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

3
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27
28 **Abstract**

29
30 Geomorphological mapping is a well-established method for examining earth surface processes
31 and landscape evolution in a range of environmental contexts. In glacial research, it provides
32 crucial data for a wide range of process-oriented and palaeoglaciological reconstruction studies;
33 in the latter case providing an essential geomorphological framework for establishing glacial
34 chronologies. In recent decades, there have been significant developments in remote sensing
35 and Geographical Information Systems (GIS), with a plethora of high-quality remotely-sensed
36 datasets now (often freely) available. Most recently, the emergence of unmanned aerial vehicle
37 (UAV) technology has allowed sub-decimetres scale aerial images and Digital Elevation Models
38 (DEMs) to be obtained. Traditional field mapping methods still have an important role in

39 glacial geomorphology, particularly in cirque glacier, valley glacier and icefield/ice-cap outlet
40 settings. Field mapping is also used in ice sheet settings, but often takes the form of necessarily
41 highly-selective ground-truthing of remote mapping. Given the increasing abundance of
42 datasets and methods available for mapping, effective approaches are necessary to enable
43 assimilation of data and ensure robustness. In this contribution, we provide a review and
44 assessment of the various glacial geomorphological methods and datasets currently available,
45 with a focus on their applicability in particular glacial settings. We distinguish two overarching
46 ‘work streams’ that recognise the different approaches typically used in mapping landforms
47 produced by ice masses of different sizes: (i) mapping of ice sheet geomorphological imprints
48 using a combined remote sensing approach, with some field checking (where feasible); and (ii)
49 mapping of alpine and plateau-style ice mass (cirque glacier, valley glacier, icefield and ice-
50 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/-method approaches
54 used in many Earth Science disciplines. Based on our review, we provide idealised frameworks
55 and 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 be collected as part of a coupled
61 inductive-deductive approach.

62
63 **Keywords:** glacial geomorphology; geomorphological mapping; GIS; remote sensing; field mapping
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76 **1. Introduction**

77

78 *1.1 Background and importance*

79

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

86

87 Two overarching traditions exist in geomorphological mapping: Firstly, the classical approach
88 involves mapping all geomorphological features in multiple thematic layers (e.g. landforms, breaks of
89 slope, slope angles, drainage), regardless of the range of different processes responsible for forming
90 the landscape. This approach to geomorphological mapping has been particularly widely used in
91 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 (3) devising glacial landsystem models that can be used to elucidate former glaciation styles or
111 inform engineering geology (e.g. Eyles, 1983; Evans et al., 1999; Evans, 2017; Bickerdike et
112 al., 2018);

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

129

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

139

140 The analysis of geomorphological evidence has been employed in the study of glaciers and ice sheets
141 for over 150 years, with the techniques used in geomorphological mapping undergoing a number of
142 significant developments in that time. The earliest geomorphological investigations involved intensive
143 field surveys (e.g. Close, 1867; Penck and Brückner, 1901/1909; De Geer, 1910; Trotter, 1929;
144 Caldenius, 1932; Raistrick, 1933), before greater efficiency was achieved through the development of
145 aerial photograph interpretation from the late 1950s onwards (e.g. Lueder, 1959; Price, 1963; Welch,
146 1967; Howarth, 1968; Prest et al., 1968; Sugden, 1970; Sissons, 1977a; Prest, 1983; Kronberg, 1984;
147 Mollard and Janes, 1984). Satellite imagery and digital elevation models (DEMs) have been in
148 widespread usage since their development in the late 20th Century and have, in particular, helped
149 revolutionise our understanding of palaeo-ice sheets (e.g. Barents-Kara Ice Sheet: Winsborrow et al.,

150 2010; British Ice Sheet: Hughes et al., 2014; Cordilleran Ice Sheet: Kleman et al., 2010;
151 Fennoscandian Ice Sheet: Stroeven et al., 2016; Laurentide Ice Sheet: Margold et al., 2018;
152 Patagonian Ice Sheet: Glasser et al., 2008). In recent times, increasingly higher-resolution DEMs have
153 become available due to the adoption of Light Detection and Ranging (LiDAR) technology (e.g.
154 Salcher et al., 2010; Jónsson et al., 2014; Miller et al., 2014; Dowling et al., 2015; Hardt et al., 2015;
155 Putniņš and Henriksen, 2017) and Unmanned Aerial Vehicles (UAVs) (e.g. Chandler et al., 2016a;
156 Evans et al., 2016a; Ewertowski et al., 2016; Tonkin et al., 2016; Ely et al., 2017). Aside from
157 improvements to remote sensing technologies, the last decade has seen a revolution in data
158 accessibility, with the proliferation of freely available imagery (e.g. Landsat data), freeware mapping
159 platforms (e.g. *Google Earth*) and open-source Geographical Information System (GIS) packages
160 (e.g. *QGIS*). As a result, tools for glacial geomorphological mapping are becoming increasingly
161 accessible, both practically and financially.

162

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

178

179 Geomorphological mapping using a combination of field mapping and remotely-sensed data
180 interpretation (hereafter ‘remote mapping’), or a number of remote sensing methods, permits a holistic
181 approach to mapping, wherein the advantages of each method/dataset can be combined to produce an
182 accurate map with robust genetic interpretations (e.g. Boston, 2012a, b; Darvill et al., 2014; Storrar
183 and Livingstone, 2017). As such, approaches are required that allow the accurate transfer and
184 assimilation of data from these various sources, particularly where data are transferred from analogue
185 (e.g. hard-copy aerial photographs) to digital format. Apart from a few recent exceptions for specific
186 locations (e.g. the Scottish Highlands: Boston, 2012a, b; Pearce et al., 2014), there has been limited

187 explicit discussion of the approaches used to integrate geomorphological data in map production (i.e.
188 the relative contributions of different methods and/or datasets and their associated uncertainties), with
189 many contributions simply stating that the maps were produced through fieldwork and/or remote
190 sensing (e.g. Ballantyne, 1989; Lukas, 2007a; Evans et al., 2009a; McDougall, 2013). Given the
191 diversity of scales, data sources and research questions inherent in glacial geomorphological research,
192 and the increasing abundance of high-quality remotely-sensed datasets, finding the most cost- and
193 time- effective approach is difficult, especially for researchers new to the field.

194

195 *1.2 Aims and scope*

196

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

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 (cf. Lukas, 2005, 2012; Bradwell et al., 2013; Boston et al.,
229 2015; Chandler et al., 2016b). Thirdly, the different mapping methodologies reflect the difficulties in
230 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). Finally, 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 obsolete.

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 Bergström, 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 mappable from remotely-sensed data (cf.
289 Kleman, 1990; Smith and Knight, 2011). Similarly, in a contemporary outlet glacier context, flutes are
290 an important indicator of ice flow direction – sometimes of annual ice flow trajectories of glacier
291 margins (cf. Chandler et al., 2016a; Evans et al., 2017) – but due to their subtlety they may only be
292 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, river bends, confluences, prominent
310 bedrock exposures and large ridges or mounds (Lukas and Lukas, 2006; Boston, 2012a, b). Where
311 geomorphological features are small, background relief is low and/or conspicuous reference points are
312 absent, a network of mapped reference points can be established by either taking a series of cross-
313 bearings on prominent features using a compass (e.g. Benn, 1990) or by verifying locations using a
314 handheld GNSS (e.g. Lukas and Lukas, 2006; Boston, 2012a, b; Brynjólfsson et al., 2014; Jónsson et
315 al. 2014; Lovell, 2014; Pearce et al., 2014; van der Bilt et al., 2016). The latter is useful for recording
316 the location of point-data such as striae, erratic or glacially-transported boulders, and sediment
317 exposures (cf. Lukas and Lukas, 2006; Boston, 2012a, b; Pearce et al., 2014). Additional information
318 between known reference points can then be interpolated and marked on the geomorphological map.

319

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

325

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

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 and palaeoglaciological reconstruction studies (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), whilst chronological data are fundamental to
343 robust palaeoglaciological reconstructions and related palaeoclimatic studies (e.g. Finlayson et al.,
344 2011; Gribenski et al., 2016; Hughes et al., 2016; Stroeven et al., 2016; Bendle et al., 2017b; Darvill
345 et al., 2017). Moreover, time and resources are limited and pragmatism necessary. Thus, observations
346 must be targeted efficiently and effectively, in line with the research aims.

347
348 Much field-based research adopts an inductive approach, in which observations are collected and used
349 to argue towards a particular conclusion. This is a valid approach at the exploratory stage of research,
350 but deeper understanding of a landscape requires a more iterative process, in which data collection is
351 conducted within a framework of hypothesis generation and testing. For this reason, it is useful to
352 adopt a number of alternative working hypotheses (Chamberlin, 1897) that can be tested and
353 gradually eliminated, following the principle of falsification (Popper, 1972). This process is best
354 conducted in the field while it is possible to make key observations to test an interpretation, especially
355 if the field site is remote and expensive to re-visit.

