quart. J. Geol. Soc. Lond.* 87, 281–359.
- 2156 Horsfield, B.R., 1983. The deglaciation pattern of the western Grampians of Scotland. Unpublished  
 2157 PhD thesis, University of East Anglia.

- 2158 Houmark-Nielsen, M., Kjær, K.H. 2003. Southwest Scandinavia, 40-15 kyr BP: Palaeogeography and  
2159 environmental change. *J. Quat. Sci.* 18, 769–786.
- 2160 Howarth, P.J., 1968. Geomorphological and Glaciological Studies, Eastern Breiðamerkurjökull,  
2161 Iceland, Unpublished PhD thesis, University of Glasgow.
- 2162 Howarth, P.J., Welch, R., 1969a. Breiðamerkurjökull, South-east Iceland, August 1945, 1:30,000  
2163 scale map. University of Glasgow.
- 2164 Howarth, P.J., Welch, R., 1969b. Breiðamerkurjökull, South-east Iceland, August 1965, 1:30,000  
2165 scale map. University of Glasgow.
- 2166 Hubbard, A., Bradwell, T., Gollidge, N., Hall, A., Patton, H., Sugden, D., Cooper, R., Stoker, M.,  
2167 2009. Dynamic cycles, ice streams and their impact on the extent, chronology and  
2168 deglaciation of the British–Irish ice sheet. *Quat. Sci. Rev.* 28, 758–776.
- 2169 Hubbard, B., Glasser, N.F., 2005. *Field techniques in glaciology and glacial geomorphology*. John  
2170 Wiley and Sons, Chichester, 400 pp.
- 2171 Hughes, A.L.C., Clark, C.D., Jordan, C.J., 2010. Subglacial bedforms of the last British Ice Sheet. *J.*  
2172 *Maps* 6, 543–563.
- 2173 Hughes, A.L.C., Clark, C.D., Jordan, C.J., 2014. Flow-pattern evolution of the last British Ice Sheet.  
2174 *Quat. Sci. Rev.* 89, 148–168.
- 2175 Hughes, A.L.C., Gyllencreutz, R., Lohne, Ø.S., Mangerud, J., Svendsen, J.I., 2016. The last Eurasian  
2176 ice sheets - a chronological database and time-slice reconstruction, DATED-1. *Boreas* 45, 1-  
2177 45.
- 2178 Hyatt, O.M., 2010. *Insights into New Zealand Glacial Processes from studies of glacial*  
2179 *geomorphology and sedimentology in Rakaia and other South Island Valleys*. Unpublished  
2180 PhD thesis, University of Canterbury, 251 pp.
- 2181 Immerzeel, W.W., Kraaijenbrink, P.D.A., Shea, J.M., Shrestha, A.B., Pellicciotti, F., Bierkens,  
2182 M.F.P., de Jong, S.M., 2014. High-resolution monitoring of Himalayan glacier dynamics  
2183 using unmanned aerial vehicles. *Remote Sens. Environ.* 150, 93–103.
- 2184 Izagirre, E., Darvill, C.M., Rada, C., Aravena, J.C., 2018. Glacial geomorphology of the Marinelli and  
2185 Pigafetta glaciers, Cordillera Darwin Icefield, southernmost Chile. *J. Maps* 14, 269–281.
- 2186 Jakobsson, M., Mayer, L., Coakley, B., Dowdeswell, J.A., Forbes, S., Fridman, B., Hodnesdal, H.,  
2187 Noormets, R., Pedersen, R., Rebecco, M., Schenke, H.W., Zarayskaya, Y., Accettella, D.,  
2188 Armstrong, A., Anderson, R.M., Bienhoff, P., Camerlenghi, A., Church, I., Edwards, M.,  
2189 Gardner, J.V., Hall, J.K., Hell, B., Hestvik, O., Kristoffersen, Y., Marcussen, C., Mohammad,  
2190 R., Mosher, D., Nghiem, S.V., Pedrosa, M.T., Travaglini, P.G., Weatherall, P., 2012. The  
2191 International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0. *Geophys. Res.*  
2192 *Lett.* 39, L12609.
- 2193 James, M.R., Robson, S., Smith, M.W., 2017. 3-D uncertainty-based topographic change detection  
2194 with structure-from-motion photogrammetry: precision maps for ground control and directly  
2195 georeferenced surveys. *Earth Surf. Process. Land.* 42, 1769–1788.
- 2196 Jamieson, S.S.R., Ewertowski, M.W., Evans, D.J.A., 2015. Rapid advance of two mountain glaciers  
2197 in response to mine-related debris loading, *J. Geophys. Res.: Earth Surf.* 120, 1418–1435.
- 2198 Jansson, K.N., 2003. Early Holocene glacial lakes and ice marginal retreat pattern in  
2199 Labrador/Ungava, Canada. *Palaeogeogr., Palaeoclim., Palaeoecol.* 193, 473–501.
- 2200 Jansson, K.N., Glasser, N.F., 2005. Using Landsat 7 ETM+ imagery and Digital Terrain Models for  
2201 mapping glacial lineaments on former ice sheet beds. *Int. J. Remote Sens.* 26(18), 3931–3941.
- 2202 Jansson, K.N., Kleman, J., Marchant, D.R., 2002. The succession of ice-flow patterns in north-central  
2203 Québec-Labrador, Canada. *Quat. Sci. Rev.* 21(4), 503–523.
- 2204 Jansson, K.N., Stroeven, A.P., Kleman, J., 2003. Configuration and timing of Ungava Bay ice  
2205 streams, Labrador–Ungava, Canada. *Boreas* 32(1), 256–262.
- 2206 Johnson, M.D., Fredin, O., Ojala, A.E.K., Peterson, G. 2015. Unravelling Scandinavian  
2207 geomorphology: the LiDAR revolution. *GFF* 137, 245–251.
- 2208 Jónsson, S.A., Schomacker, A., Benediktsson, Í.Ö., Ingólfsson, Ó., Johnson, M.D., 2014. The drumlin  
2209 field and the geomorphology of the Múlajökull surge-type glacier, central Iceland.  
2210 *Geomorphology* 207, 213–220.



- 2211 Jónsson, S.A., Benediktsson, Í.Ö., Ingólfsson, Ó., Schomacker, A., Bergsdóttir, H.L., Jacobsson,  
 2212 W.R., Linderson, H. 2016. Submarginal drumlin formation and late Holocene history of  
 2213 Fláajökull, southeast Iceland. *Ann. Glaciol.* 57, 128–141.
- 2214 Jorge, M.G., Brennand, T.A., 2017a. Measuring (subglacial) bedform orientation, length, and  
 2215 longitudinal asymmetry–Method assessment. *PloS one*, 12(3), e0174312.
- 2216 Jorge, M.G., Brennand, T.A., 2017b. Semi-automated extraction of longitudinal subglacial bedforms  
 2217 from digital terrain models–Two new methods. *Geomorphology*, 288, 148–163.
- 2218 Juyal, N., Thakkar, P.S., Sundriyal, Y.P., 2011. Geomorphic evidence of glaciations around Mount  
 2219 Kailash (Inner Kora): implication to past climate. *Current Science* 100(4), 535–541.
- 2220 Karlén, W., 1973. Holocene glacier and climatic variations, Kebnekaise Mountains, Swedish Lapland.  
 2221 *Geogr. Ann.* 55A, 29–63.
- 2222 Kassab, C., Wang, J., Harbor, J., 2013. Glacial geomorphology of the Dalijia Shan region,  
 2223 northeastern Tibetan Plateau. *J. Maps* 9(1), 98–105.
- 2224 Kelley, S.E., Kaplan, M.R., Schaefer, J.M., Andersen, B.G., Barrell, D.J.A., Putnam, A.E., Denton,  
 2225 G.H., Schwartz, R., Finkel, R.C., Doughty, A.M., 2014. High-precision <sup>10</sup>Be chronology of  
 2226 moraines in the Southern Alps indicates synchronous cooling in Antarctica and New Zealand  
 2227 42,000 years ago. *Earth Planet. Sci. Lett.* 405, 194–206.
- 2228 Kendall, P.F. 1902. A system of glacier lakes in the Cleveland Hills. *Quart. J. Geol. Soc. Lond.* 58,  
 2229 471–571.
- 2230 Kerschner, H., Kaser, G., Sailer, R., 2000. Alpine Younger Dryas glaciers as palaeo-precipitation  
 2231 gauges. *Ann. Glaciol.* 31, 80–84.
- 2232 Kienholz, H., 1977. Kombinierte geomorphologische Gefahrenkarte 1:10,000 von Grindelwald.  
 2233 *Geographica Bernensia*, G4: 1–204.
- 2234 King, E.C., Woodward, J., Smith, A. M., 2007. Seismic and radar observations of subglacial bed  
 2235 forms beneath the onset zone of Rutford Ice Stream, Antarctica. *J. Glaciol.* 53(183), 665–672.
- 2236 King, E.C., Hindmarsh, R.C., Stokes, C.R., 2009. Formation of mega-scale glacial lineations observed  
 2237 beneath a West Antarctic ice stream. *Nat. Geosci.* 2(8), 585–588.
- 2238 King, E.C., Pritchard, H.D., Smith, A.M., 2016a. Subglacial landforms beneath Rutford Ice Stream,  
 2239 Antarctica: detailed bed topography from ice-penetrating radar. *Earth Syst. Sci. Data* 8(1),  
 2240 151–158.
- 2241 King, O., Hambrey, M.J., Irvine-Fynn, T.D.L., Holt, T.O., 2016b. The structural, geometric and  
 2242 volumetric changes of a polythermal Arctic glacier during a surge cycle: Comfortlessbreen,  
 2243 Svalbard. *Earth Surf. Process. Land.* 41, 162–177.
- 2244 King, O., Quincey, D.J., Carrivick, J.L., Rowan, A.V., 2017. Spatial variability in mass loss of  
 2245 glaciers in the Everest region, central Himalayas, between 2000 and 2015. *The Cryosphere*  
 2246 11, 407–426.
- 2247 Kirchner, N., Greve, R., Stroeven, A.P., Heyman, J., 2011. Paleoglaciological reconstructions for the  
 2248 Tibetan Plateau during the last glacial cycle: evaluating numerical ice sheet simulations  
 2249 driven by GCM-ensembles. *Quat. Sci. Rev.* 30, 248–267.
- 2250 Kirkbride, M.P., Winkler, S., 2012. Correlation of Late Quaternary moraines: impact of climate  
 2251 variability, glacier response, and chronological resolution. *Quat. Sci. Rev.* 46, 1–29.
- 2252 Kjær, K.H., Krüger, J., 2001. The final phase of dead-ice moraine development: processes and  
 2253 sediment architecture, Kotlujökull, Iceland. *Sedimentology* 48, 935–952.
- 2254 Kjær, K.H., Houmark-Nielsen, M., Richardt, N. 2003. Ice-flow patterns and dispersal of erratics at the  
 2255 southwestern margin of the last Scandinavian Ice Sheet: signature of paleo-ice streams.  
 2256 *Boreas* 32, 130–148.
- 2257 Kjær, K.H., Korsgaard, N.J., Schomacker, A., 2008. Impact of multiple glacier surges – a  
 2258 geomorphological map from Brúarjökull, East Iceland. *J. Maps* 4, 5–20.
- 2259 Kłapyta, P., 2013. Application of Schmidt hammer relative age dating to Late Pleistocene moraines  
 2260 and rock glaciers in the Western Tatra Mountains, Slovakia. *Catena* 111, 104–121.
- 2261 Klassen, R.A., 1993. Quaternary geology and glacial history of Bylot Island, Northwest Territories.  
 2262 Geological Survey of Canada Memoir 429.
- 2263 Kleman, J., 1990. On the use of glacial striae for reconstruction of palaeo-ice sheet flow patterns.  
 2264 *Geogr. Ann.* 72A, 217–236.

