

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

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63 **Keywords:** glacial geomorphology; geomorphological mapping; GIS; remote sensing; field mapping
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76 **1. Introduction**

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78 *1.1 Background and importance*

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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).

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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 20th 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: Stroeven 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 19th Century and early 20th 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 (≤ 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 km². 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 ± 20 m and a vertical accuracy of ± 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 km²), 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

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1636

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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 (γ). 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 (earthexplorer.usgs.gov)	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 (landcover.org)	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 (LPDAAC.usgs.gov)	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 (earth.esa.int)	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 (earthexplorer.usgs.gov)	Alexanderson et al (2002); Zech et al. (2005); Lifton et al (2014)
IKONOS	HRG	1999–2015	1 4	1 4	DigitalGlobe (digitalglobe.com)	Juyal et al. (2011); Kłapyta (2013); Zasadni and Kłapyta (2016)
COSMO-Skymed	SAR	2008–	1/3/15/16/20	1	e-GEOS (e-geos.it)	da Rosa et al. (2013a)
Quickbird	HRG	2001–2014	1 4	0.61 2.44	DigitalGlobe (digitalglobe.com)	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 (europeanspaceimaging.com)	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 ¹	Global	~90 (3 arc-second) ~30 (1 arc-second)	~5–13	-	Global Land Cover Facility (landcover.org) USGS Earth Resources and Science Center (eros.usgs.gov)	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 (gdex.cr.usgs.gov/gdex) NASA Reverb (reverb.echo.nasa.gov/reverb)	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 (geogratis.gc.ca)	Margold et al. (2011, 2015a); Evans et al. (2016c); Storrar and Livingstone (2017)
USGS National Elevation Dataset (NED) ²	US	~30 (1 arc-second) ~10 (1/3 arc-second)	~2.4	-	US Geological Survey (ned.usgs.gov)	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) (tandemx-science.dlr.de)	Pipaud et al. (2015)
NEXMap Britain TM	UK	5	~1	2.5	NERC Earth Observation Data Centre ³ (ceda.ac.uk)	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 (pgc.umn.edu/data/arcticdem)	Levy et al. (2017)
Maanmittauslaitos LiDAR DEM	Finland	2	~0.3	-	National Land Survey of Finland (maanmittauslaitos.fi)	Ojala et al. (2015); Ojala (2016); Mäkinen et al. (2017)
Ny Nationell Höjdmodell	Sweden	2	~0.1	-	Lantmäteriet (lantmateriet.se)	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 (environment.data.gov.uk)	Miller et al. (2014)
Iceland Met Office and Institute of Earth Sciences, University of Iceland, LiDAR DEM ⁴	Iceland (partial)	<5	<0.5	-	Iceland Meteorological Office (en.vedur.is)	Brynjólfsson et al. (2014, 2016); Benediktsson et al. (2016); Jónsson et al. (2016)

¹ 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/>)

² 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)

³ 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)

⁴ 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			●	✓	✓	✓	✓