356
357 Following initial data collection, preliminary interpretations can be used to predict the outcome of
358 new observations, which can then be used to test and refine the interpretation. Well-framed
359 hypotheses allow an investigator to anticipate other characteristics of a glacial landscape, then to test
360 those predictions by targeted investigation of key localities (see Benn, 2006). For example, the
361 presence of a certain group of landforms (e.g. moraines trending downslope into a side valley) can be
362 used to formulate hypotheses (e.g. blockage of the side-valley by glacier ice), which in turn can be
363 used to predict the presence of other sediment-landform associations in a particular locality (e.g.
364 lacustrine sediments or shoreline terraces in the side-valley). Further detailed geomorphological
365 mapping (and sedimentological analyses) in that area would then allow testing and falsification of the
366 alternative working hypotheses. Iterations of this process during field mapping enable an increasingly
367 detailed and robust understanding of the glacier system to be constructed. This coupled inductive-
368 deductive approach is much more powerful than a purely inductive process: narratives that ‘explain’ a
369 set of observations can appear very persuasive, even self-evident, but there may be other narratives
370 that are also consistent with the same observations (cf. Popper, 1972).

371

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

383

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

389

390 **3. Remote mapping methods**

391

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

401

402 We focus principally on remotely-sensed datasets relevant to terrestrial (onshore) glacial settings in
403 the following sections, since submarine (bathymetric) datasets and mapping of submarine glacial
404 landforms have been subject to recent reviews elsewhere (see Dowdeswell et al., 2016; Batchelor et
405 al., 2017). Nevertheless, we do acknowledge that the emergence of geophysical techniques to
406 investigate submarine (offshore) glacial geomorphology is a major development over the last two
407 decades. Similarly, the emergence of geophysical datasets of sub-ice geomorphology in the last

408 decade or so has been revolutionary, particularly in relation to subglacial bedforms (see Stokes, 2018).
409 Many of the issues we discuss in relation to mapping from DEMs are transferable to those
410 environments.

411

412 *3.1 Analogue remote mapping*

413

414 *3.1.1 Background and applicability of analogue remote mapping*

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

424

425 Despite continued development of remote sensing technologies and the availability of digital aerial
426 photographs (see Section 3.2.2.2), analogue stereoscopic aerial photographs are still used for glacial
427 geomorphological mapping (e.g. Hättstrand, 1998; Benn and Ballantyne, 2005; Lukas et al., 2005;
428 Boston, 2012a, b; Evans and Orton, 2015). Additionally, the availability of high-quality
429 photogrammetric scanners means that archival, hard-copy aerial photographs can be scanned at high
430 resolutions, processed using digital photogrammetric methods and subsequently used for on-screen
431 digitisation (Section 3.2; e.g. Bennett et al., 2010; Jónsson et al., 2014). As with field mapping, the
432 interpretation of analogue aerial photographs is primarily used for mapping alpine- and plateau-style
433 ice mass geomorphological imprints. Historically, analogue aerial photograph interpretation was
434 extensively used for mapping palaeo-ice sheet geomorphological imprints, particularly by the
435 Geological Survey of Canada, who combined aerial photograph interpretation with detailed ground
436 checking and helicopter-based surveys (e.g. Craig, 1961, 1964; Hodgson et al., 1984; Aylsworth and
437 Shilts, 1989; Dyke et al., 1992; Klassen, 1993; Dyke and Hooper, 2001). This approach has largely
438 been superseded by satellite imagery and DEM interpretation in palaeo-ice sheet settings (see Section
439 5.1) but is applied in palaeo-ice sheet contexts for more detailed mapping of selected/complex areas
440 (e.g. Dyke, 1990; Kleman et al., 2010; Stokes et al., 2013; Storrar et al., 2013; Darvill et al., 2014;
441 Evans et al., 2014).

442

443 *3.1.2 Mapping from analogue datasets*

444 For glacial geomorphological mapping purposes, vertical panchromatic aerial photographs have
445 traditionally been employed, with pairs of photographs (stereopairs) viewed in stereo using a
446 stereoscope (with magnification) (e.g. Melander, 1975; Horsfield, 1983; Krüger, 1994; Kleman et al.,
447 1997; Hättestrand, 1998; Evans and Twigg, 2002; Benn and Ballantyne, 2005; Lukas and Lukas,
448 2006; Boston, 2012a, b; Chandler and Lukas, 2017). During aerial surveys, longitudinally-
449 overlapping photographs along the flight path (endlap $\geq 60\%$) are captured in a series of laterally-
450 overlapping parallel strips (sidelap $\geq 30\%$), with the two different viewing angles of the same area
451 resulting in the stereoscopic effect (due to the principle of parallax; see Lillesand et al., 2015, for
452 further details). This form of aerial photograph interpretation has been demonstrated to be a
453 particularly valuable tool for determining the exact location, shape and planform of small features in
454 glaciated terrain (e.g. Ballantyne, 1989, 2002, 2007a, b; Bickerton and Matthews, 1992, 1993; Lukas
455 and Lukas, 2006; Boston, 2012a, b), provided the photographs are of appropriate scale, quality and
456 tonal contrast (cf. Benn, 1990; Benn et al., 1992).

457
458 Mapping from hard-copy aerial photographs is undertaken by drawing onto acetate sheets
459 (transparency films) whilst viewing the aerial photographs through a stereoscope, with the acetate
460 overlain on one photograph of a stereopair (Figure 2). Ideally, mapping should be conducted using a
461 super-fine pigment liner with a nib size of 0.05 mm to enable small features to be mapped. Even so, it
462 may still be necessary to compromise on the level of detail mapped; for example, meltwater channels
463 between ice-marginal moraines have been left off maps in some studies due to map scale, with the
464 associated text describing chains of moraines interspersed with meltwater channels (e.g. Benn and
465 Ballantyne, 2005; Lukas, 2005).

466
467 Examining stereopairs from multiple sorties ('flight missions') in parallel or in combination with
468 digital aerial photographs may be beneficial and help alleviate issues such as localised cloud cover,
469 snow cover, poor tonal contrast, afforestation and anthropogenic developments (e.g. Horsfield, 1983;
470 Bennett, 1991; McDougall, 2001). Additionally, it is advantageous to examine stereopairs multiple
471 times – preferably before and after field mapping – to increase feature identification and improve the
472 accuracy of genetic interpretations (Lukas and Lukas, 2006; Sahlin and Glasser, 2008). When
473 conducting mapping over a large area with multiple stereopairs, examining stereopairs from a sortie
474 'out of sequence' (i.e. not mapping from consecutive pairs of photographs) may provide a means of
475 internal corroboration and ensure objectivity and robustness (Bennett, 1991).

476
477 In order to reduce geometric distortion, which increases towards the edges of aerial photographs due
478 to the central perspective (Lillesand et al., 2015), it is advisable to keep the areas mapped onto the
479 acetate as close as possible to the centre of one aerial photograph of a stereopair (Kronberg, 1984;
480 Lukas, 2002, 2005a; Evans and Orton, 2015). These hand-drawn overlays can subsequently be

481 scanned at high resolutions and then georeferenced and digitised using GIS and graphics software (see
482 also Section 3.3.1; e.g. Lukas and Lukas, 2006; Boston, 2012a, b).

483

484 *3.2 Digital remote mapping*

485

486 *3.2.1 Background and applicability of digital remote mapping*

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

497

498 Digital mapping (on-screen digitisation) also provides georeferenced geomorphological data, which
499 has two important benefits: Firstly, these data can easily be used to derive landform metrics (e.g.
500 Hättestrand et al., 2004; Clark et al., 2009; Spagnolo et al., 2010, 2014; Storrar et al., 2014; Ojala et
501 al., 2015; Dowling et al., 2016; Ely et al., 2016a, 2017a); and, secondly, these data can be seamlessly
502 incorporated into wider, regional-scale GIS compilations (e.g. Bickerdike et al., 2016; Stroeven et al.,
503 2016; Clark et al., 2018a). Additionally, digital remote mapping allows the user to record attribute
504 data (e.g. data source) tied to individual map (vector) layers, which can be useful for large
505 compilations of previously published mapping (e.g. Bickerdike et al., 2016; Clark et al., 2018a). Such
506 compendia help to circumvent issues relating to the often-fragmented nature of geomorphological
507 evidence (i.e. numerous spatially separate studies) and identify gaps in the mapping record. Once
508 assembled across large areas, they also enable evidence-based reconstructions of entire ice sheets and
509 regional ice sheet sectors (see Clark et al., 2004, 2018a). Indeed, the ongoing open access data
510 revolution in academia and the increasing publication/availability of mapping output (in the form of
511 GIS files; e.g. Finlayson et al., 2011; Darvill et al., 2014; Bickerdike et al., 2016; Bendle et al.,
512 2017a), means that geomorphological mapping can have wider impact beyond individual local to
513 regional studies.

514

515 *3.2.2 Datasets for digital remote mapping*

516 There is now a plethora of remotely-sensed datasets covering a wide range of horizontal resolutions
517 (10^{-2} to 10^2 m), enabling the application of digital mapping (in some form) to all glacial settings. We

518 provide an overview of the principal datasets used in digital mapping below, with mapping
519 approaches in specific glacial settings reviewed in Section 5.