- 2265 Kleman, J., 1992. The Palimpsest Glacial Landscape in Northwestern Sweden. Late Weichselian  
2266 Deglaciation Landforms and Traces of Older West-Centered Ice Sheets. *Geogr. Ann.* 74A(4),  
2267 305–325.
- 2268 Kleman, J., Borgström, I., 1996. Reconstruction of Palaeo-Ice Sheets: The Use of Geomorphological  
2269 Data. *Earth Surf. Process. Land.* 21, 893–909.
- 2270 Kleman, J. Stroeven, A.P., 1997. Preglacial surface remnants and Quaternary glacial regimes in  
2271 northwestern Sweden. *Geomorphology* 19(1–2), 35–54.
- 2272 Kleman, J., Hättestrand, C., Borgström, I., Stroeven, A., 1997. Fennoscandian palaeoglaciology  
2273 reconstructed using a glacial geological inversion model. *J. Glaciol.* 43(144), 283–299.
- 2274 Kleman, J., Fastook, J., Stroeven, A.P., 2002. Geologically and geomorphologically constrained  
2275 numerical model of Laurentide Ice Sheet inception and build-up. *Quat. Int.* 95-96, 87–98.
- 2276 Kleman, J., Hättestrand, C., Stroeven, A.P., Jansson, K.N., De Angelis, H., Borgström, I., 2006.  
2277 Reconstruction of palaeo-ice sheets; inversion of their glacial geomorphological record. In:  
2278 Knight, P.G. (Ed.), *Glacier Science and Environmental Change*. Blackwell, Oxford, pp. 192–  
2279 199.
- 2280 Kleman, J., Stroeven, A.P., Lundqvist, J., 2008. Patterns of Quaternary ice sheet erosion and  
2281 deposition in Fennoscandia. *Geomorphology* 97, 73–90.
- 2282 Kleman, J., Jansson, K., De Angelis, H., Stroeven, A.P., Hättestrand, C., Alm, G., Glasser, N., 2010.  
2283 North American Ice Sheet build-up during the last glacial cycle, 115–21kyr. *Quat. Sci. Rev.*  
2284 29, 2036–2051.
- 2285 Klimaszewski, M., 1990. Thirty years of detailed geomorphological mapping. *Geogr. Pol.* 58, 11–18.
- 2286 Kneisel, C., Lehmkuhl, F., Winkler, S., Tressel, E., Schröder, H., 1998. Legende für  
2287 geomorphologische Kartierungen in Hochgebirgen (GMK Hochgebirge). *Trier. Geogr. Stud.*  
2288 18, 1–24.
- 2289 Knight, J., Mitchell, W., Rose, J., 2011. Geomorphological Field Mapping. In: Smith, M.J., Paron, P.,  
2290 Griffiths, J. (Eds.), *Geomorphological Mapping: Methods and Applications*. Developments in  
2291 Earth Surface Processes 15. Elsevier, London, pp. 151–188.
- 2292 Kocurek, G., Ewing, R.C., Mohrig, D., 2010. How do bedform patterns arise? New views on the role  
2293 of bedform interactions within a set of boundary conditions. *Earth Surf. Process. Land.* 35,  
2294 51–63.
- 2295 Korsgaard, N.J., Schomacker, A., Benediktsson, Í.Ö., Larsen, N.K., Ingólfsson, Ó., Kjær, K.H., 2015.  
2296 Spatial distribution of erosion and deposition during a glacier surge: Brúarjökull, Iceland.  
2297 *Geomorphology* 250, 258–270.
- 2298 Kraak, M.–J., Oremling, F.J., 2010. *Cartography: visualization of spatial data* (3<sup>rd</sup> Edition). Routledge,  
2299 London.
- 2300 Kronberg, P., 1984. *Photogeologie. Eine Einführung in die Grundlagen und Methoden der*  
2301 *geologischen Auswertung von Luftbildern*. Enke, Stuttgart.
- 2302 Krüger, J., 1994. Glacial processes, sediments, landforms and stratigraphy in the terminus region of  
2303 Mýrdalsjökull, Iceland. *Folia Geographica Danica* 21, 1–233.
- 2304 Krüger, J., 1995. Origin, chronology and climatological significance of annual moraine ridges at  
2305 Mýrdalsjökull, Iceland. *The Holocene* 5, 420–427.
- 2306 Krüger, J., Kjær, K.H., 2000. De-icing progression of ice-cored moraines in a humid, subpolar  
2307 climate, Kötlujökull, Iceland. *The Holocene* 10, 737–747.
- 2308 Krygowski B. (Ed.), 1963. *Mapa Geomorfologiczna Niziny Wielkopolsko-Kujawskiej*  
2309 *[Geomorphological Map of Wielkopolska-Kujawy lowland]*. 1:300 000 Map. Adam  
2310 Mickiewicz University.
- 2311 Kuhle, M., 1990. Quantificational reductionism as a risk in geography instanced by the 1:25,000  
2312 Geomorphological Map of the Federal Republic of Germany. *Geogr. Pol.* 58, 41–54.
- 2313 Lam, N.S.N., Quattrochi, D.A., 1992. On the issues of scale, resolution, and fractal analysis in the  
2314 mapping sciences. *The Prof. Geogr.* 44(1), 88–98.
- 2315 Lane, S.N., Reid, S.C., Westaway, R.M., Hicks, D.M., 2005. Remotely Sensed Topographic Data for  
2316 River Channel Research: The Identification, Explanation and Management of Error. In: R.E.J.  
2317 Kelly, Drake, N.A., Barr, S.L. (Eds.), *Spatial Modelling of the Terrestrial Environment*. John  
2318 Wiley & Sons, Ltd, Chichester, UK, pp. 113–136.

- 2319 Lardeux, P., Glasser, N., Holt, T., Hubbard, B., 2015. Glaciological and geomorphological map of  
2320 Glacier Noir and Glacier Blanc, French Alps. *J. Maps* 12, 582–596.
- 2321 Leser, H., 1983. Anwendung und Auswertung geomorphologischer Kartierungen und Karten. *Mater.*  
2322 *Physiogeogr.* 5, 5–13.
- 2323 Leser, H., Stäblein, G., 1975. Geomorphologische Kartierung – Richtlinien zur Herstellung  
2324 geomorphologischer Karten 1: 25,000. *Berliner Geographische Abhandlungen Sonderheft*, 1–  
2325 33.
- 2326 Levy, L.B., Larsen, N.K., Davidson, T.A., Strunk, A., Olsen, J., Jeppesen, E., 2017. Contrasting  
2327 evidence of Holocene ice margin retreat, south-western Greenland. *J. Quat. Sci.* 32, 604–616.
- 2328 Li, Y., Li, Y., Chen, Y., Lu, X., 2016. Presumed Little Ice Age glacial extent in the eastern Tian Shan,  
2329 China. *J. Maps* 12(1), 71–78.
- 2330 Lidmar-Bergström, K., Elvhage, C., Ringberg, B., 1991. Landforms in Skane, south Sweden.  
2331 *Geografiska Annaler* 73A, 61–91.
- 2332 Lifton, N., Beel, C., Hättestrand, C., Kassab, C., Rogozhina, I., Heermance, R., Oskin, M., Burbank,  
2333 D., Blomdin, R., Gribenski, N., Caffee, M., 2014. Constraints on the late Quaternary glacial  
2334 history of the Inylchek and Sary-Dzaz valleys from in situ cosmogenic <sup>10</sup>Be and <sup>26</sup>Al,  
2335 eastern Kyrgyz Tian Shan. *Quat. Sci. Rev.* 101, 77–90.
- 2336 Lillesand, T.M., Kiefer, R.W., Chipman, J.W., 2015. *Remote Sensing and Image Interpretation* (7<sup>th</sup>  
2337 Edition). John Wiley & Sons, Hoboken, USA, 768 pp.
- 2338 Lindholm, M.S., Heyman, J., 2016. Glacial geomorphology of the Maidika region, Tibetan Plateau. *J.*  
2339 *Maps* 12(5), 797–803.
- 2340 Livingstone, S.J., Ó Cofaigh, C., Evans, D.J.A., 2008. The glacial geomorphology of the central  
2341 sector of the British-Irish Ice Sheet. *J. Maps* 4, 358–377.
- 2342 Livingstone, S.J., Evans, D.J.A., Ó Cofaigh, C., 2010. Re-advance of Scottish ice into the Solway  
2343 Lowlands (Cumbria, UK) during the Main Late Devensian deglaciation. *Quat. Sci. Rev.* 29,  
2344 2544–2570.
- 2345 Livingstone, S.J., Ó Cofaigh, C., Stokes, C.R., Hillenbrand, C.-D., Vieli, A., Jamieson, S.S.R., 2012.  
2346 Antarctic palaeo-ice streams. *Earth-Sci. Rev.* 111, 90–128.
- 2347 Livingstone, S.J., Storrar, R.D., Hillier, J.K., Stokes, C.R., Clark, C.D., Tarasov, L., 2015. An ice-  
2348 sheet scale comparison of eskers with modelled subglacial drainage routes. *Geomorphology*  
2349 246, 104–112.
- 2350 Loibl, D., Hochreuther, P., Schulte, P., Hülle, D., Zhu H, Bräuning, A., Lehmkuhl, F., 2015. Toward a  
2351 late Holocene glacial chronology for the eastern Nyainqêntanglha Range, southeastern Tibet.  
2352 *Quat. Sci. Rev.* 107, 243–259.
- 2353 Lønne, I., 2016. A new concept for glacial geological investigations of surges, based on High-Arctic  
2354 examples (Svalbard). *Quat. Sci. Rev.*, 132, 74–100.
- 2355 Lovell, H., 2014. On the ice-sediment-landform associations of surging glaciers on Svalbard.  
2356 Unpublished PhD thesis, Queen Mary University of London, 312 pp.
- 2357 Lovell, H., Boston, C.M., 2017. Glacitectonic composite ridge systems and surge-type glaciers: an  
2358 updated correlation based on Svalbard, Norway. *arktos* 3, 2.
- 2359 Lovell, H., Stokes, C.R., Bentley, M.J., 2011. A glacial geomorphological map of the Seno Skyring-  
2360 Seno Otway-Strait of Magellan region, southernmost Patagonia. *J. Maps* 7, 318–339.
- 2361 Lovell, H., Stokes, C.R., Bentley, M.J., Benn, D.I., 2012. Evidence for rapid ice flow and proglacial  
2362 lake evolution around the central Strait of Magellan region, southernmost Patagonia. *J. Quat.*  
2363 *Sci.* 27, 625–638.
- 2364 Lovell, H., Benn, D.I., Lukas, S., Spagnolo, M., Cook, S.J., Swift, D.A., Clark, C.D., Yde, J.C.,  
2365 Watts, T.P., 2018. Geomorphological investigation of multiphase glacitectonic composite  
2366 ridge systems in Svalbard. *Geomorphology* 300, 176–188.
- 2367 Lueder, D.R., 1959. *Aerial Photographic Interpretation – Principles and Applications*. McGraw-Hill,  
2368 New York.
- 2369 Lukas, S., 2002. Geomorphological evidence for the pattern of deglaciation around the Drumochter  
2370 Pass, Central Grampian Highlands, Scotland. Unpublished MSc thesis, Ruhr-University of  
2371 Bochum, Germany, 115 pp.
- 2372 Lukas, S., 2005. A test of the englacial thrusting hypothesis of 'hummocky' moraine formation – case  
2373 studies from the north-west Highlands, Scotland. *Boreas* 34, 287–307.