520

521 *3.2.2.1 Satellite imagery.* The development of satellite-based remote sensing in the 1970s and
522 subsequent advances in technology have revolutionised understanding of glaciated terrain, particularly
523 with respect to palaeo-ice sheet geomorphology and dynamics (see Section 5.1; Clark, 1997; Stokes,
524 2002; Stokes et al., 2015). The potential of satellite imagery was first demonstrated by the pioneering
525 work of Sugden (1978), Andrews and Miller (1979) and Punkari (1980), with the availability of large-
526 area view (185 km x 185 km) Landsat Multi-Spectral Scanner (MSS) images affording a new
527 perspective of glaciated regions. These allowed a single analyst to systematically map ice sheet-scale
528 (1:45,000 to 1: 1,000,000) glacial geomorphology (e.g. Boulton and Clark, 1990a, b) in a way that
529 previously would have required the painstaking mosaicking of thousands of aerial photographs (e.g.
530 Prest et al., 1968). Since the 1980s, there has been an explosion in the use of satellite imagery for
531 glacial geomorphological mapping and there is now a profusion of datasets available (Table 1).
532 Importantly, many of these sensors capture multispectral data, which can enhance landform detection
533 through image processing and the use of different band combinations (see Section 3.3.2). The uptake
534 of satellite imagery has coincided with improvements in the availability and spatial and spectral
535 resolution of satellite datasets globally, with Landsat (multispectral: 30 m; panchromatic: 15 m),
536 ASTER (15 m), Sentinel-2 (10 m) and SPOT (up to 1.5 m) images proving the most popular. More
537 recently, satellite sensor advancements have enabled the capture of satellite images with resolutions
538 comparable to aerial photographs (Figure 4; e.g. SPOT6/7, QuickBird, WorldView). Thus, these
539 datasets are also suitable for mapping typically smaller and/or complex glacial landforms produced by
540 cirque glaciers, valley glaciers and icefield/ice-cap outlets (e.g. Chandler et al., 2016a; Evans et al.,
541 2016b; Ewertowski et al., 2016; Gribenski et al., 2016; Małeckki et al., 2018).

542

543 In general, as better-resolution imagery has become more widely available at low to no cost, older,
544 coarser-resolution datasets (e.g. Landsat MSS: 60 m) have largely become obsolete. Nevertheless,
545 Landsat data (TM, ETM+ and OLI: 15 to 30 m) are still the standard data source for ice-sheet scale
546 mapping, with the uptake of high-resolution commercial satellite imagery still relatively slow in such
547 studies. This is primarily driven by the cost of purchasing high-resolution commercial datasets,
548 making freely-available imagery such as Landsat a valuable resource. In addition, archival satellite
549 data afford time-series of multi-spectral images that may facilitate assessments of geomorphological
550 changes through time; for example, fluctuations in highly dynamic (surging or rapidly retreating)
551 glacial systems (e.g. Flink et al., 2015; Jamieson et al., 2015). Conversely, for smaller research areas
552 (e.g. for a single valley or foreland), high-resolution satellite imagery is becoming an increasingly
553 viable option, with prices for georeferenced and orthorectified products comparable to those for
554 digital aerial photographs (see Section 3.2.2.2). This also has the benefit of saving time on

555 photogrammetric processing, with many vendors providing consumers with various processing
556 options. Consequently, on-demand, high-resolution (commercial) satellite imagery will inevitably
557 come into widespread usage, where costs are not prohibitive. Alternatively, freeware virtual globes
558 and web mapping services (e.g. *Bing Maps*, *Google Earth*) offer valuable resources for free
559 visualisation of such high-resolution imagery (see Section 3.2.2.4).

560

561 *3.2.2.2 Digital aerial photographs.* With improvements in technology, high-resolution (ground
562 resolution <0.5 m per pixel) digital copies of aerial photographs have become widely available and
563 used for glacial geomorphological mapping (e.g. Brown et al., 2011a; Bradwell et al., 2013;
564 Brynjólfsson et al., 2014; Jónsson et al., 2014; Pearce et al., 2014; Schomacker et al., 2014; Chandler
565 et al., 2016a; Evans et al., 2016c; Lardeux et al., 2016; Lønne, 2016; Allaart et al., 2018). Indeed,
566 digital aerial photographs, along with scanned copies of archival aerial photographs, are now more
567 widely used than hard-copy stereoscopic aerial photographs, particularly in modern glacial settings.
568 Additionally, the introduction of UAV technology in recent years has allowed sub-decimetre
569 resolution aerial photographs to be captured on demand (see Section 3.2.2.5). Aside from their
570 typically superior resolution/scale compared with hard-copy aerial photographs, a key advantage of
571 aerial photographs in digital format is the ability to produce orthorectified aerial photograph mosaics
572 (or ‘orthophotographs’) and DEMs with low root mean square errors (RMSEs <1 m; see Section 4.4),
573 when combined with ground control points collected using surveying equipment (e.g. Kjær et al.
574 2008; Bennett et al., 2010; Schomacker et al., 2014; Chandler et al., 2016b; Evans et al., 2017). These
575 photogrammetric products can then be used for on-screen digitisation and generation of georeferenced
576 geomorphological mapping (Figure 5), as outlined above.

577

578 Typically, digital aerial photographs are captured by commercial surveying companies (e.g.
579 Loftmyndir ehf, Iceland; Getmapping, UK), meaning that they may be expensive to purchase and
580 costs may be prohibitive for large study areas. This is in contrast to hard-copy (archival) aerial
581 photographs that are often freely available for viewing in national collections. Additionally, digital
582 aerial photographs are not readily viewable in stereo with a standard desktop setup, although on-
583 screen mapping in stereoscopic view is possible on workstations equipped with stereo display and
584 software such as *BAE Systems SOCET SET* (e.g. Kjær et al., 2008; Benediktsson et al., 2009).
585 However, this approach is not applicable to orthophotographs. An alternative approach is to visualise
586 orthophotographs in 3D by draping them over a DEM (see Section 3.2.2.3) in GIS software such as
587 *ESRI ArcScene* or similar (Figure 6; e.g. Benediktsson et al., 2010; Jónsson et al., 2014; Schomacker
588 et al., 2014; van der Bilt et al., 2016). Three-dimensional assessment in *ArcScene*, parallel to mapping
589 in *ArcMap*, may aid in landform detection, delineation and interpretation.

590

591 3.2.2.3 *Digital Elevation Models*. Over the last ~15 years there has been increasing use of DEMs in
592 glacial geomorphology, particularly for mapping at the ice-sheet scale (e.g. Glasser and Jansson,
593 2008; Hughes et al., 2010; Ó Cofaigh et al., 2010; Evans et al., 2014, 2016d; Principato et al., 2016;
594 Ojala, 2016; Stokes et al., 2016a; Mäkinen et al., 2017; Norris et al., 2017). DEMs are raster-based
595 models of topography that record absolute elevation, with each pixel or grid cell in a DEM
596 representing the average height for the area it covers (Clark, 1997; Smith et al., 2006). Terrestrial
597 DEMs can be generated by a variety of means, including from surveyed contour data, directly from
598 stereo imagery (aerial photographs, satellite and UAV-captured imagery), or from air- and space-
599 borne radar and LiDAR systems (Smith and Clark, 2005). An important recent development in this
600 regard has been the Surface Extraction with TIN-based Search-space Minimization (SETSM)
601 algorithm for automated extraction of DEMs from stereo satellite imagery (Noh and Howat, 2015),
602 which has been used to generate the ArcticDEM dataset (<https://www.pgc.umn.edu/data/arcticdem/>).
603 However, SETSM DEMs may contain systematic vertical errors that require correction (e.g. Carrivick
604 et al., 2017; Storrar et al., 2017).

605
606 The majority of DEMs with national- to international-scale coverage (Table 2) typically have a
607 coarser spatial resolution than aerial photographs and satellite imagery and represent surface
608 elevations rather than surface reflectance. As a result, it may be difficult to identify glacial landforms
609 produced by relatively small ice masses (cirque glaciers, valley glaciers and icefield outlets),
610 precluding detailed mapping of their planforms (cf. Smith et al., 2006; Hughes et al., 2010; Brown et
611 al., 2011a; Boston, 2012a, b; Pearce et al., 2014). Conversely, these DEMs can be particularly
612 valuable for mapping glacial erosional features (e.g. glacial valleys, meltwater channels), as well as
613 major glacial depositional landforms produced by larger ice masses (e.g. Greenwood and Clark, 2008;
614 Heyman et al., 2008; Livingstone et al., 2008; Hughes et al., 2010; Morén et al., 2011; Barr and Clark,
615 2012; Stroeven et al., 2013; Turner et al., 2014a; Margold et al., 2015a; Blomdin et al., 2016a, b;
616 Lindholm and Heyman, 2016; Mäkinen et al., 2017; Storrar and Livingstone, 2017). However, the
617 recent development of UAV (see section 3.2.2.5) and LiDAR technologies have allowed the
618 generation of very high resolution DEMs (<0.1 m), enabling the application of DEMs to map small
619 glacial landforms (e.g. Evans et al., 2016a; Ewertowski et al., 2016; Ely et al., 2017). We anticipate
620 national-scale LiDAR DEMs becoming widely-used in the future, with a number of nations recently
621 releasing or currently capturing/processing high horizontal resolution (≤ 2 m) LiDAR data (Table 2;
622 e.g. Dowling et al. 2013; Johnson et al. 2015).

623
624 Although the principal focus of this contribution is terrestrial/onshore glacial geomorphological
625 mapping, it is worth highlighting here that the availability of spatially-extensive bathymetric charts,
626 such as the General Bathymetric Chart of the Oceans (GEBCO) and International Bathymetric Chart
627 of the Arctic Ocean (IBCAO: Jakobsson et al., 2012), and high-resolution, regional (often industry-

628 acquired) bathymetric data has been an important development in submarine/offshore glacial
629 geomorphological mapping. This has enabled the gridding of DEMs to map submarine glacial
630 geomorphological imprints (see Dowdeswell et al., 2016), markedly enhancing understanding of
631 palaeo-ice sheets in marine sectors (e.g. Ottesen et al., 2005, 2008a, 2016; Bradwell et al., 2008;
632 Winsborrow et al., 2010, 2012; Livingstone et al., 2012; Ó Cofaigh et al., 2013; Hodgson et al., 2014;
633 Stokes et al., 2014; Margold et al., 2015a, b; Greenwood et al., 2017) and modern tidewater (often
634 surging) glaciers (e.g. Ottesen and Dowdeswell, 2006; Ottesen et al., 2008b, 2017; Robinson and
635 Dowdeswell, 2011; Dowdeswell and Vazquez, 2013; Flink et al., 2015; Streuff et al., 2015; Allaart et
636 al., 2018). In addition, recent years have seen the production of DEMs of sub-ice topography from
637 geophysical datasets (radar and seismics) at spatial resolutions suitable for identifying and mapping
638 bedforms (see King et al., 2007, 2009, 2016a; Smith et al., 2007; Smith and Murray, 2009). This work
639 has advanced understanding of the evolution of bedforms beneath Antarctic ice streams, providing
640 important genetic links between the formation of landforms beneath modern ice sheets and those left-
641 behind by palaeo-ice masses (Stokes, 2018). The interested reader is directed to recent reviews
642 (Livingstone et al., 2012; Ó Cofaigh, 2012; Stokes et al., 2015; Dowdeswell et al., 2016; Batchelor
643 and Dowdeswell, 2017; Stokes, 2018) for further discussion on the importance of geophysical
644 evidence for understanding ice sheet extent and dynamics.

645

646 *3.2.2.4 Freeware virtual globes.* The advent of freeware virtual globes (e.g. *Google Earth*, *NASA*
647 *Worldwind*) and web mapping services (e.g. *Bing Maps*, *Google Maps*) have provided platforms for
648 free visualisation of imagery from various sources and low-cost mapping resources. A key benefit of
649 virtual globes is the ability to visualise imagery and terrain in 3D and from multiple viewing angles,
650 which may aid landform detection when used in conjunction with other datasets and software (e.g.
651 Heyman et al., 2008; Bendle et al., 2017a). Moreover, a number of virtual globes and web mapping
652 services have the ability to link with other freeware and open-source programmes; for example, free
653 plugins are available to import *Google Earth* and *Bing Maps* imagery into the open-source GIS
654 software package *QGIS*. Thus, a mapper can combine freely available, often high-resolution (e.g.
655 SPOT6/7, QuickBird, WorldView), imagery and the capabilities of GIS technology without the
656 expense associated with commercial imagery and software (see Sections 3.2.2.1 and 3.2.2.2).

657

658 The most widely-used virtual globe is *Google Earth*, with a ‘professional’ version (*Google Earth Pro*)
659 freely available since 2015 (see Mather et al., 2015, for a review). An increasing number of glacial
660 geomorphological studies are noting the use of *Google Earth* (but not necessarily the imagery type) as
661 a mapping tool (see Table 1), principally to cross-check mapping conducted from other imagery.
662 However, some studies have also utilised the built-in digitising tools for mapping (e.g. Margold and
663 Jansson, 2011; Margold et al., 2011; Fu et al., 2012). There is a compromise on the functionality of
664 freeware virtual globes and digitisation tools are often not as flexible and/or user-friendly, but these

665 can be counteracted by the option to import imagery into GIS software. In the case of *Google Earth*, it
666 is also possible to export Keyhole Markup Language (KML) files that can be used for subsequent
667 analyses and map production in GIS software (following file conversion). Open access remotely-
668 sensed datasets are also available through commercial GIS software, with high resolution satellite
669 imagery (e.g. GeoEye-1, SPOT-5, WorldView) available for mapping through the in-built ‘World
670 Imagery’ service in *ESRI ArcGIS* (e.g. Bendle et al., 2017a).

671

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

681

682 *3.2.2.5 UAV-captured imagery.* The recent emergence of UAV technology provides an alternative
683 method for the acquisition of very high-resolution (<0.1 m per pixel) geospatial data that circumvents
684 some of the issues associated with more established approaches, particularly in relation to temporal
685 resolution and the high-cost of acquiring commercial remotely-sensed data (see also Smith et al.,
686 2016a). This method provides a rapid, flexible and relatively inexpensive (following the initial
687 acquisition of the UAV and associated software) means of acquiring up-to-date imagery at an
688 unprecedented spatial resolution and is becoming increasingly employed in glacial research (Figure 7;
689 Rippin et al., 2015; Ryan et al., 2015; Chandler et al., 2016b; Ewertowski et al., 2016; Tonkin et al.,
690 2016; Westoby et al., 2016; Ely et al., 2017; Allaart et al., 2018). UAV-captured images are processed
691 using Structure-from-Motion (SfM) photogrammetry techniques, with *Agisoft Photoscan* being the
692 most common software in use at present (e.g. Chandler et al., 2016b; Evans et al., 2016a; Ely et al.,
693 2017; Allaart et al., 2018). This methodology has enabled the production of sub-decimetre resolution
694 orthophotographs and DEMs with centimetre-scale error values (RMSEs <0.1 m; see Section 4.4) for
695 glacial geomorphological mapping (e.g. Evans et al., 2016a; Ely et al., 2017). Although surveying of
696 ground control points is still preferable for processing UAV-captured imagery, a direct georeferencing
697 workflow (see Turner et al., 2014b, for further details) is capable of producing reliable geospatial
698 datasets from imagery captured using consumer-grade UAVs and cameras, without the need for
699 expensive survey equipment (see Carbonneau and Dietrich, 2017).

700

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

709

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

722

723 *3.3 Image processing for mapping*

724

725 An important part of geomorphological mapping is processing remotely-sensed datasets in preparation
726 for mapping, but this is often given limited prominence in glacial geomorphological studies.
727 Crucially, processing of remotely-sensed data aids the identification of glacial landforms and ensures
728 accurate transfer of geomorphological data from the imagery. In the sections below, we provide a
729 brief overview of image processing solutions for aerial photographs (Section 3.3.1), satellite imagery
730 (Section 3.3.2) and DEMs (Section 3.3.3). Reference is made to common processing techniques used
731 to remove distortion and displacement evident in aerially-captured imagery (see Campbell and Wynne
732 (2011) and Lillesand et al. (2015) for further details), but these are not discussed in detail for reasons
733 of brevity and clarity. However, a detailed workflow diagram outlining the potential procedures for a
734 range of scenarios (depending on data, resources and time) is available as Supplementary Material.
735 We emphasise that compromises and pragmatic solutions are necessary, particularly in the case of
736 aerial photographs, as the ‘idealised’ scenario is frequently not an option due to data limitations or
737 logistical constraints.

738

739 *3.3.1 Aerial photograph processing*

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

748

749 Ideally, aerial photographs would be corrected using stereoscopic (or conventional) photogrammetric
750 processing in software packages such as *Imagine Photogrammetry* (formerly *Leica Photogrammetry*
751 *Suite*, or *LPS*). This approach involves the extraction of quantitative elevation data from stereoscopic
752 (overlapping) imagery to generate DEMs and orthorectified imagery (see also Section 3.2). Internal
753 and external parameters, along with the location of GCPs, are used to establish the relationship
754 between the position of the images and a ground coordinate system (e.g. Kjær et al., 2008; Bennett et
755 al., 2010). However, this approach may be impractical and unsuitable in many glacial settings; for
756 example, it is unrealistic to collect GCPs using (heavy) survey equipment (e.g. RTK-GPS) in former
757 plateau icefield and ice-cap settings due to their location (remote, upland environments) and the size
758 of the study area (and thus quantity of aerial photographs and GCPs required). Moreover, camera
759 calibration data (focal length, fiducial marks, principal point coordinates and lens distortion) are
760 frequently unavailable or incomplete for archive datasets, and the process is also not applicable to
761 acetate overlays. Thus, orthorectification of imagery – correction of geometric distortions in both the
762 horizontal (x and y coordinates) and vertical (z coordinates) dimensions – is typically precluded over
763 larger areas, although it may be possible to employ this approach for individual cirque basins, valleys
764 and glacier forelands (e.g. Wilson, 2005; Bennett et al., 2010; Chandler et al., 2016a). Consequently,
765 pragmatic solutions are required for georectification of imagery, i.e. the process of transforming and
766 projecting imagery to a (local) planar coordinate system. Several approaches have been used to
767 overcome this and we briefly outline these below in relation to analogue aerial photographs (Section
768 3.3.1.1) and digital aerial photographs (Section 3.3.1.2).