- 2374 Lukas, S., 2006. Morphostratigraphic principles in glacier reconstruction -a perspective from the  
2375 British Younger Dryas. *Prog. Phys. Geogr.* 30, 719–736.
- 2376 Lukas, S., 2007a. Early-Holocene glacier fluctuations in Krundalen, south central Norway: palaeo-  
2377 glacier dynamics and palaeoclimate. *The Holocene* 17, 585–598.
- 2378 Lukas, S., 2007b. ‘A test of the englacial thrusting hypothesis of “hummocky” moraine formation:  
2379 case studies from the northwest Highlands, Scotland’: Reply to comments. *Boreas* 36, 108–  
2380 113.
- 2381 Lukas, S., 2011. Ice-cored moraines. In: Singh, V., Singh, P. Haritashya, U.K. (Eds.), *Encyclopedia of*  
2382 *Snow, Ice and Glaciers*. Springer, Heidelberg, pp. 616–619.
- 2383 Lukas, S., 2012. Processes of annual moraine formation at a temperate alpine valley glacier: insights  
2384 into glacier dynamics and climatic controls. *Boreas* 41(3), 463–480.
- 2385 Lukas, S., Benn, D.I., 2006. Retreat dynamics of Younger Dryas glacier in the far NW Scottish  
2386 Highlands reconstructed from moraine sequences. *Scott. Geogr. J.* 122, 308–325.
- 2387 Lukas, S., Lukas, T., 2006. A glacial geological and geomorphological map of the far NW Highlands,  
2388 Scotland. Parts 1 and 2. *J. Maps* 2, 43–56, 56–58.
- 2389 Lukas, S., Sass, O., 2011. The formation of Alpine lateral moraines inferred from sedimentology and  
2390 radar reflection patterns: a case study from Gornergletscher, Switzerland. *Geological Society,*  
2391 *London, Special Publications* 354, 77–92.
- 2392 Lukas, S., Nicholson, L.I., Ross, F.H., Humlum, O., 2005. Formation, meltout processes and  
2393 landscape alteration of High-Arctic ice-cored moraines—examples from Nordenskiöld Land,  
2394 Central Spitsbergen. *Polar Geogr.* 29, 157–187.
- 2395 Lukas, S., Nicholson, L.I., Humlum, O., 2007. Comment on Lønne and Lyså (2005): “Deglaciation  
2396 dynamics following the Little Ice Age on Svalbard: Implications for shaping of landscapes at  
2397 high latitudes”, *Geomorphology* 72, 300–319. *Geomorphology* 84, 145–149.
- 2398 Lukas, S., Benn, D.I., Boston, C.M., Brook, M.S., Coray, S., Evans, D.J.A., Graf, A., Kellerer-  
2399 Pirklbauer-Eulenstein, A., Kirkbride, M.P., Krabbendam, M., Lovell, H., Machiedo, M.,  
2400 Mills, S.C., Nye, K., Reinardy, B.T.I., Ross, F.H., Signer, M., 2013. Clast shape analysis and  
2401 clast transport paths in glacial environments: A critical review of methods and the role of  
2402 lithology. *Earth-Sci. Rev.* 121, 96–116.
- 2403 Lukas, S., Preusser, F., Evans, D.J.A., Boston, C.M., Lovell, H., 2017. Chapter 2 – The Quaternary.  
2404 In: Griffiths, J.S., Martin, C.J. (Eds.), *Engineering Geology and Geomorphology of Glaciated*  
2405 *and Periglaciated Terrains: Engineering Group Working Party Report*. Engineering Geology  
2406 Special Publication 28. The Geological Society, London, pp. 31–57.
- 2407 Maclachlan, J.C., Eyles, C.H., 2013. Quantitative geomorphological analysis of drumlins in the  
2408 Peterborough drumlin field, Ontario, Canada. *Geogr. Ann.* 95A, 125–144.
- 2409 Mäkinen, J., Kajuutti, K., Palmu, J., Ojala, A., Ahokangas, E., 2017. Triangular-shaped landforms  
2410 reveal subglacial drainage routes in SW Finland. *Quat. Sci. Rev.* 164, 37–53.
- 2411 Małeckı, J., Lovell, H., Ewertowski, W., Górski, Ł., Kurczba, T., Latos, B., Miara, M., Piniarska, D.,  
2412 Płocieniczak, J., Sowada, T., Spiralski, M., Warczachowska, A., Rabatel, A., 2018. The  
2413 glacial landsystem of a tropical glacier: Charquini Sur, Bolivian Andes. *Earth Surf. Proc.*  
2414 *Land.*, in press. doi: 10.1002/esp.4417
- 2415 Marc, O., Hovius, N., 2015. Amalgamation in landslide maps: effects and automatic detection. *Nat.*  
2416 *Hazards Earth Syst. Sci.* 15, 723–733.
- 2417 Margold, M., Jansson, K.N., 2011. Glacial geomorphology and glacial lakes of central Transbaikalia,  
2418 Siberia, Russia. *J. Maps* 7, 18–30.
- 2419 Margold, M., Jansson, K.N., 2012. Evaluation of data sources for mapping glacial meltwater features.  
2420 *Int. J. Remote Sens.* 33, 2355–2377.
- 2421 Margold, M., Jansson, K.N., Kleman, J., Stroeven, A.P., 2011. Glacial meltwater landforms of central  
2422 British Columbia. *J. Maps* 7, 486–506.
- 2423 Margold, M., Stokes, C.R., Clark, C.D., Kleman, J., 2015a. Ice streams in the Laurentide Ice Sheet: a  
2424 new mapping inventory. *J. Maps* 11, 380–395.
- 2425 Margold, M., Stokes, C.R., Clark, C.D., 2015b. Ice streams in the Laurentide Ice Sheet: Identification,  
2426 characteristics and comparison to modern ice sheets. *Earth-Sci. Rev.* 143, 117–146.

- 2427 Margold, M., Stokes, C.R., Clark, C.D., 2018. Reconciling records of ice streaming and ice margin  
2428 retreat to produce a palaeogeographic reconstruction of the deglaciation of the Laurentide Ice  
2429 Sheet. *Quat. Sci. Rev.* 189, 1–30.
- 2430 Mather, A.E., Mills, S., Stokes, M., Fyfe, R., 2015. Ten years on: what can Google Earth offer the  
2431 Geoscience community? *Geology Today* 31(6), 216–221.
- 2432 May, J.H., Zech, J., Zech, R., Preusser, F., Argollo, J., Kubik, P.W., Veit, H., 2011. Reconstruction of  
2433 a complex late Quaternary glacial landscape in the Cordillera de Cochabamba (Bolivia) based  
2434 on a morphostratigraphic and multiple dating approach. *Quat. Res.* 76(1), 106–118.
- 2435 McDougall, D.A., 2001. The geomorphological impact of Loch Lomond (Younger Dryas) Stadial  
2436 plateau icefields in the central Lake District, northwest England. *J. Quat. Sci.* 16, 531–543.
- 2437 McDougall, D.A., 2013. Glaciation style and the geomorphological record: evidence for Younger  
2438 Dryas glaciers in the eastern Lake District, northwest England. *Quat. Sci. Rev.* 73, 48–58.
- 2439 McHenry, M., Dunlop, P., 2016. The subglacial imprint of the last Newfoundland Ice Sheet, Canada.  
2440 *J. Maps* 12(3), 462–483.
- 2441 Melander, O., 1975. Geomorfologiska kartbladet 29 I Kebnekaise. Statens naturvårdsverk. 78 pp.,  
2442 map scale 1:250,000.
- 2443 Mertes, J.R., Gullely, J.D., Benn, D.I., Thompson, S.S., Nicholson, L.I., 2017. Using structure-from-  
2444 motion to create glacier DEMs and orthoimagery from historical terrestrial and oblique aerial  
2445 imagery. *Earth Surf. Process. Land.* 42, 2350–2364.
- 2446 Midgley, N.G., Tonkin, T.N., 2017. Reconstruction of former glacier surface topography from archive  
2447 oblique aerial images. *Geomorphology* 282, 18–26.
- 2448 Midgley, N.G., Cook, S.J., Graham, D.J., Tonkin, T.N., 2013. Origin, evolution and dynamic context  
2449 of a Neoglacial lateral–frontal moraine at Austre Lovénbreen, Svalbard. *Geomorphology* 198,  
2450 96–106.
- 2451 Midgley, N.G., Tonkin, T.N., Graham, D.J., Cook, S.J., 2018. Evolution of high-Arctic glacial  
2452 landforms during deglaciation. *Geomorphology* 311, 63–75.
- 2453 Miller, H., Cotterill, C.J., Bradwell, T., 2014. Glacial and paraglacial history of the Troutbeck Valley,  
2454 Cumbria, UK: integrating airborne LiDAR, multibeam bathymetry, and geological field  
2455 mapping. *Proc. Geol. Assoc.* 125, 31–40.
- 2456 Mills, S.C., Grab, S.W., Rea, B.R., Carr, S.J., Farrow, A., 2012. Shifting westerlies and precipitation  
2457 patterns during the Late Pleistocene in southern Africa determined using glacier  
2458 reconstruction and mass balance modelling. *Quaternary Science Reviews* 55, 145–159.
- 2459 Mitchell, W.A., Riley, J.M., 2006. Drumlin map of the Western Pennines and southern Vale of Eden,  
2460 Northern England, UK. *J. Maps* 2, 10–16.
- 2461 Mollard, J.D., Janes, J.R., 1984. Airphoto Interpretation and the Canadian Landscape. Energy, Mines  
2462 and Resources Canada, Ottawa.
- 2463 Möller, P., Dowling, T.P.F., 2016. Streamlined subglacial bedforms on the Närke plain, south-central  
2464 Sweden – Areal distribution, morphometrics, internal architecture and formation. *Quat. Sci.*  
2465 *Rev.* 146, 182–215.
- 2466 Möller, P., Dowling, T.P.F., 2018. Equifinality in glacial geomorphology: instability theory examined  
2467 via ribbed moraine and drumlins in Sweden. *GFF* 140(2), 106–135.
- 2468 Morén, B., Heyman, J., Stroeven, A.P., 2011. Glacial geomorphology of the central Tibetan Plateau.  
2469 *J. Maps* 7, 115–125.
- 2470 Murray, A.B., Goldstein, E.B., Coco, G., 2014. The shape of patterns to come: from initial formation  
2471 to long-term evolution. *Earth Surf. Process. Land.* 39, 62–70.
- 2472 Napieralski, J., Hubbard, A., Li, Y.K., Harbor, J., Stroeven, A.P., Kleman, J., Alm, G., Jansson, K.N.,  
2473 2007a. Towards a GIS assessment of numerical ice sheet model performance using  
2474 geomorphological data. *J. Glaciol.* 53 (180), 71–83.
- 2475 Napieralski, J., Harbor, J., Li, Y., 2007b. Glacial geomorphology and geographic information  
2476 systems. *Earth-Sci. Rev.* 85, 1–22.
- 2477 Näslund, J.O., Rodhe, L., Fastook, J.L., Holmlund, P., 2003. New ways of studying ice sheet flow  
2478 directions and glacial erosion by computer modelling — examples from Fennoscandia. *Quat.*  
2479 *Sci. Rev.* 22, 245–258.

- 2480 Noh, M.J., Howat, I.M., 2015. Automated stereo-photogrammetric DEM generation at high latitudes:  
2481 Surface Extraction from TIN-Based Search Minimization (SETSM) validation and  
2482 demonstration over glaciated regions. *GIScience Remote Sens.* 52(2), 198–217.
- 2483 Norris, S.L., Margold, M., Froese, D.G., 2017. Glacial landforms of northwest Saskatchewan. *J. Maps*  
2484 13, 600–607.
- 2485 Norris, S.L., Evans, D.J.A., Cofaigh, C.Ó., 2018. Geomorphology and till architecture of terrestrial  
2486 palaeo-ice streams of the southwest Laurentide Ice Sheet: A borehole stratigraphic approach.  
2487 *Quat. Sci. Rev.* 186, 186–214.
- 2488 Nuth, C., Kääb, A., 2011. Co-registration and bias corrections of satellite elevation data sets for  
2489 quantifying glacier thickness change. *The Cryosphere* 5, 271–290.
- 2490 Ó Cofaigh, C., 2012. Ice sheets viewed from the ocean: the contribution of marine science to  
2491 understanding modern and past ice sheets. *Phil. Trans. R. Soc. A* 370(1980), 5512–5539.
- 2492 Ó Cofaigh, C., Evans, D.J.A., Smith, I.R., 2010. Large-scale reorganization and sedimentation of  
2493 terrestrial ice streams during late Wisconsinan Laurentide Ice Sheet deglaciation. *Geol. Soc.  
2494 Am. Bull.* 122, 743–756.
- 2495 Ó Cofaigh, C., Dowdeswell, J.A., Jennings, A.E., Hogan, K.A., Kilfeather, A., Hiemstra, J.F.,  
2496 Noormets, R.M., Evans, J., McCarthy, D.J., Andrews, J.T., Lloyd, J.M., Moros, M., 2013. An  
2497 extensive and dynamic ice sheet on the West Greenland shelf during the last glacial cycle.  
2498 *Geology* 41 (2), 219–222.
- 2499 Ojala, A.E.K., 2016. Appearance of De Geer moraines in southern and western Finland —  
2500 Implications for reconstructing glacier retreat dynamics. *Geomorphology* 255, 16–25.
- 2501 Ojala, A.E.K., Putkinen, N., Palmu, J.P., Nenonen, K., 2015. Characterization of De Geer moraines in  
2502 Finland based on LiDAR DEM mapping. *GFF* 137(4), 304–318.
- 2503 Orkhonselenge, A., 2016. Glacial Geomorphology of Mt. Munkh Saridag in the Khuvsgul Mountain  
2504 Range, Northern Mongolia. *Géomorphologie: relief, processus, environnement* 22(4), 389-  
2505 398.
- 2506 Ottesen, D., Dowdeswell, J.A., 2006. Assemblages of submarine landforms produced by tidewater  
2507 glaciers in Svalbard. *J. Geophys. Res.* 111, F01016.
- 2508 Ottesen, D., Dowdeswell, J.A., Rise, L., 2005. Submarine landforms and the reconstruction of fast-  
2509 flowing ice streams within a large Quaternary ice sheet: the 2500 km long Norwegian-  
2510 Svalbard margin (57 degrees – 80 degrees N). *Geol. Soc. Am. Bull.* 117 (7–8), 1033–1050.
- 2511 Ottesen, D., Dowdeswell, J.A., 2006. Assemblages of submarine landforms produced by tidewater  
2512 glaciers in Svalbard. *J. Geophys. Res.* 111, F01016.
- 2513 Ottesen, D., Stokes, C.R., Rise, L., Olsen, L., 2008a. Ice-sheet dynamics and ice streaming along the  
2514 coastal parts of northern Norway. *Quat. Sci. Rev.* 27, 922–940
- 2515 Ottesen, D., Dowdeswell, J.A., Benn, D.I., Kristensen, L., Christiansen, H.H., Christensen, O.,  
2516 Hansen, L., Lebesbye, E., Forwick, M., Vorren, T.O., 2008b. Submarine landforms  
2517 characteristic of glacier surges in two Spitsbergen fjords. *Quat. Sci. Rev.* 27, 1583–1599.
- 2518 Ottesen, D., Stokes, C.R., Bøe, R., Rise, L., Longva, O., Thorsnes, T., Olesen, O., Bugge, T., Lepland,  
2519 A., Hestvik, O.B., 2016. Landform assemblages and sedimentary processes along the  
2520 Norwegian Channel Ice Stream. *Sediment. Geol.* 338, 115–137.
- 2521 Ottesen, D., Dowdeswell, J.A., Bellec, V.K., Bjarnadóttir, L.R., 2017. The geomorphic imprint of  
2522 glacier surges into open-marine waters: Examples from eastern Svalbard. *Mar. Geol.* 392, 1–  
2523 29.
- 2524 Otto, J.-C., Smith, M.J., 2013. Section 2.6: Geomorphological mapping. In: Clarke, L. (Ed.),  
2525 *Geomorphological Techniques* (Online Edition). British Society for Geomorphology, London.  
2526 ISSN: 2047-0371.
- 2527 Owen, L.A., Finkel, R.C., Barnard, P.L., Haizhou, M., Asahi, K., Caffee, M.W., Derbyshire, E., 2005.  
2528 Climatic and topographic controls on the style and timing of Late Quaternary glaciation  
2529 throughout Tibet and the Himalaya defined by <sup>10</sup>Be cosmogenic radionuclide surface  
2530 exposure dating. *Quat. Sci. Rev.* 24(12), 1391–1411.
- 2531 Paron, P., Claessens, L., 2011. Makers and Users of Geomorphological Maps. In: Smith, M.J., Paron,  
2532 P., Griffiths, J.S. (Eds.), *Geomorphological Mapping: Methods and applications.*  
2533 *Developments in Earth Surface Processes*, Volume 15. Elsevier, Oxford; pp. 75–106.

- 2534 Partsch, J., 1894. Die Vergletscherung des Riesengebirges zur Eiszeit. Forschungen zur Deutschen  
2535 Landes- und Volkskunde VIII/2, 103–194.
- 2536 Patton, H., Hubbard, A., Andreassen, K., Auriac, A., Whitehouse, P.L., Stroeven, A.P., Shackleton,  
2537 C., Winsborrow, M., Heyman, J., Hall, A.M., 2017a. Deglaciation of the Eurasian ice sheet  
2538 complex. *Quat. Sci. Rev.* 169, 148–172.
- 2539 Patton, H., Hubbard, A., Bradwell, T., Schomacker, A., 2017b. The configuration, sensitivity and  
2540 rapid retreat of the Late Weichselian Icelandic ice sheet. *Earth-Sci. Rev.* 166, 223–245.
- 2541 Pearce, D., Rea, B.R., Bradwell, T., McDougall, D., 2014. Glacial geomorphology of the Tweedsmuir  
2542 Hills, Central Southern Uplands, Scotland. *J. Maps* 10(3), 457–465.
- 2543 Pearce, D.M., Mair, D.W.F., Rea, B.R., Lea, J.M., Schofield, J.E., Kamenos, N., Schoenrock, K.,  
2544 2018. The glacial geomorphology of upper Godthåbsfjord (Nuup Kangerlua) in southwest  
2545 Greenland. *J. Maps* 14, 45–55.
- 2546 Penck, A., Brückner, E., 1901/1909. Die Alpen im Eiszeitalter. Tauchnitz, Leipzig.
- 2547 Peterson, G., Johnson, M.D., Smith, C.A., 2017. Glacial geomorphology of the south Swedish uplands  
2548 – focus on the spatial distribution of hummock tracts. *J. Maps* 13, 534–544.
- 2549 Petrie, G., Price, R.J., 1966. Photogrammetric measurements of the ice wastage and morphological  
2550 changes near the Casement Glacier, Alaska. *Can. J. Earth Sci.* 3, 827–840.
- 2551 Phillips, E., Evans, D.J.A., Atkinson, N., Kendall, A., 2017. Structural architecture and glacial tectonic  
2552 evolution of the Mud Buttes cupola hill complex, southern Alberta, Canada. *Quat. Sci. Rev.*  
2553 164, 110–139.
- 2554 Pike, R.J., 1988. The geometric signature: quantifying landslide-terrain types from digital elevation  
2555 models. *Math. Geol.* 20, 491–511.
- 2556 Pipaud, I., Loibl, D., Lehmkuhl, F., 2015. Evaluation of TanDEM-X elevation data for  
2557 geomorphological mapping and interpretation in high mountain environments — A case study  
2558 from SE Tibet, China. *Geomorphology* 246, 232–254.
- 2559 Popper, K.R., 1972. *Objective Knowledge*. Oxford University Press, Oxford.
- 2560 Prest, V.K., 1983. Canada's Heritage of Glacial Features. GSC Miscellaneous Report 28.
- 2561 Prest, V.K., Grant, D.R., Rampton, V.N. 1968. Glacial map of Canada. Geological Survey of Canada,  
2562 Map 1253A.
- 2563 Priamonosov, A.P., Kuznetsova, E.J., Abaturova, I.V., 2000. National geological map of the Russian  
2564 Federation, Map of Quaternary Formations, Polar-Ural series, map sheet Q-41-XII Kharp.  
2565 Ministry of Natural Resources of the Russian Federation. 1:200,000.
- 2566 Price, R.J., 1961. The Deglaciation of the Upper Tweed Basin. Unpublished PhD thesis, University of  
2567 Edinburgh.
- 2568 Price, R.J., 1963. A glacial meltwater drainage system in Peebleshire, Scotland. *Scott. Geogr. Mag.*  
2569 79, 133–141.
- 2570 Price, R.J., 1966. Eskers near the Casement Glacier, Alaska. *Geogr. Ann.* 48, 111–125.
- 2571 Price, R.J., 1970. Moraines at Fjallsjökull, Iceland. *Arctic Alp. Res.* 2, 27–42.
- 2572 Principato, S.M., Moyer, A.N., Hampsch, A.G., Ipsen, H.A., 2016. Using GIS and streamlined  
2573 landforms to interpret palaeo-ice flow in northern Iceland. *Boreas* 45, 470–482.
- 2574 Punkari, M., 1980. The ice lobes of the Scandinavian ice sheet during the deglaciation in Finland.  
2575 *Boreas* 9(4), 307–310.
- 2576 Punkari, M., 1995. Glacial flow systems in the zone of confluence between the Scandinavian and  
2577 Novaja Zemlya Ice Sheets. *Quat. Sci. Rev.* 14(6), 589–603.
- 2578 Putniņš, A., Henriksen, M., 2017. Reconstructing the flow pattern evolution in inner region of the  
2579 Fennoscandian Ice Sheet by glacial landforms from Gausdal Vestfjell area, south-central  
2580 Norway. *Quat. Sci. Rev.* 163, 56–71.
- 2581 Rabus, B., Eineder, M., Roth, A., Bamler, R., 2003. The shuttle radar topography mission—a new  
2582 class of digital elevation models acquired by spaceborne radar. *ISPRS J. Photogramm.*  
2583 *Remote Sens.* 57(4), 241–262.
- 2584 Rączkowska Z., Zwoliński Z., 2015. Digital geomorphological map of Poland. *Geogr. Pol.* 88(2),  
2585 205–210.
- 2586 Raistrick, A., 1933. The glacial and post-glacial periods in West Yorkshire. *Proc. Geol. Assoc.* 44,  
2587 263–269.
- 2588 Raisz, E.J., 1962. *Principles of cartography*. McGraw-Hill, New York, 315 pp.