769

770 *3.3.1.1 Analogue aerial photograph processing.* A potential pragmatic solution to correcting analogue
771 (hard-copy) aerial photographs is to georeference scanned copies of acetate overlays or the original
772 aerial photographs to reference points on other forms of (coarser) georeferenced digital imagery (if
773 available; e.g. DEMs, orthorectified radar images, satellite images). The scanned images can then be
774 georectified and resampled using the georeferencing functions within GIS and remote sensing

775 programmes such as *ArcGIS* or *Erdas Imagine* (cf. Boston, 2012a, for further details). This approach
776 is particularly useful where hard-copy aerial photographs are used in combination with (coarser)
777 digital imagery. Using this procedure, georeferenced acetate overlays of Quaternary features in the
778 Scottish Highlands have been produced with RMSE values ranging between 2.71 m and 7.82 m
779 (Boston, 2012a), comparable to archival aerial photographs that have been processed using
780 conventional photogrammetric techniques (e.g. Bennett et al., 2010).

781

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

794

795 *3.3.1.2 Digital aerial photograph processing.* Digital aerial photographs can be georeferenced within
796 GIS and remote sensing software following a similar process to that outlined in Section 3.3.1.1, i.e.
797 digital aerial photographs can be georeferenced to other forms of (coarser) georeferenced imagery.
798 Alternatively, SfM photogrammetry can be used to produce orthophotographs and DEMs from digital
799 aerial photographs, which partly circumvents issues relating to incomplete or absent camera
800 calibration data (e.g. Chandler et al., 2016a; Evans et al., 2016e, 2017; Tonkin et al., 2016; Midgley
801 and Tonkin, 2017; Mertes et al., 2017). SfM photogrammetry functions under the same basic
802 principles as stereoscopic photogrammetry but there are fundamental differences: the geometry of the
803 ‘scene’, camera positions and orientation are solved automatically in an arbitrary ‘image-space’
804 coordinate system without the need to specify either the 3D location of the camera or a network of
805 GCPs with known ‘object-space’ coordinates (cf. Westoby et al., 2012; Carrivick et al., 2016; Smith
806 et al., 2016a, for further details). However, positional data (GCPs) are still required to process the
807 digital photographs for geomorphological mapping, i.e. to assign the SfM models to an ‘object-space’
808 coordinate system. Ideally, this should be conducted through ground control surveys (see above), but
809 a potential pragmatic solution is to utilise coordinate data from freeware virtual globes such as *Bing*
810 *Maps* (see also Supplementary Material). Position information (‘object-space’ coordinates) is

811 introduced after model production, with the benefit that errors in GCPs will not propagate in the
812 DEM.

813

814 *3.3.2 Satellite imagery processing*

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

824

825 Although satellite imagery does not typically require geometric correction for mapping, it is important
826 to consider the choice of band combinations when using multispectral satellite imagery (e.g. Landsat,
827 ASTER; Table 1). Since the detection of glacial landforms from optical satellite imagery relies on the
828 interaction of reflected radiation with topography, different combinations of spectral bands can be
829 employed to optimise landform identification (see Jansson and Glasser, 2005). Manipulating the order
830 of bands with different spectral wavelengths allows the generation of various visualisations, or false-
831 colour composites, of the terrain. For example, specific band combinations may be particularly useful
832 for detecting moraine ridges (7, 5, 2 and 5, 4, 2), mega-scale glacial lineations (4, 5, 6) and meltwater
833 channels (4, 3, 2) from Landsat TM and ETM+ imagery (Jansson and Glasser, 2005; Lovell et al.,
834 2011; Morén et al., 2011). This is principally due to the change in surface vegetation characteristics
835 (e.g. type, density and degree of development) between different landforms, between landforms and
836 the surrounding terrain. For example, former meltwater channels typically appear as overly-wide
837 corridors (relative to any modern drainage) of lush green vegetation and stand out clearly as bright red
838 when using a near-infrared false-colour composites (bands 4, 3, 2: Landsat TM and ETM+), since the
839 green colour of surface vegetation is strongly reflected in near-infrared bands (band 4: Landsat TM
840 and ETM+). In addition to the manipulation of band combinations during the mapping process, it can
841 also be beneficial to use satellite image derivatives based on ratios of band combinations, such as
842 vegetation indices (see Walker et al., 1995) and semi-automated image classification techniques (e.g.
843 Smith et al., 2000, 2016b).

844

845 Aside from manipulating spectral band combinations, it may also be beneficial to use the higher-
846 resolution panchromatic band as a semi-transparent layer alongside the multispectral bands to aid
847 landform detection (e.g. Morén et al., 2011; Stroeven et al., 2013; Lindholm and Heyman, 2016), or to

848 merge the pixel resolutions of the panchromatic and multispectral bands through pan-sharpening
849 techniques (e.g. Glasser and Jansson, 2008; Greenwood and Clark, 2008; Storrar et al., 2014;
850 Chandler et al., 2016a; Ewertowski et al., 2016). Pan-sharpening can be particularly valuable when it
851 is desirable to have both multispectral capabilities (e.g. different band combinations to differentiate
852 between features with varying surface characteristics) and higher-spatial resolutions to help determine
853 the extent and morphology of individual landforms.

854

855 *3.3.3 Digital Elevation Model processing*

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

874

875 **4. Assessment of mapping errors and uncertainties**

876

877 In this section, we provide an overview of the main errors and uncertainties associated with the
878 various geomorphological mapping methods introduced in the preceding sections. Consideration and
879 management of mapping errors should be an important part of glacial geomorphological mapping
880 studies, since any errors/uncertainties incorporated in the geomorphological map will propagate into
881 subsequent palaeoglaciological and palaeoclimatic reconstructions. This is of most relevance to small
882 ice masses (cirque glaciers, valley glaciers, outlet glaciers), e.g. metre-scale geolocation errors would
883 have significant implications for studies aiming to establish ice-margin retreat rates at the order of
884 tens of metres (e.g. Krüger, 1995; Lukas and Benn, 2006; Lukas, 2012; Bradwell et al., 2013;

885 Chandler et al., 2016b). Conversely, mapping errors might be negligible in the context of continental-
886 scale ice sheet reconstructions (e.g. Hughes et al., 2014; Stroeven et al., 2016; Margold et al., 2018).

887

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

899

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

913

914 *4.1 Field mapping errors and uncertainty*

915

916 The correct positioning, orientation and scale of individual geomorphological features on field maps
917 is dependent on the skill of the mapper and the ability to correctly interpret and record landforms. If a
918 handheld GNSS device is used to locate landforms in the field, the positional accuracy is usually
919 restricted to several metres and related to three factors: (i) the quality of the device (e.g. antenna,
920 number of channels, ability to use more than one GNSS); (ii) the position of satellites; and (iii) the
921 characteristics of the surrounding landscapes and space weather (solar activity can affect signal

922 quality). Higher accuracy (cm- or even mm-scale) can only be achieved when supplemented by
923 measurements using additional surveying (e.g. differential Global Positioning Systems (dGPS), real
924 time kinematic (RTK-) GPS or total station). Alongside positioning errors, the horizontal resolution
925 (and, consequently, accuracy) of the field map is related to line thickness on the field map (Knight et
926 al., 2011; Boston, 2012a, b; Otto and Smith, 2013). A pencil line has a thickness of between 0.20 and
927 0.50 mm on a field map; therefore, individual lines represent a thickness of between 2 and 5 m on 1:
928 10,000 scale maps, rendering the maps accurate to this level at best (Raisz, 1962; Robinson et al.,
929 1995; Boston, 2012a). This necessitates some element of selection during field mapping of relatively
930 small landforms formed by alpine- and plateau-style ice masses, as not all the information that can be
931 seen in the field can be mapped, even at a large scale such as 1: 10,000. In terms of the vertical
932 accuracy of field maps, it should be recognised that the mapping is only as accurate as the resolution
933 of the source elevation data: if the topographic base map has contours at 10 m intervals, the mapping
934 has a vertical resolution, and thus accuracy, of 10 m at best, irrespective of the (perceived) skill of the
935 cartographer. As with positional accuracy, higher vertical accuracy necessitates the use of geodetic-
936 grade surveying equipment.

937

938 *4.2 Analogue remote mapping errors and uncertainty*

939

940 Accurate detection and mapping of individual landforms from analogue (hard-copy) aerial
941 photographs is influenced by factors such as the scale or resolution of the photographs, shadow length
942 (shadows may obscure the ‘true’ planform or landforms altogether), the presence/absence of
943 vegetation, cloud cover and tonal contrast (photographs may appear ‘flat’, thus limiting landform
944 detection). The resolution of analogue remotely-sensed datasets is associated with scale, which results
945 from the altitude of the plane and camera lens focal length, and the optical resolution of the lens and
946 sensor (Wolf et al., 2013). It should also be recognised that the accuracy of the (non-rectified)
947 mapping, as with field mapping, is limited by the thickness of the pen used for drawing on the acetate
948 sheets. Super-fine pens typically have a nib size of 0.05–0.20 mm; thus, lines on an acetate overlay
949 typically represent thicknesses between ~1.25 m and 5.00 m at a common aerial photograph average
950 scale of 1: 25,000. Despite being particularly useful for detailed mapping of small features and
951 complex landform patterns, the level of accuracy achievable using this methodology is therefore
952 ~1.25 m at best. However, further errors will be introduced to the geomorphological mapping once
953 the raw, non-rectified acetates are georectified (see Section 3.3.1).