- 2589 Rea, B.R., Whalley, W.B., Dixon, T.S., Gordon, J.E., 1999. Plateau icefields as contributing areas to  
2590 valley glaciers and the potential impact on reconstructed ELAs: a case study from the Lyngen  
2591 Alps, North Norway. *Ann. Glaciol.* 28, 97–102.
- 2592 Reinardy, B.T.I., Leighton, I., Marx, P.J., 2013. Glacier thermal regime linked to processes of annual  
2593 moraine formation at Midtdalsbreen, southern Norway. *Boreas* 42(4), 896–911.
- 2594 Reuther, A.U., Urdea, P., Geiger, C., Ivy-Ochs, S., Niller, H.P., Kubik, P.W., Heine, K., 2007. Late  
2595 Pleistocene glacial chronology of the Pietrele Valley, Retezat Mountains, Southern  
2596 Carpathians constrained by <sup>10</sup>Be exposure ages and pedological investigations. *Quat. Int.*  
2597 164, 151–169.
- 2598 Rippin, D.M., Pomfret, A., King, N., 2015. High resolution mapping of supra-glacial drainage  
2599 pathways reveals link between microchannel drainage density, surface roughness and surface  
2600 reflectance. *Earth Surf. Proc. Land.* 40(10), 1279–1290.
- 2601 Robb, C., Willis, I., Arnold, N., Guðmundsson, S., 2015. A semi-automated method for mapping  
2602 glacial geomorphology tested at Breiðamerkurjökull, Iceland. *Remote Sens. Environ.* 163,  
2603 80–90.
- 2604 Robinson, A.H., Morrison, J.L., Muehrcke, P.C., Kimerling, A.J., Guphill, S.C., 1995. Elements of  
2605 cartography (6<sup>th</sup> Edition). Wiley & Sons, Chichester, 674 pp.
- 2606 Robinson, P., Dowdeswell, J.A., 2011. Submarine landforms and the behavior of a surging ice cap  
2607 since the last glacial maximum: The open-marine setting of eastern Austfonna, Svalbard. *Mar.*  
2608 *Geol.* 286(1), 82–94.
- 2609 Rose, J., Smith, M.J., 2008. Glacial geomorphological maps of the Glasgow region, western central  
2610 Scotland. *J. Maps* 4, 399–416.
- 2611 Rossi, C., Rodriguez Gonzalez, F., Fritz, T., Yague-Martinez, N., Eineder, M., 2012. TanDEM-X  
2612 calibrated raw DEM generation. *ISPRS J. Photogramm. Remote Sens.* 73, 12–20.
- 2613 Rupke, J., De Jong, M.G.G., 1983. Slope collapse destroying ice-marginal topography in the Walgau  
2614 (Vorarlberg, Austria)- an example of the application of a 1:10000 geomorphological mapping  
2615 system. *Mater. Physiogeogr.* 5, 33–41.
- 2616 Ryan, J.C., Hubbard, A.L., Todd, J., Carr, J.R., Box, J.E., Christoffersen, P., Holt, T.O., Snooke, N.,  
2617 2015. Repeat UAV photogrammetry to assess calving front dynamics at a large outlet glacier  
2618 draining the Greenland Ice Sheet. *The Cryosphere* 9, 1–11.
- 2619 Sagredo, E.A., Moreno, P.I., Villa-Martínez, R., Kaplan, M.R., Kubik, P.W., Stern, C.R., 2011.  
2620 Fluctuations of the Última Esperanza ice lobe (52 S), Chilean Patagonia, during the last  
2621 glacial maximum and termination 1. *Geomorphology* 125(1), 92–108.
- 2622 Saha, K., Wells, N.A., Munro-Stasiuk, M., 2011. An object-oriented approach to automated landform  
2623 mapping: A case study of drumlins. *Computers & Geosciences* 37(9), 1324–1336.
- 2624 Sahlin, E.A.U., Glasser, N.F., 2008. A geomorphological map of Cadair Idris, Wales. *J. Maps* 4, 299–  
2625 314.
- 2626 Salcher, B.C., Hirsch, R., Wagneich, M., 2010. High-resolution mapping of glacial landforms in the  
2627 North Alpine Foreland, Austria. *Geomorphology* 122, 283–293.
- 2628 Schoeneich, P., 1993. Cartographie géomorphologique en Suisse, Institut de Géographie Lausanne,  
2629 Travaux et recherches, Lausanne, pp. 1–13.
- 2630 Schomacker, A., 2008. What controls dead-ice melting under different climate conditions? A  
2631 discussion. *Earth-Sci. Rev.* 90, 103–113.
- 2632 Schomacker, A., Kjaer, K.H., 2008. Quantification of dead-ice melting in ice-cored moraines at the  
2633 high-Arctic glacier Holmströmbreen, Svalbard. *Boreas* 37, 211–225.
- 2634 Schomacker, A., Benediktsson, Í.Ö., Ingólfsson, Ó., 2014. The Eyjabakkajökull glacial landsystem,  
2635 Iceland: Geomorphic impact of multiple surges. *Geomorphology* 218, 98–107.
- 2636 Seguinot, J., Rogozhina, I., Stroeven, A.P., Margold, M., Kleman, J., 2016. Numerical simulations of  
2637 the Cordilleran ice sheet through the last glacial cycle. *The Cryosphere* 10, 639–664.
- 2638 Shean, D.E., Alexandrov, O., Moratto, Z.M., Smith, B.E., Joughin, I.R., Porter, C., Morin, P., 2016.  
2639 An automated, open-source pipeline for mass production of digital elevation models (DEMs)  
2640 from very-high-resolution commercial stereo satellite imagery. *ISPRS J. Photogramm.*  
2641 *Remote Sens.* 116, 101–117.
- 2642 Sissons, J.B., 1967. *The Evolution of Scotland's Scenery*. Oliver & Boyd, Edinburgh, 259 pp.



- 2643 Sissons, J.B., 1977a. The Loch Lomond Readvance in the northern mainland of Scotland. In: Gray,  
2644 J.M., Lowe, J.J. (Eds.), *Studies in the Scottish Lateglacial Environment*. Pergamon Press,  
2645 Oxford, pp. 45–60.
- 2646 Sissons, J.B., 1977b. The Loch Lomond Readvance in southern Skye and some palaeoclimatic  
2647 implications. *Scott. J. Geol.* 13, 23–36.
- 2648 Sissons, J.B., 1979a. The limit of the Loch Lomond Advance in Glen Roy and vicinity. *Scott. J. Geol.*  
2649 15, 31–42.
- 2650 Sissons, J.B., 1979b. The Loch Lomond advance in the Cairngorm Mountains. *Scott. Geogr. Mag.* 95,  
2651 66–82.
- 2652 Smith, A.M., Murray, T., 2009. Bedform topography and basal conditions beneath a fast-flowing  
2653 West Antarctic ice stream. *Quat. Sci. Rev.* 28(7), 584–596.
- 2654 Smith, A.M., Murray, T., Nicholls, K.W., Makinson, K., Aðalgeirsdóttir, G., Behar, A.E., Vaughan,  
2655 D. G., 2007. Rapid erosion, drumlin formation, and changing hydrology beneath an Antarctic  
2656 ice stream. *Geology* 35(2), 127–130.
- 2657 Smith, G.R., Woodward, J.C., Heywood, D.I., Gibbard, P.L., 2000. Interpreting Pleistocene glacial  
2658 features from SPOT HRV data using fuzzy techniques. *Computers & Geosciences* 26(4),  
2659 479–490.
- 2660 Smith, M.J., Clark, C.D., 2005. Methods and visualisation of digital elevation models for landform  
2661 mapping. *Earth Surf. Process. Land.* 30, 885–900.
- 2662 Smith, M.J., Knight, J., 2011. Palaeoglaciology of the last Irish ice sheet reconstructed from striae  
2663 evidence. *Quat. Sci. Rev.* 30(1-2), 147–160.
- 2664 Smith, M.J., Wise, S.M., 2007. Problems of bias in mapping linear landforms from satellite imagery.  
2665 *Int. J. Appl. Earth Obs. Geoinform.* 9(1), 65–78.
- 2666 Smith, M.J., Rose, J., Booth, S., 2006. Geomorphological mapping of glacial landforms from  
2667 remotely sensed data: An evaluation of the principal data sources and an assessment of their  
2668 quality. *Geomorphology* 76, 148–165.
- 2669 Smith, M.J., Griffiths, J., Paron, P. (Eds.), 2011. *Geomorphological Mapping: Methods and*  
2670 *Applications*. Developments in Earth Surface Processes, Volume 15. Elsevier, Oxford, 610  
2671 pp.
- 2672 Smith, M.J., Anders, N.S., Keesstra, S.D., 2016b. CLustre: semi-automated lineament clustering for  
2673 palaeo-glacial reconstruction. *Earth Surf. Process. Land.* 41(3), 364–377.
- 2674 Smith, M.W., Carrivick, J.L., Quincey, D.J., 2016a. Structure from motion photogrammetry in  
2675 physical geography. *Prog. Phys. Geogr.* 40(2), 247–275.
- 2676 Sollas, W.J., 1896. A map to show the distribution of eskers in Ireland. *The Sci. Trans. R. Dublin Soc.*  
2677 5, 785–822.
- 2678 Sollid, J.L., Andersen, S., Hamre, N., Kjeldsen, O., Salvigsen, O., Sturød, S., Tveitå, T., Wilhemsen,  
2679 A., 1973. Deglaciation of Finnmark, North Norway. *Norsk Geogr. Tidsskr.* 27(4), 233–325.
- 2680 Spagnolo, M., Clark, C.D., Hughes, A.L.C., Dunlop, P., Stokes, C.R., 2010. The planar shape of  
2681 drumlins. *Sediment. Geol.* 232, 119–129.
- 2682 Spagnolo, M., Clark, C.D., Ely, J.C., Stokes, C.R., Anderson, J.B., Andreassen, K., Graham, A.G.C.,  
2683 King, E.C., 2014. Size, shape and spatial arrangement of megascale glacial lineations from a  
2684 large and diverse dataset. *Earth Surf. Process. Land.* 39, 1432–1448.
- 2685 Spagnolo, M., Phillips, E., Piotrowski, J.A., Rea, B.R., Clark, C.D., Stokes, C.R., Carr, S.J., Ely, J.C.,  
2686 Ribolini, A., Wysota, W., Szuman, I., 2016. Ice stream motion facilitated by a shallow-  
2687 deforming and accreting bed. *Nat. Commun.* 7, 10723.
- 2688 Spagnolo, M., Bartholomaeus, T.C., Clark, C.D., Stokes, C.R., Atkinson, N., Dowdeswell, J.A., Ely,  
2689 J.C., Graham, A.G.C., Hogan, K.A., King, E.C., Larter, R.D., Livingstone, S.J., Pritchard,  
2690 H.D., 2017. The periodic topography of ice stream beds: Insights from the Fourier spectra of  
2691 mega-scale glacial lineations. *J. Geophys. Res.: Earth Surf.* 122, 1355–1373.
- 2692 Stansell, N.D., Polissar, P.J., Abbott, M.B., 2007. Last glacial maximum equilibrium-line altitude and  
2693 paleo-temperature reconstructions for the Cordillera de Mérida, Venezuelan Andes. *Quat.*  
2694 *Res.* 67, 115–127.
- 2695 Stokes, C.R., 2002. Identification and mapping of palaeo-ice stream geomorphology from satellite  
2696 imagery: implications for ice stream functioning and ice sheet dynamics. *Int. J. Remote Sens.*  
2697 23(8), 1557–1563.