954

955 *4.3 Digital remote mapping errors and uncertainty*

956

957 A key influence on landform detectability from digital remotely-sensed data is the scale of the feature
958 relative to the resolution of the digital dataset, with a particular challenge being the mapping of

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

971

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

987

988 Aside from the factors outlined above, (raw) remotely-sensed data will contain distortion and/or
989 geometric artefacts of varying degrees. Distortions inherent in raw aerial photographs can be partially
990 or almost fully removed during georeferencing of acetate sheets or photogrammetric processing of
991 aerial photographs (see Section 3.3.1). Raw satellite imagery will contain biases related to attitude,
992 ephemeris and drift errors as well as displacements related to the relief, which, similarly to aerial
993 photographs, is more visible in mountainous areas than in lowland settings (Grodecki and Dial, 2003;
994 Shean et al., 2016). With respect to DEMs, some datasets captured using air- and space-borne radar
995 approaches may contain a number of artefacts (Clark, 1997; Figure 11), with geometric artefacts

996 particularly significant in upland settings. Geometric artefacts, such as foreshortening and layover, are
997 corrected during image processing by stretching high terrain into the correct position, which can result
998 in a smoothed region on steep slopes (Figure 12). In other parts of upland terrain, information will be
999 lost on the leeward side of slopes, away from the sensor, where high ground prevents the radar beam from
1000 reaching the lower ground beneath it (Figure 11). Such issues can be alleviated, at least partly, by
1001 examining multiple complementary remotely-sensed datasets and mapping at a variety of scales.

1002

1003 *4.4. Assessment and management of uncertainties*

1004

1005 Due to the subjective nature of geomorphological mapping, assessing mapping precision is not an
1006 easy task. One possible approach is to compare results of mapping using different datasets/methods
1007 with a perceived more ‘truthful’ dataset (i.e. field-based survey) (Smith et al., 2006). The number, size
1008 and shape of mapped landforms in comparison with a ‘true’ dataset can be used as an approximation
1009 of mapping reliability. Precision and accuracy of the produced geomorphological map can also be
1010 estimated based on the quality of the source data. Most of the datasets are delivered with at least some
1011 assessment of uncertainties, often expressed as accuracy; for example, the SRTM DEM has a
1012 horizontal accuracy of ± 20 m and a vertical accuracy of ± 16 m (Rabus et al., 2003). Alternatively,
1013 some remotely-sensed datasets have an associated *total root mean square error* (RMSE), which
1014 indicates displacement between ‘true’ control points and corresponding points on the remotely-sensed
1015 data (Wolf et al., 2013). However, both are measures of the overall (‘global’) quality of the dataset.
1016 Thus, these errors may be deceptive because such ‘global’ measures ignore spatial patterns of errors
1017 and local terrain characteristics (cf. Lane et al., 2005; James et al., 2017). For example, DEM errors
1018 will typically be more pronounced on steep slopes, where even a small horizontal shift will incur large
1019 differences in elevation.

1020

1021 Ideally, remotely-sensed datasets should be evaluated independently by the mapper to establish their
1022 geolocation accuracy (accuracy of x , y and z coordinates). If feasible, surveys of ground control points
1023 (GCPs) should be conducted using geodetic-grade surveying equipment (e.g. RTK-GPS, total station).
1024 A sub-sample of this GCP dataset can be used for photogrammetric processing, and RMSE values
1025 calculated. Subsequently, the remaining GCPs (i.e. those not used for photogrammetric processing)
1026 can be used to perform a further quality check, by quantifying deviations from the coordinates of the
1027 GCPs and the corresponding points on the generated DEM (e.g. Carrivick et al., 2017). An additional
1028 approach, in geomorphologically stable areas, is to compare the location of individual data points
1029 from the DEM (or raw point cloud) being used for mapping with those on a reference DEM (or raw
1030 point cloud) (e.g. King et al., 2016b; Carrivick et al., 2017; James et al., 2017; Midgley and Tonkin,
1031 2017; Mertes et al., 2017). Parameters such as the mean deviation, standard deviation and relative
1032 standard deviation between the two datasets can then be calculated to perform a quantitative

1033 assessment of quality and accuracy of the DEM (e.g. King et al., 2016b; Mertes et al., 2017).
1034 Performing these assessments may then facilitate correction of the processed datasets (e.g. Nuth and
1035 Käab, 2011; Carrivick et al., 2017; King et al., 2017).

1036

1037 To some extent, residual uncertainties relating to the skill, philosophy and experience of the mapper
1038 may be reduced by developing a set of clear criteria for identifying and mapping particular landforms
1039 (e.g. Barrell et al., 2011; Darvill et al., 2014; Bendle et al., 2017a; Lovell and Boston, 2017). That
1040 said, there are currently no ‘agreed’ genetic classification schemes for interpreting glacial sediment-
1041 landform assemblages, despite the development of facies and landsystem models for particular glacial
1042 environments (e.g. Eyles, 1983; Brodzikowski and van Loon, 1991; Evans, 2003a; Benn and Evans,
1043 2010). Indeed, terminologies are inconsistently used in glacial geomorphological research, as different
1044 ‘schools’ or traditions still exist. Thus, it is probably most appropriate to select a scheme that has been
1045 in frequent use in a given area (to enable ready comparison) or to develop one suited for a particular
1046 area or problem. Notwithstanding potential discrepancies relating to genetic classification or
1047 terminology, this will at least ensure transparency in future use and analysis of the geomorphological
1048 mapping.

1049

1050 Given the influence of the individual mapper on accuracy and precision, it may be beneficial and
1051 desirable for multiple mappers to complete (initially) independent field surveys and examination of
1052 remotely-sensed datasets to enhance reliability and reproducibility (cf. Hillier et al., 2015; Ewertowski
1053 et al., 2017). However, this approach would only be applicable in collaborative efforts and may be
1054 impractical due to various factors (e.g. study area size, data access restrictions). The level of detection
1055 of individual landforms might be improved by employing multiple methods to enhance landform
1056 detectability, whilst the genetic interpretation of landforms (landform classification) can be tested by
1057 detailed sedimentological investigations (see Section 2.3). Some uncertainties associated with the
1058 quality of data source (e.g. shadows, artefacts) can be alleviated, at least partly, by examining multiple
1059 complementary remotely-sensed datasets and mapping at a variety of scales.

1060

1061 **5. Scale-appropriate mapping approaches**

1062

1063 The following sections place the main geomorphological mapping methods (see Sections 2 and 3) in
1064 the spatial and temporal context of the glacial settings in which they are commonly used,
1065 demonstrating that particular methods are employed depending on factors such as the size of the study
1066 area, former glacial system and landforms (Table 3). We focus on three broad glacial settings for the
1067 purposes of this discussion: palaeo-ice sheets (Section 5.1), alpine- and plateau-style ice masses
1068 (Section 5.2) and modern glacier forelands (Section 5.3). Although geomorphological mapping in
1069 modern glacial settings follows the same general procedures as in former alpine and plateau-style ice

1070 mass settings (see Section 6.2), specific consideration of contemporary glacier forelands is warranted
1071 due to important issues relating to the temporal resolution of remotely-sensed data and landform
1072 preservation potential, which are not as significant in palaeoglaciological settings.

1073

1074 *5.1 Palaeo-ice sheet settings*

1075

1076 The continental-scale of palaeo-ice sheets typically necessitates a mapping approach that enables
1077 systematic mapping of a large area in a time and cost-effective manner while still allowing accurate
1078 identification of landform assemblages at a variety of scales. However, the nature of the approach will
1079 differ depending on the aim of the investigation, as this fundamentally determines *what* needs to be
1080 mapped and *how* it should be mapped. Palaeo-ice sheet reconstructions have been produced at a range
1081 of scales, from entire ice sheets (e.g. Dyke and Prest, 1987a, b, c; Kleman et al., 1997, 2010; Boulton
1082 et al., 2001; Glasser et al., 2008; Clark et al., 2012; Livingstone et al., 2015) to regional/local sectors
1083 (e.g. Hättestrand, 1998; Jansson et al., 2003; Stokes and Clark, 2003; Ó Cofaigh et al., 2010;
1084 Astakhov et al., 2016; Darvill et al., 2017). Depending on the aim of the study, some investigations
1085 may focus specifically on mapping particular landforms. For example, studies of ice-sheet flow
1086 patterns frequently focus on mapping subglacial bedforms, such as drumlins (e.g. Boulton and Clark,
1087 1990a, b; Kleman et al., 1997, 2010; Stokes and Clark, 2003; Hughes et al., 2010). Nonetheless,
1088 cartographic reduction is often still required to manage the volume of information, resulting in the
1089 grouping of similarly-orientated bedforms into flow-sets (occasionally termed fans or swarms) (e.g.
1090 Jansson et al., 2002, 2003; De Angelis and Kleman, 2007; Greenwood and Clark, 2009a, b; Stokes et
1091 al., 2009; Hughes et al., 2014; Atkinson et al., 2016).