- 2698 Stokes, C.R., 2018. Geomorphology under ice streams: moving from form to process. *Earth Surf.*  
 2699 *Process. Land.*, 43, 85–123.
- 2700 Stokes, C.R., Clark, C.D., 1999. Geomorphological criteria for identifying Pleistocene ice streams.  
 2701 *Ann. Glaciol.* 28(1), 67–74.
- 2702 Stokes, C.R., Clark, C.D., 2001. Palaeo-ice streams. *Quat. Sci. Rev.* 20(13), 1437–1457.
- 2703 Stokes, C.R., Clark, C.D., 2002. Are long subglacial bedforms indicative of fast ice flow? *Boreas*,  
 2704 31(3), 239–249.
- 2705 Stokes, C.R., Clark, C.D. 2003. The Dubawnt Lake palaeo-ice stream: evidence for dynamic ice sheet  
 2706 behaviour on the Canadian Shield and insights regarding the controls on ice-stream location  
 2707 and vigour. *Boreas* 32, 263–279.
- 2708 Stokes, C.R., Tarasov, L., 2010. Ice streaming in the Laurentide Ice Sheet: A first comparison  
 2709 between data-calibrated numerical model output and geological evidence. *Geophys. Res. Lett.*  
 2710 37, L01501.
- 2711 Stokes, C.R., Clark, C.D., Storrar, R., 2009. Major changes in ice stream dynamics during  
 2712 deglaciation of the north-western margin of the Laurentide Ice Sheet. *Quat. Sci. Rev.* 28, 721–  
 2713 738.
- 2714 Stokes, C.R., Spagnolo, M., Clark, C.D., Ó Cofaigh, C., Lian, O.B., Dunstone, R.B., 2013. Formation  
 2715 of mega-scale glacial lineations on the Dubawnt Lake Ice Stream bed: 1. size, shape and  
 2716 spacing from a large remote sensing dataset. *Quat. Sci. Rev.* 77, 190–209.
- 2717 Stokes, C.R., Corner, G.D., Winsborrow, M.C.M., Husum, K., Andreassen, K., 2014. Asynchronous  
 2718 response of marine-terminating outlet glaciers during deglaciation of the Fennoscandian Ice  
 2719 Sheet. *Geology* 42, 455–458.
- 2720 Stokes, C.R., Tarasov, L., Blomdin, R., Cronin, T.M., Fisher, T.G., Gyllencreutz, R., Hättestrand, C.,  
 2721 Heyman, J., Hindmarsh, R.C.A., Hughes, A.L.C., Jakobsson, M., Kirchner, N., Livingstone,  
 2722 S.J., Margold, M., Murton, J.B., Noormets, R., Peltier, W.R., Peteet, D.M., Piper, D.J.W.,  
 2723 Preusser, F., Renssen, H., Roberts, D.H., Roche, D.M., Saint-Ange, F., Stroeven, A.P., Teller,  
 2724 J.T., 2015. On the reconstruction of palaeo-ice sheets: Recent advances and future challenges.  
 2725 *Quat. Sci. Rev.* 125, 15–49.
- 2726 Stokes, C.R., Margold, M., Creyts, T.T., 2016a. Ribbed bedforms on palaeo-ice stream beds resemble  
 2727 regular patterns of basal shear stress ('traction ribs') inferred from modern ice streams. *J.*  
 2728 *Glaciol.* 62, 696–713.
- 2729 Stokes, C.R., Margold, M., Clark, C.D., Tarasov, L., 2016b. Ice stream activity scaled to ice sheet  
 2730 volume during Laurentide Ice Sheet deglaciation. *Nature* 530(7590), 322–326.
- 2731 Storrar, R.D., Livingstone, S.J., 2017. Glacial geomorphology of the northern Kivalliq region,  
 2732 Nunavut, Canada, with an emphasis on meltwater drainage systems. *J. Maps* 13, 153–164.
- 2733 Storrar, R., Stokes, C.R., 2007. A Glacial geomorphological map of Victoria Island, Canadian Arctic.  
 2734 *J. Maps* 3, 191–210.
- 2735 Storrar, R.D., Stokes, C.R., Evans, D.J.A., 2013. A map of large Canadian eskers from Landsat  
 2736 satellite imagery. *J. Maps* 9, 456–473.
- 2737 Storrar, R.D., Stokes, C.R., Evans, D.J.A., 2014. Morphometry and pattern of a large sample  
 2738 (>20,000) of Canadian eskers and implications for subglacial drainage beneath ice sheets.  
 2739 *Quat. Sci. Rev.* 105, 1–25.
- 2740 Storrar, R.D., Jones, A., Evans, D.J.A., 2017. Small-scale topographically-controlled glacier flow  
 2741 switching in an expanding proglacial lake at Breiðamerkurjökull, SE Iceland. *J. Glaciol.*  
 2742 63(240), 745–750.
- 2743 Streuff, K., Forwick, M., Szczuciński, W., Andreassen, K., Ó Cofaigh, C., 2015. Submarine landform  
 2744 assemblages and sedimentary processes related to glacier surging in Kongsfjorden, Svalbard.  
 2745 *arktos* 1(1), 14.
- 2746 Stroeven, A.P., Fabel, D., Harbor, J., Hättestrand, C., Kleman, J., 2002a. Quantifying the erosional  
 2747 impact of the Fennoscandian ice sheet in the Torneträsk-Narvik corridor, northern Sweden,  
 2748 based on cosmogenic radionuclide data. *Geogr. Ann.* 84A, 275–287.
- 2749 Stroeven, A.P., Fabel, D., Hättestrand, C., Harbor, J., 2002b. A relict landscape in the centre of  
 2750 Fennoscandian glaciation: Cosmogenic radionuclide evidence of tors preserved through  
 2751 multiple glacial cycles. *Geomorphology* 44, 145–154.

- 2752 Stroeven, A.P., Harbor, J., Fabel, D., Kleman, J., Hättestrand, C., Elmore, D., Fink, D., Fredin, O.,  
2753 2006. Slow, patchy landscape evolution in northern Sweden despite repeated ice-sheet  
2754 glaciation. *GSA Special Paper* 398, 387–396.
- 2755 Stroeven, A.P., Fabel, D., Harbor, J.M., Fink, D., Caffee, M.W., Dahlgren, T., 2011. Importance of  
2756 sampling across an assemblage of glacial landforms for interpreting cosmogenic ages of  
2757 deglaciation. *Quat. Res.* 76, 148–156.
- 2758 Stroeven, A.P., Hättestrand, C., Heyman, J., Kleman, J., Morén, B.M., 2013. Glacial geomorphology  
2759 of the Tian Shan. *J. Maps* 9(4), 505–512.
- 2760 Stroeven, A.P., Fabel, D., Margold, M., Clague, J.J., Xu, S., 2014. Investigating absolute chronologies  
2761 of glacial advances in the NW sector of the Cordilleran Ice Sheet with terrestrial in situ  
2762 cosmogenic nuclides. *Quat. Sci. Rev.* 92, 429–443.
- 2763 Stroeven, A.P., Hättestrand, C., Kleman, J., Heyman, J., Fabel, D., Fredin, O., Goodfellow, B.W.,  
2764 Harbor, J.M., Jansen, J.D., Olsen, L., Caffee, M.W., Fink, D., Lundqvist, J., Rosqvist, G.C.,  
2765 Strömberg, B., Jansson, K.N., 2016. Deglaciation of Fennoscandia. *Quat. Sci. Rev.* 147, 91–  
2766 121.
- 2767 Sugden, D.E., 1970. Landforms of Deglaciation in the Cairngorm Mountains, Scotland. *Trans. Inst.*  
2768 *Br. Geogr.* 51, 201–219.
- 2769 Sugden, D.E., 1978. Glacial erosion by the Laurentide Ice Sheet. *J. Glaciol.* 20, 367–391.
- 2770 Sugden, D.E., John, B.S., 1976. *Glaciers and Landscape*. Arnold, London, 376 pp.
- 2771 Thorp, P.W., 1986. A mountain icefield of Loch Lomond Stadial age, western Grampians, Scotland.  
2772 *Boreas* 15, 83–97.
- 2773 Tonkin, T.N., Midgley, N.G., Cook, S.J., Graham, D.J., 2016. Ice-cored moraine degradation mapped  
2774 and quantified using an unmanned aerial vehicle: A case study from a polythermal glacier in  
2775 Svalbard. *Geomorphology* 258, 1–10.
- 2776 Trommelen, M.S., Ross, M., 2010. Subglacial landforms in northern Manitoba, Canada, based on  
2777 remote sensing data. *J. Maps* 2010, 618–638.
- 2778 Trommelen, M.S., Ross, M., 2014. Distribution and type of sticky spots at the centre of a deglacial  
2779 streamlined lobe in northeastern Manitoba, Canada. *Boreas* 43, 557–576.
- 2780 Trotter, F.M., 1929. The glaciation of the eastern Edenside, the Alston Block and the Carlisle Plain.  
2781 *Quart. J. Geol. Soc. Lond.* 88, 549–607.
- 2782 Turner, A.J., Woodward, J., Stokes, C.R., Ó Cofaigh, C., Dunning, S., 2014a. Glacial geomorphology  
2783 of the Great Glen Region of Scotland. *J. Maps* 10, 159–178.
- 2784 Turner, D., Lucieer, A., Wallace, L., 2014b. Direct georeferencing of ultrahigh-resolution UAV  
2785 imagery. *IEEE Trans. Geosci. Remote Sens.* 52(5), 2738–2745.
- 2786 van der Bilt, W.G.M., Bakke, J., Balascio, N.L., 2016. Mapping sediment–landform assemblages to  
2787 constrain lacustrine sedimentation in a glacier-fed lake catchment in northwest Spitsbergen. *J.*  
2788 *Maps* 12(5), 985–993.
- 2789 Van Dorsser, J.J., Salomé, A.I., 1973. Different methods of detailed geomorphological mapping.  
2790 *K.N.A.G. Geografisch Tijdschrift* VII: 71–74.
- 2791 Walker, D.A., Auerbach, N.A., Shippert, M.M., 1995. NDVI, biomass, and landscape evolution of  
2792 glaciated terrain in northern Alaska. *Polar Record*, 31(177), 169–178.
- 2793 Welch, R., 1966. A comparison of aerial films in the study of the Breiðamerkur glacier area, Iceland,  
2794 *The Photogramm. Rec.* 5, 289–306.
- 2795 Welch, R., 1967. *The Application of Aerial Photography to the Study of a Glacial Area.*  
2796 Breiðamerkur, Iceland, Unpublished PhD thesis, University of Glasgow.
- 2797 Welch, R., 1968. Color aerial photography applied to the study of a glacial area. In: Smith, J.T. (Ed.),  
2798 *Manual of Color Aerial Photography.* American Society of Photogrammetry and Remote  
2799 Sensing, Falls Church, VA, pp. 400–401.
- 2800 Westoby, M.J., Brasington, J., Glasser, N.F., Hambrey, M.J., Reynolds, J.M., 2012. ‘Structure-from-  
2801 Motion’ photogrammetry: A low-cost, effective tool for geoscience applications.  
2802 *Geomorphology* 179, 300–314.
- 2803 Westoby, M.J., Glasser, N.F., Hambrey, M.J., Brasington, J., Reynolds, J.M., Hassan, M.A., 2014.  
2804 Reconstructing historic Glacial Lake Outburst Floods through numerical modelling and  
2805 geomorphological assessment: Extreme events in the Himalaya. *Earth Surf. Process. Land.*  
2806 39(12), 1675–1692.

2807 Westoby, M.J., Dunning, S.A., Woodward, J., Hein, A.S., Marrero, S.M., Winter, K., Sugden, D.E.,  
2808 2016. Interannual surface evolution of an Antarctic blue-ice moraine using multi-temporal  
2809 DEMs. *Earth Surf. Dyn.* 4, 515–529.

2810 Wilson, S.B., 2005. Morphological analysis and mapping of Loch Lomond Stadial moraines using  
2811 digital photogrammetry and geographical information systems. Unpublished PhD thesis,  
2812 University of Glasgow, 360 pp.

2813 Winkler, S., 2018. Investigating Holocene mountain glaciations: a plea for the supremacy of glacial  
2814 geomorphology when reconstructing glacier chronologies. *Erdkunde*, in press.

2815 Winsborrow, M.C.M., Andreassen, K., Corner, G.D., Laberg, J.S., 2010. Deglaciation of a marine-  
2816 based ice sheet: Late Weichselian palaeo-ice dynamics and retreat in the southern Barents Sea  
2817 reconstructed from onshore and offshore glacial geomorphology. *Quat. Sci. Rev.* 29(3–4),  
2818 424–442.

2819 Winsborrow, M.C.M., Stokes, C.R., Andreassen, K., 2012. Ice stream flow switching during  
2820 deglaciation of the southwestern Barents Sea. *Geol. Soc. Am. Bull.* 124(3–4), 275–290.

2821 Wolf, P.R., DeWitt, B.A., Wilkinson, B.E., 2013. *Elements of Photogrammetry with Application in*  
2822 *GIS*, Fourth Edition. McGraw-Hill Education.

2823 Wright, W.B., 1912. The drumlin topography of south Donegal. *Geol. Mag.* 9, 153–159.

2824 Wyshnytzky, C.E., 2017. On the mechanisms of minor moraine formation in high-mountain  
2825 environments of the European Alps. Unpublished PhD thesis, Queen Mary University of  
2826 London, 329 pp.

2827 Yu, P., Eyles, N., Sookhan, S., 2015. Automated drumlin shape and volume estimation using high  
2828 resolution LiDAR imagery (Curvature Based Relief Separation): A test from the Wadena  
2829 Drumlin Field, Minnesota. *Geomorphology* 246, 589–601.