1092

1093 In many cases, studies incorporate all or most of the landforms across ice sheet scales to derive
1094 palaeoglaciological reconstructions (e.g. Kleman et al., 1997, 2010; Stroeven et al., 2016). The
1095 rationale for this is that glaciation styles and processes (e.g. ice-marginal, subglacial) can be inferred
1096 from particular combinations of landforms in landform assemblages (e.g. Clayton et al., 1985; Stokes
1097 and Clark, 1999; Evans, 2003b; Kleman et al., 2006; Evans et al., 2008, 2014; Darvill et al., 2017;
1098 Norris et al., 2018). Establishing relationships between landforms is therefore valuable, not only in
1099 understanding glaciation styles, but also in helping decipher the relative sequence of formation (e.g.
1100 Clark, 1993; Kleman and Borgström, 1996) that may lay the foundations for absolute dating.
1101 Typically, ice sheet investigations are focused on the spatial and temporal evolution of these various
1102 aspects, requiring the robust integration of geomorphological mapping with absolute dating
1103 techniques (see Stokes et al., 2015). For example, following pioneering palaeoglaciological studies of
1104 the Fennoscandian ice sheet (e.g. Kleman, 1990, 1992; Kleman and Stroeven, 1997; Kleman et al.,
1105 1997), cosmogenic nuclide exposure dating offered a means to quantify dates and rates (e.g. Fabel et
1106 al., 2002, 2006; Stroeven et al., 2002a, b, 2006; Harbor et al., 2006). Such data are crucial to tune and

1107 validate numerical models used to reconstruct evolving ice sheet limits, flow configurations and
1108 subglacial processes (e.g. Boulton and Clark, 1990a, b; Näslund et al., 2003; Evans et al., 2009b;
1109 Hubbard et al., 2009; Stokes and Tarasov, 2010; Kirchner et al., 2011; Livingstone et al., 2015; Stokes
1110 et al., 2016b; Patton et al., 2017a, b).

1111

1112 *5.1.1 Manual mapping of palaeo-ice sheet geomorphological imprints*

1113 Satellite imagery and DEMs are the prevailing remotely-sensed datasets used for mapping ice sheet-
1114 scale landforms, and these datasets have been at the forefront of key developments in the
1115 understanding of palaeo-ice sheets (cf. Stokes, 2002; Stokes et al., 2015). Notably, the use of satellite
1116 imagery resulted in the identification of hitherto-unrecognised mega-scale glacial lineations (MSGs;
1117 Boulton and Clark, 1990a, b; Clark, 1993), which are now recognised as diagnostic geomorphological
1118 evidence of ice streams within palaeo-ice sheets (see Stokes and Clark, 1999, 2001, and references
1119 therein). This has allowed tangible links to be made between the behaviours of former Quaternary ice
1120 sheets and present-day ice sheets (e.g. King et al., 2009; Stokes and Tarasov, 2010; Stokes et al.,
1121 2016b). Aerial photograph interpretation and field mapping are also used in some studies (e.g.
1122 Hättestrand and Clark, 2006; Kleman et al., 2010; Darvill et al., 2014), but satellite imagery and
1123 DEMs are in wider usage for practical reasons (see also Section 3.2). In recent years, the development
1124 of LiDAR datasets has led to their increasing application for high resolution mapping of landforms
1125 formed by palaeo-ice sheets, particularly in Scandinavia (e.g. Dowling et al., 2015; Greenwood et al.,
1126 2015; Ojala et al., 2015; Ojala, 2016; Mäkinen et al., 2017; Peterson et al., 2017). We expect this to be
1127 a major area of growth in future mapping studies of former ice sheets.

1128

1129 Mapping glacial landforms from remotely-sensed data typically involves manual on-screen
1130 digitisation using one of two main approaches: (i) creating polylines along the crestline or thalweg of
1131 landforms or (ii) digitising polygons that delineate the breaks of slope around landform margins (i.e.
1132 digitising the planform). The approach employed will depend on the requirements of the study; for
1133 example, flow-parallel bedforms (e.g. drumlins and MSGs) have variously been mapped as polylines
1134 (e.g. Kleman et al., 1997, 2010; Stokes and Clark, 2003; De Angelis and Kleman, 2007; Storrar and
1135 Stokes, 2007; Livingstone et al., 2008; Brown et al., 2011b) and polygons (e.g. Hättestrand and
1136 Stroeven, 2002; Hättestrand et al., 2004; Hughes et al., 2010; Spagnolo et al., 2010, 2014; Stokes et
1137 al., 2013; Ely et al., 2016a; Bendle et al., 2017a) (Figure 13). The rationale behind mapping flow-
1138 parallel bedforms as linear features is that dominant orientations of a population provide sufficient
1139 information when investigating ice sheet-scale flow patterns and organisation, although image
1140 resolution may also be a determining factor. Mapping polygons allows the extraction of individual
1141 landform metrics (e.g. elongation ratios) that can provide insights into subglacial processes (e.g. Ely
1142 et al., 2016a) and regional variations in ice sheet flow dynamics (e.g. Stokes and Clark, 2002, 2003;
1143 Hättestrand et al., 2004; Spagnolo et al., 2014), but it is far more time-consuming than digitising

1144 linear features. Increasingly, it is being recognised that the population metrics and spectral
1145 characteristics of the subglacial bedform ‘field’ as a whole are most important for quantifying
1146 bedforms and deciphering subglacial processes and conditions (see Hillier et al., 2013, 2016;
1147 Spagnolo et al., 2017; Clark et al., 2018b; Ely et al., 2018; Stokes, 2018).

1148

1149 *5.1.2 Automated mapping of palaeo-ice sheet geomorphological imprints*

1150

1151 Comprehensive mapping of palaeo-ice sheet geomorphological imprints, and particularly of
1152 bedforms, typically entails the identification and mapping of large numbers (in some cases >10,000)
1153 of the same, or very, similar types of features (e.g. Clark et al., 2009; Kleman et al., 2010; Storrar et
1154 al., 2013). The manual digitisation of such large numbers of landforms is a time-consuming process.
1155 Consequently, semi-automated and automated mapping techniques are increasingly being applied to
1156 glacial geomorphology (e.g. Napieralski et al., 2007b; Saha et al., 2011; Maclachlan and Eyles, 2013;
1157 Eisank et al., 2014; Robb et al., 2015; Yu et al., 2015; Jorge and Brennand, 2017a, b), particularly
1158 given that features of a single landform type (e.g. drumlins or MSGs) will have fairly uniform
1159 characteristics (orientation, dimensions and morphology). Automated and semi-automated mapping
1160 techniques typically use either a pixel- or object-based approach (see Robb et al., 2015, and references
1161 therein). Thus far, automated and semi-automated approaches have primarily focused on mapping
1162 drumlins or MSGs from medium- to high-resolution DEMs. Several methods have been used,
1163 including multi-resolution segmentation (MRS) algorithms (Eisank et al., 2014), a Curvature Based
1164 Relief Separation (CBRS) technique (Yu et al., 2015), Object Based Image Analysis (OBIA) (Saha et
1165 al., 2011; Robb et al., 2015), and clustering algorithms (Smith et al., 2016b).

1166

1167 Most recently, 2D discrete Fourier transformations have been applied to automatically quantify
1168 MSGs (see Spagnolo et al., 2017). In contrast to traditional mapping approaches, this new method
1169 analyses the whole topography simultaneously to identify the wavelength and amplitude of periodic
1170 features (i.e. waves or ripples across the topography) without the need to manually digitise them. This
1171 automated approach is in its infancy but is likely to provide quantitative data that are useful for (i)
1172 testing and parameterising models of subglacial processes and landforms (e.g. Barchyn et al., 2016;
1173 Stokes, 2018) and (ii) facilitating comparison between subglacial bedforms and other bedforms (e.g.
1174 Fourrière et al., 2010; Kocurek et al., 2010; Murray et al., 2014).

1175

1176 *5.2 Alpine and plateau glacial settings*

1177

1178 Mapping the geomorphological imprints of former alpine- and plateau-style ice masses (cirque
1179 glaciers, valley glaciers, icefields and ice-caps) is particularly significant, since the geomorphological
1180 imprints of such discrete ice masses facilitate reconstructions of their three-dimensional form (extent,

1181 morphology and thickness). By contrast, establishing the vertical limits, thickness distribution and
1182 surface topography of palaeo-ice sheets is challenging (cf. Stokes et al., 2015). Importantly, three-
1183 dimensional glacier reconstructions permit the calculation of palaeoclimatic boundary conditions for
1184 glaciated regions (e.g. Kerschner et al., 2000; Bakke et al., 2005; Stansell et al., 2007; Mills et al.,
1185 2012; Boston et al., 2015), data that cannot be obtained from point-source palaeoenvironmental
1186 records in distal settings (e.g. lacustrine archives). Empirical palaeoclimatic data derived from glacier
1187 reconstructions are important for three reasons. Firstly, these data facilitate analyses of wind patterns
1188 across loci of former glaciers and, in a wider context, regional precipitation gradients and atmospheric
1189 circulation patterns (e.g. Ballantyne, 2007a, b). Secondly, the data allow glaciodynamic conditions
1190 reconstructed from sediment-landform assemblages (e.g. moraines) to be directly linked to climatic
1191 regimes, thereby providing insights into glacier-climate interactions at long-term timescales (e.g.
1192 Benn and Lukas, 2006; Lukas, 2007a). Finally, independent, empirical information on climatic
1193 boundary conditions is fundamental to parameterising and testing numerical models used to simulate
1194 past glacier-climate interactions (e.g. Golledge et al., 2008). Thus, the geomorphological records of
1195 alpine and plateau-style ice masses are powerful proxies for understanding the interactions of such ice
1196 masses with climate.