2830 Zasadni, J., Kłapyta, P., 2016. From valley to marginal glaciation in alpine-type relief: Lateglacial  
2831 glacier advances in the Pięć Stawów Polskich/Roztoka Valley, High Tatra Mountains, Poland.  
2832 *Geomorphology* 253, 406–424.

2833 Zech, R., Abramowski, U., Glaser, B., Sosin, P., Kubik, P.W. and Zech, W., 2005. Late Quaternary  
2834 glacial and climate history of the Pamir Mountains derived from cosmogenic <sup>10</sup>Be exposure  
2835 ages. *Quat. Res.* 64(2), 212–220.

2836 Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S.U., Hoelzle, M., Paul, F., Haeberli, W.,  
2837 Denzinger, F., Ahlstrøm, A.P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L.N.,  
2838 Cáceres, B.E., Casassa, G., Cobos, G., Dávila, L.R., Delgado Granados, H., Demuth, M.N.,  
2839 Espizua, L., Fischer, A., Fujita, K., Gadek, B., Ghazanfar, A., Hagen, J.O., Holmlund, P.,  
2840 Karimi, N., Li, Z., Pelto, M., Pitte, P., Popovnin, V.V., Portocarrero, C.A., Prinz, R.,  
2841 Sangewar, C.V., Severskiy, I., Sigurðsson, O., Soruco, A., Usubaliev, R., Vincent, C., 2015.  
2842 Historically unprecedented global glacier decline in the early 21st century. *J. Glaciology* 61,  
2843 745–762.

2844

2845

2846

2847

2848

2849

2850

2851

2852

2853

2854

2855

2856 **Figure captions**

2857

2858 **Figure 1.** Vectorised versions of two geomorphological maps drawn in the field for (A) Coire  
2859 Easgainn and (B) Glen Odhar in the Monadhliath, Central Scottish Highlands. These field maps were  
2860 used in the production of a 1:57,500 geomorphological map for the entire region (Boston, 2012a, b).

2861

2862 **Figure 2.** The aerial photograph overlay-mapping process using an example from the mountain Arkle,  
2863 NW Scotland. (A) aerial photograph at an average scale of ~1:25,000 (extract from photo 38 88 087;  
2864 ©RCAHMS 1988); (B) scan of original overlay mapped through a stereoscope from (A) (see Section  
2865 2.2.2 for method description), focusing on moraines, fluted moraines and the approximate upper limit  
2866 of scree slopes as seen from the aerial photograph; (C) compiled, rectified geomorphological map,  
2867 incorporating moraines and fluted moraines from (B) and additional data from field mapping, such as  
2868 the exact upper limits of scree slopes, orientation of striae, solifluction lobes and mountaintop detritus.  
2869 For description and interpretation of the geomorphology, see Lukas (2006).

2870

2871 **Figure 3.** Example of geomorphological mapping produced through on-screen vectorisation (tracing)  
2872 in GIS software. Satellite image (A) and geomorphological mapping (B) showing suites of moraines  
2873 formed by the Lago General Carrera–Buenos Aires ice lobe of the former Patagonian Ice Sheet,  
2874 located to the east of the present-day Northern Patagonian Icefield. A combination of remotely-sensed  
2875 datasets and field mapping were used to circumvent issues of localised cloud cover, as visible in (A).  
2876 Where areas were obscured, SPOT-5 and DigitalGlobe images available in *Google Earth* were used.  
2877 The geomorphological map extract is taken from Bendle et al. (2017a).

2878

2879 **Figure 4.** Comparison of WorldView-2 satellite imagery (June 2012, European Space Imaging) with  
2880 digital colour aerial photographs (2006, Loftmyndir ehf) for the Skálafellsjökull foreland, SE Iceland.  
2881 (A) Panchromatic satellite image (0.5 m ground sampled distance, GSD). (B) Multispectral satellite  
2882 image (2.0 m GSD). (C) Pansharpened three-band natural colour satellite image (0.5 m GSD). (D)  
2883 Digital colour aerial photographs (0.41 m GSD). The satellite imagery is of sufficient resolution to  
2884 allow mapping of small-scale (<2 m in height) annual moraines (see Chandler et al., 2016a, b).

2885

2886 **Figure 5.** Geomorphological map of the Finsterwalderbreen foreland, Svalbard, produced digitally in  
2887 GIS software through mapping from a digital aerial photograph (captured in 2004). Field mapping  
2888 was also conducted and incorporated in the final map. Aerial photograph provided by the NERC Earth  
2889 Observation Data Centre. Modified from Lovell et al. (2018).

2890

2891 **Figure 6.** Views at various points along the length of the 1890 surge end moraine at Eyjabakkajökull,  
2892 Iceland, visualised in *ESRI ArcScene* (Benediktsson et al., 2010). Aerial orthophotographs from 2008  
2893 are draped over a 3 m grid DEM with 1.5x vertical exaggeration.

2894

2895 **Figure 7.** High-resolution geomorphological mapping of part of the Fláajökull foreland, Iceland,  
2896 based on UAV-derived imagery (Evans et al., 2016a). A 1:350 scale version of this map is freely  
2897 available for download from *Journal of Maps*: <http://dx.doi.org/10.1080/17445647.2015.1073185>.

2898

2899 **Figure 8.** Example of geomorphological mapping conducted from hillshaded relief models (modified  
2900 from Norris et al., 2017). (A) Densely spaced drumlins and (B) highly elongated flutings in northwest  
2901 Saskatchewan, Canada, visualised in hillshaded relief models generated from SRTM DEM data.  
2902 Geomorphological map extracts in (C) and (D) show lineations (black lines), eskers (red lines) and  
2903 meltwater channels (dashed blue lines).

2904

2905 **Figure 9.** Examples of landforms in relief-shaded DEMs. Red indicates higher elevations and blue  
2906 lower elevations. (A) Lineations in N Canada shown in 16 m resolution CDED data. (B) De Geer  
2907 moraines in SW Finland shown in 2 m resolution LiDAR data. (C) Lineations of the Dubawnt Lake  
2908 Ice Stream shown in 5 m resolution ArcticDEM mosaic data. (D) Esker-fed ice-contact outwash fan in  
2909 SW Finland shown in 2 m resolution LiDAR data. See Table 2 for DEM data sources.

2910

2911 **Figure 10.** Conceptual diagrams illustrating the distinction between ground sampled distance (B and  
2912 E) and pixel size (C and F). The ground distances between two measurements by the detector (i.e. the  
2913 ground sampled distances) are 30 m and 50 m in (B) and (E), respectively. These ground sample  
2914 distances are then assigned to pixels in the resulting 30 x 30 m (C) and 50 x 50 m (F) digital images.  
2915 Note, resultant images may fail to accurately represent the shape of the objects (upper row) or even  
2916 may fail to reproduce them (lower row), even where the size of the object is the same or larger than  
2917 the sampling distance.

2918

2919 **Figure 11.** Geometric artefacts that may be present in space- and air-borne radar captured imagery,  
2920 resulting from the effects of relief. (A) **Foreshortening**, occurring where the slope of the local terrain  
2921 is less than the incidence angle ( $\gamma$ ). The facing slope,  $a - b$ , becomes compressed to  $a_l - b_l$  in the  
2922 resulting image. (B) **Layover**, occurring in steep terrain when the slope angle is greater than the  
2923 incidence angle. As a mountain-top,  $b$ , is closer to the sensor than the base,  $a$ , this causes layover in  
2924 the imagery (an incorrect positioning of  $b_l$  relative to  $a_l$ ). (C) **Radar shadow** in areas of rugged  
2925 terrain as the illumination is from an oblique source. No data is recorded for the region  $b_l - d_l$ . (D) In  
2926 regions of varying topography, a **combination of artefacts** may be present: points  $b$  and  $c$  will be  
2927 impacted by layover and will be positioned incorrectly relative to  $a$ ; no data will be recorded for the

2928 region between *c* and *d* due to radar shadow; foreshortening occurs at slope facet *d* – *e*; further radar  
2929 shadow occurs at *e* – *f*; and foreshortening at *f* and *g*. After Clark (1997).

2930

2931 **Figure 12.** Extracts from hillshaded relief models of Ben More Coigach, NW Scottish Highlands,  
2932 showing the effect of geometric artefacts on the models. The hillshades were generated with azimuths  
2933 of 45° (A) and 315° (B). Stretching of upland terrain during processing of the DEM data results in  
2934 blurred regions on the hillshaded relief models. NEXTMap DSM from Intermap Technologies Inc.  
2935 provided by NERC via the NERC Earth Observation Data Centre.

2936

2937 **Figure 13.** Example mapping of subglacial bedforms from the Strait of Magellan, Patagonia (A–C),  
2938 and the Dubawnt Lake Ice Stream (D–F). The bedforms are mapped as polylines along landform  
2939 crests in (B) and (E), and they are mapped as polygons delineating lower-break-of-slope in (C) and  
2940 (F). The Dubawnt Lake Ice Stream polylines (Stokes and Clark, 2003) and polygons (Dunstone, 2014)  
2941 were mapped by different mappers at different times, which may account for small inconsistencies.  
2942 For further details on the bedform examples from the Strait of Magellan, see Lovell et al. (2011) and  
2943 Darvill et al. (2014).

2944

2945 **Figure 14.** Geomorphological mapping of Coire Easgainn, Monadhliath, Scotland, using a  
2946 combination of NEXTMap DSMs, analogue aerial photographs and field mapping. Modified from  
2947 Boston (2012a, b).

2948

2949 **Figure 15.** Examples of landforms in icefield and valley glacier settings mapped on medium to coarse  
2950 resolution imagery. Landforms observed in the Chagan Uzun Valley, Russian Altai, displayed on (A)  
2951 SPOT image and (B) Landsat 7 ETM+ image. (C) Associated geomorphological map extract from  
2952 Gribenski et al. (2016). Moraines in the Anadyr Lowlands, Far NE Russia, displayed on (D) semi-  
2953 transparent shaded ViewFinder Panorama (VFP) DEM data (NE solar azimuth) draped over the raw  
2954 VFP DEM. (E) Associated mapping of moraines (black polygons) from Barr and Clark (2012).

2955

2956 **Figure 16.** Geomorphological mapping (A) from the Múlajökull foreland, Iceland, completed as part  
2957 of a process-oriented study examining the internal architecture and structural evolution of a Little Ice  
2958 Age terminal moraine at this surge-type glacier (Benediktsson et al., 2015). The mapping was  
2959 combined with sedimentological investigations (B) to produce a process-form model of moraine  
2960 formation and evolution (C).

2961

2962 **Figure 17.** Geomorphological mapping of the foreland of Skálafellsjökull, an active temperate outlet  
2963 of Vatnajökull, SE Iceland. (A) Digital aerial photographs (2006; 0.41 m GSD; *Loftmyndir ehf*), pan-  
2964 sharpened WorldView-2 multi-spectral satellite imagery (2012; 0.5 m GSD; *European Space*

2965 *Imaging*), a UAV-derived DEM (2013; 0.09 m GSD) and field mapping were employed to produce  
2966 the mapping extract (B). A compromise on the level of detail was made, with annual moraines  
2967 mapped along crestlines due to image resolution and map readability. This mapping detail was  
2968 sufficient for calculating crest-to-crest moraine spacing (ice-margin retreat rates) shown in (C), which  
2969 was the principal purpose of the study. Modified from Chandler et al. (2016a, b).

2970

2971 **Figure 18.** Idealised workflow for mapping palaeo-ice sheet geomorphology. Some pathways in the  
2972 workflow are optional (grey dashed lines) depending on data availability and the feasibility and  
2973 applicability of particular methods. Note, where analogue (hard-copy) aerial photographs are used for  
2974 mapping, processing of acetate overlays would be undertaken after mapping from the aerial  
2975 photographs. Further details on image processing are shown on the processing workflow available as  
2976 Supplementary Material.

2977

2978 **Figure 19.** Idealised workflow for mapping alpine- and plateau-style ice mass geomorphology. In this  
2979 scenario, digital remotely-sensed datasets are used and this necessitates image processing before  
2980 mapping is undertaken. Ideally, GNSS surveys would be conducted in order to process digital aerial  
2981 photographs, as depicted in the workflow. Some pathways are optional (grey dashed lines) depending  
2982 on data availability and the feasibility and applicability of particular methods. Although  
2983 sedimentology is shown as ‘optional’, it is highly desirable to undertake sedimentological  
2984 investigations, wherever possible. Alternative image processing solutions are available and readers  
2985 should consult with the detailed processing workflow which is available as Supplementary Material.

2986

2987 **Figure 20.** Idealised workflow for mapping alpine- and plateau-style ice mass geomorphology. In this  
2988 scenario, analogue (hard-copy) aerial photographs are used and this necessitates image processing  
2989 after mapping is undertaken. Some pathways are optional (grey dashed lines) depending on data  
2990 availability and the feasibility and applicability of particular methods. Although sedimentology is  
2991 shown as ‘optional’, it is highly desirable to undertake sedimentological investigations, wherever  
2992 possible. Alternative image processing solutions are available and readers should consult with the  
2993 detailed processing workflow which is available as Supplementary Material.

2994



2995 **Table 1.** Satellite imagery types that have been used in glacial geomorphological mapping and example applications. The satellites are broadly ordered in  
 2996 terms of spatial resolution the captured imagery. Note, we also anticipate imagery from the Planet (RapidEye, PlanetScope and SkySat) and Sentinel  
 2997 constellations being widely used in future.

Satellite	Sensor	Temporal coverage	Spectral bands	Spatial resolution (m)	Source	Example studies
Landsat 1–5	MSS	1972–2013	4	80	USGS Earth Explorer ( <a href="http://earthexplorer.usgs.gov">earthexplorer.usgs.gov</a> )	Clark and Stokes (2001); Stokes and Clark (2002, 2003); Jansson et al. (2003); see also Clark (1997, Table 1)
Landsat 4–5	TM	1982–2013	1 6	120 30	Global Land Cover Facility ( <a href="http://landcover.org">landcover.org</a> )	Punkari (1995); Alexanderson et al. (2002); De Angelis (2007); Storrar et al. (2013); Orkhonselenge (2016)
Landsat 7	ETM+	1999–	1 6 1	60 30 15		Kassab et al (2013); Stroeven et al. (2013); Darvill et al. (2014); Blomdin et al. (2016a); Ely et al. (2016b); Ercolano et al. (2016); Lindholm and Heyman (2016); Storrar and Livingstone (2017); see also Clark (1997, Table 1)
Landsat 8	OLI/TIRS	2013–	2 8 1	100 30 15		Espinoza (2016); Carrivick et al. (2017); Storrar and Livingstone (2017)
Terra	ASTER	2000–	5 6 5	90 20 15	LP DAAC ( <a href="http://LPDAAC.usgs.gov">LPDAAC.usgs.gov</a> )	Glasser and Jansson (2005, 2008); Glasser et al. (2005); Lovell et al. (2011); Sagredo et al. (2011); Darvill et al (2014); Ercolano et al. (2016)
ERS 1	SAR	1991–2000	1	30	European Space Agency ( <a href="http://earth.esa.int">earth.esa.int</a> )	Clark et al. (2000); Clark and Stokes (2001); Heiser and Roush (2001); see also Clark (1997, Table 1)
SPOT 1–3	HRV	1986–	3	20	Airbus Defence and Space	Smith et al. (2000); Coronato et al. (2009)

			1	20		
			1	10		
SPOT 4	HRVIR	1998– 2013	1 3	10 20		Trommelen and Ross (2010, 2014); Ercolano et al. (2016) [viewed in Google Earth™]; McHenry and Dunlop (2016); Principato et al. (2016)
			1	20		
SPOT 5	HRG/HRS	2002– 2015	1 3	2.5, 5 10		Trommelen and Ross (2010, 2014); Ercolano et al. (2016) [viewed in Google Earth™]; McHenry and Dunlop (2016); Principato et al. (2016); Bendle et al. (2017a)
			1	20		
SPOT 6–7	NAOMI	2012–	1 4	1.5 6		Gribenski et al. (2016)
CORONA/ARGON/LANYARD	KH1–KH6	1959– 1972	1	1.8–140	USGS Earth Explorer ( <a href="http://earthexplorer.usgs.gov">earthexplorer.usgs.gov</a> )	Alexanderson et al (2002); Zech et al. (2005); Lifton et al (2014)
IKONOS	HRG	1999– 2015	1 4	1 4	DigitalGlobe ( <a href="http://digitalglobe.com">digitalglobe.com</a> )	Juyal et al. (2011); Kłapyta (2013); Zasadni and Kłapyta (2016)
COSMO-Skymed	SAR	2008–	1/3/15/16/20	1	e-GEOS ( <a href="http://e-geos.it">e-geos.it</a> )	da Rosa et al. (2013a)
Quickbird	HRG	2001– 2014	1 4	0.61 2.44	DigitalGlobe ( <a href="http://digitalglobe.com">digitalglobe.com</a> )	da Rosa et al. (2011, 2013b); May et al (2011); Lovell et al. (2011)
GeoEye-1		2008–	1 4	0.46 1.84		Westoby et al. (2014)
WorldView-2		2009–	1 8	0.46 1.84	European Space Imaging ( <a href="http://europeanspaceimaging.com">europeanspaceimaging.com</a> )	Jamieson et al. (2015); Chandler et al. (2016a); Evans et al. (2016e); Ewertowski et al (2016)
Google Earth™ (specific image details not given)	n/a	n/a	n/a	n/a	Google Earth	Margold and Jansson (2011); Margold et al. (2011); Kassab et al (2013); Stroeven et al. (2013); Darvill et al (2014); Blomdin et al. (2016a); Evans et al. (2016d); Li et al (2016); Lindholm and Heyman (2016); Orkhonselenge (2016)

**Table 2.** Examples of DEM datasets with national- to international-coverage that have been employed in glacial geomorphological map production.

Dataset	Coverage	Spatial resolution (m)	RMSE or CE90 (m)		Data source(s)	Example studies
			Vertical	Horizontal		
SRTM <sup>1</sup>	Global	~90 (3 arc-second) ~30 (1 arc-second)	~5–13	-	Global Land Cover Facility ( <a href="http://landcover.org">landcover.org</a> ) USGS Earth Resources and Science Center ( <a href="http://eros.usgs.gov">eros.usgs.gov</a> )	Glasser and Jansson (2008); Barr and Clark (2009); Ó Cofaigh et al. (2010); Morén et al. (2011); Stroeve et al. (2013); Darvill et al. (2014); Evans et al. (2014, 2016d); Trommelen and Ross (2014); Stokes et al. (2016a); Ely et al. (2016b); Lindholm and Heyman (2016)
ASTER GDEM (V2)	Global	~30 (1 arc-second)	~8.7	-	LP DAAC Global Data Explorer ( <a href="http://gdex.cr.usgs.gov/gdex">gdex.cr.usgs.gov/gdex</a> ) NASA Reverb ( <a href="http://reverb.echo.nasa.gov/reverb">reverb.echo.nasa.gov/reverb</a> )	Barr and Clark (2012); Blomdin et al. (2016a, b); Lindholm and Heyman (2016)
Canadian Digital Elevation Dataset (CDED)	Canada	~20 (0.75 arc-second)	-	-	Natural Resources Canada ( <a href="http://geogratis.gc.ca">geogratis.gc.ca</a> )	Margold et al. (2011, 2015a); Evans et al. (2016c); Storrar and Livingstone (2017)
USGS National Elevation Dataset (NED) <sup>2</sup>	US	~30 (1 arc-second) ~10 (1/3 arc-second)	~2.4	-	US Geological Survey ( <a href="http://ned.usgs.gov">ned.usgs.gov</a> )	Hess and Briner (2009); Margold et al. (2015a); Ely et al. (2016a)
TanDEM-X	Global	~12 (0.4 arc-second)	<10	<10	German Aerospace Center (DLR) ( <a href="http://tandemx-science.dlr.de">tandemx-science.dlr.de</a> )	Pipaud et al. (2015)
NEXMap Britain <sup>TM</sup>	UK	5	~1	2.5	NERC Earth Observation Data Centre <sup>3</sup> ( <a href="http://ceda.ac.uk">ceda.ac.uk</a> )	Livingstone et al. (2008); Finlayson et al. (2010, 2011); Hughes et al. (2010); Brown et al. (2011a); Boston (2012a, b); Pearce et al. (2014); Turner et al. (2014a)
ArcticDEM	Arctic	2	2.0	3.8	Polar Geospatial Center ( <a href="http://pgc.umn.edu/data/arcticdem">pgc.umn.edu/data/arcticdem</a> )	Levy et al. (2017)
Maanmittauslaitos LiDAR DEM	Finland	2	~0.3	-	National Land Survey of Finland ( <a href="http://maanmittauslaitos.fi">maanmittauslaitos.fi</a> )	Ojala et al. (2015); Ojala (2016); Mäkinen et al. (2017)
Ny Nationell Höjdmodell	Sweden	2	~0.1	-	Lantmäteriet ( <a href="http://lantmateriet.se">lantmateriet.se</a> )	Dowling et al. (2015, 2016); Greenwood et al. (2015); Möller and Dowling (2016); Peterson et al. (2017)
Environment Agency LiDAR DEM	UK (partial)	2, 1, 0.5 and 0.25	0.05 – 0.15	0.4	DEFRA Environment Data ( <a href="http://environment.data.gov.uk">environment.data.gov.uk</a> )	Miller et al. (2014)
Iceland Met Office and Institute of Earth Sciences, University of Iceland, LiDAR DEM <sup>4</sup>	Iceland (partial)	<5	<0.5	-	Iceland Meteorological Office ( <a href="http://en.vedur.is">en.vedur.is</a> )	Brynjólfsson et al. (2014, 2016); Benediktsson et al. (2016); Jónsson et al. (2016)

<sup>1</sup> SRTM data was only freely available with a spatial resolution of ~90 m (3 arc-seconds) outside of the United States until late 2015 when the highest resolution data were thereafter made available globally (see <http://www2.jpl.nasa.gov/srtm/>)

<sup>2</sup> The USGS NED dataset has been superseded by the 3D Elevation Program (3DEP), with this data available as seamless 1/3 arc-second, 1 arc-second and 2 arc-second DEMs (see [https://nationalmap.gov/3DEP/3dep\\_prodserv.html](https://nationalmap.gov/3DEP/3dep_prodserv.html))

<sup>3</sup> NEXTMap Britain™ data is freely available to NERC staff and NERC-funded researchers, though subsets can be applied for by non-NERC-funded researchers under a Demonstrator User License Agreement (DULA)

<sup>4</sup> The Icelandic LiDAR DEM data are available at 5 m resolution, but it is possible to derive higher-resolution DEMs (e.g. 2 m) from the point clouds using denser interpolation.

**Table 3.** Summary of the glacial settings where the main geomorphological mapping methods and remotely-sensed data types are *most* appropriate. ✓ = the method/dataset is appropriate and should be used (where the dataset is available). ● = the method is applicable in certain cases, depending on factors such as the resolution of the *specific* dataset, the size of the study area and landforms, and the accessibility of the study area.

Glacial setting	DEMs	Coarse satellite imagery	LiDAR DEMs	High-resolution satellite imagery	Aerial photographs	UAV imagery	Field mapping
Ice sheets	✓	✓	✓				
Ice sheet sectors/lobes	✓	✓	✓	●	●		●
Ice-caps	●	●	●	✓	✓		✓
Icefields			●	✓	✓		✓
Valley (outlet) glaciers			●	✓	✓	●	✓
Cirque glaciers			●	✓	✓	●	✓
Modern glacier forelands			●	✓	✓	✓	✓