1197
1198 Alpine- and plateau-style ice masses encompass a broad spatial spectrum of glacier morphologies (cf.
1199 Sugden and John, 1976; Benn and Evans, 2010), but geomorphological mapping of glacial landforms
1200 in alpine and plateau settings generally follows a similar approach that combines remote sensing and
1201 considerable field mapping/checking (Figure 14; e.g. Federici et al., 2003, 2017; Bakke et al., 2005;
1202 Lukas and Lukas, 2006; Reuther et al., 2007; Hyatt, 2010; Bendle and Glasser, 2012; Pearce et al.,
1203 2014; Borsellino et al., 2017). Hence, alpine- and plateau-style ice masses are considered collectively
1204 here. The similarities in mapping approaches across a wider range of spatial scales partly reflect the
1205 fact that, in both alpine and plateau settings, the majority of (preserved) glacial landforms are
1206 confined to spatially- and/or topographically-restricted areas (e.g. glaciated valleys), i.e. glacial
1207 landforms relating to plateau-style ice masses (i.e. plateau icefields, ice-caps) are dominantly formed
1208 by outlet glaciers. Conversely, an important component of mapping in upland environments is often
1209 assessing any glacial geomorphological evidence for connections between supposed valley glaciers
1210 and plateau surfaces/rounded summits, i.e. alpine vs. plateau styles of glaciation (e.g. McDougall,
1211 2001; Boston et al., 2015). The recognition of any plateau-based ice has significant implications for
1212 studies aiming to assess glacier dynamics and regional palaeoclimate (see Rea et al., 1999; Boston,
1213 2012a, and references therein). Consequently, it is important to utilise a versatile geomorphological
1214 mapping approach in alpine and plateau settings that allows mapping of glacial landforms at a wide
1215 range of spatial scales and potentially across very large areas (>500 km²), whilst also providing
1216 sufficiently high resolution imagery to map planforms of individual, small landforms (e.g. moraines).

1217

1218 5.2.1 Remote mapping of alpine and plateau settings

1219

1220 Glacial geomorphological mapping from remotely-sensed data in alpine and plateau ice mass settings
1221 typically involves interpretation of either analogue or digital aerial photographs (see Sections 3.1 and
1222 3.2.2.2; e.g. Bickerton and Matthews, 1993; Boston, 2012a; Finlayson et al., 2011; Lukas, 2012;
1223 Izagirre et al., 2018). This reflects the superior resolution required to map in detail the frequently
1224 smaller glacial landforms produced by alpine and plateau-style ice masses, by contrast to the coarser
1225 resolution satellite imagery and DEMs predominantly used in ice sheet settings (see Section 5.1). The
1226 use of analogue (hard-copy) and digital aerial photographs varies in alpine and plateau settings,
1227 depending on data availability and the preference of individual mappers. For example, hard-copy,
1228 panchromatic aerial photographs have been widely used in conjunction with stereoscopes (see Section
1229 3.1) for mapping Younger Dryas glacial landforms in Scotland, owing to their excellent tonal contrast
1230 (e.g. Benn and Ballantyne, 2005; Lukas and Lukas, 2006; Boston, 2012a, b). Indeed, depending on the
1231 environment and quality/resolution of available remotely-sensed imagery, panchromatic, stereoscopic
1232 aerial photographs can provide the most accurate approach (in terms of landform identification), with
1233 photographs of this format having superior tonal contrast than their digital (colour) counterparts:
1234 digital colour aerial photographs may appear ‘flat’ (i.e. shadows are absent or less pronounced)
1235 making it more difficult to pick out subtle features, particularly in the absence of *SOCET SET* stereo
1236 display software and equipment (see Section 3.2.2.2). Nevertheless, mapping from digital aerial
1237 photographs has the advantage of providing georeferenced data and avoiding the duplication of effort,
1238 with hand-drawing on acetate overlays necessitating subsequent digitisation (see Sections 3.1 and
1239 3.2). Although panchromatic aerial photographs are invariably older, temporality usually presents no
1240 issue in palaeoglaciological (non-glacierised) settings, with the critical factor being image quality.

1241

1242 Irrespective of the type of aerial photographs used for geomorphological mapping, georectification is
1243 required to ensure accurate depiction of glacial landforms on the final maps (Section 3.3). This is
1244 important for minimising potential geospatial errors that will propagate into any subsequent glacier
1245 reconstructions and analyses of glacier-climate interactions. Ideally, georectification would involve
1246 stereoscopic photogrammetry, as discussed in Section 3.3, but this approach is impractical for larger
1247 ice masses (i.e. plateau icefields and plateau ice-caps). Thus, it is necessary to apply the pragmatic
1248 solutions described in Section 3.3.1.1, namely georectifying the aerial photographs or acetate overlays
1249 to other (coarser) georeferenced digital imagery or topographic data. Conversely, geomorphological
1250 studies at the scale of individual cirque basins, valley glaciers or glacier forelands would be
1251 appropriate for topographic surveys and hence stereoscopic photogrammetry, provided (i) the
1252 accessibility of the study area permits the use of surveying equipment and (ii) camera calibration data
1253 are available (see Section 3.3).

1254

1255 In some locations, coarse to medium resolution satellite imagery may be sufficient to map the
1256 geomorphological imprint of former or formerly more extensive icefields and ice-caps (Figure 15; e.g.
1257 Glasser et al., 2005; Heyman et al., 2008; Barr and Clark, 2009, 2012; Morén et al., 2011;
1258 Hochreuther et al., 2015; Loibl et al., 2015; Gribenski et al., 2016). However, these coarse remotely-
1259 sensed datasets may only allow for mapping of broad landform arrangements and patterns, rather than
1260 the intricate details of individual landforms, and preclude mapping of small features (cf. Barr and
1261 Clark, 2012; Fu et al., 2012; Stroeven et al., 2013; Blomdin et al., 2016b). The emergence of high-
1262 resolution (commercial) satellite imagery may result in more widespread use of satellite imagery for
1263 mapping in alpine and plateau settings, although the benefits of increased resolution may be
1264 counteracted by prohibitive costs for large study areas (see Section 3.2.2.1).

1265

1266 *5.2.2 Field mapping in alpine and plateau settings*

1267

1268 Detailed field mapping, following the procedures outlined in Section 2.2, has been widely applied as
1269 part of geomorphological studies focused on alpine- and plateau-style ice masses (e.g. Benn, 1992;
1270 Federici et al., 2003, 2017; Lukas, 2007a; Reuther et al., 2007; Boston, 2012a; Małecki et al., 2018).
1271 Although field mapping is widely used in such settings, many studies do not explicitly report whether
1272 this entails field mapping *sensu stricto* (i.e. the procedure outlined in Section 2.2), or verification of
1273 landforms mapped from remotely-sensed data by direct ground observations ('ground truthing'). We
1274 reaffirm the points raised in Sections 2.2 and 2.3 that, whenever possible, field mapping should be
1275 combined with remote mapping in cirque glacier, valley glacier, icefield and ice-cap settings in order
1276 to identify subtle glacial landforms and test interpretations of ambiguous features. While we advocate
1277 the application of detailed field mapping, we recognise that logistical and/or financial issues may
1278 preclude this and that ground truthing (of selected areas) may only be possible. Nevertheless, some
1279 form of field survey is important in alpine and plateau settings to (i) circumvent potential issues with
1280 the quality/resolution of remotely-sensed data (e.g. poor tonal contrast) and (ii) arrive at definitive of
1281 glacial landforms and landscapes (see also Section 2.3)

1282

1283 *5.3 Modern glacial settings*

1284

1285 Many contemporary glacier forelands are rapidly evolving and new landscapes are emerging. This is
1286 largely due to changes resulting from the current retreat of ice masses and exposure of previously-
1287 glaciated terrain, leading to destabilisation of some landforms (e.g. Krüger and Kjær, 2000; Kjær and
1288 Krüger, 2001; Lukas et al., 2005; Lukas, 2011), erosion by changing meltwater routes and remoulding
1289 or complete obliteration of extant landforms in areas following a glacier re-advance or surge (e.g.
1290 Evans et al., 1999; Evans and Twigg, 2002; Evans, 2003b; Evans and Rea, 2003; Benediktsson et al.,
1291 2008). Glaciofluvial processes on active temperate glacier forelands (e.g. Iceland) often make these

1292 environments unfavourable for preservation of (small) landforms (e.g. Evans and Twigg, 2002;
1293 Evans, 2003b, Kirkbride and Winkler, 2012; Evans and Orton, 2015; Evans et al., 2016a). In addition,
1294 de-icing and sediment re-working processes prevalent in many modern glacial environments (e.g.
1295 Iceland, Svalbard) typically result in substantial ice-marginal landscape modification and topographic
1296 inversion (e.g. Etzelmüller et al., 1996; Krüger and Kjær, 2000; Kjær and Krüger, 2001; Lukas et al.,
1297 2005; Schomacker, 2008; Bennett and Evans, 2012; Ewertowski and Tomczyk, 2015). Anthropogenic
1298 activity can also have considerable implications for glacial systems (Jamieson et al., 2015; Evans et
1299 al., 2016b). The rapidity, ubiquity and efficacy of these censoring processes (cf. Kirkbride and
1300 Winkler, 2012, for further details) in contemporary glacial environments should be key considerations
1301 in geomorphological mapping studies; in particular, the recognition that ice-cored features mapped at
1302 a given interval in time are not the ‘final’ geomorphological products (cf. Krüger and Kjær, 2000;
1303 Kjær and Krüger, 2001; Everest and Bradwell, 2003; Lukas et al., 2005, 2007; Lukas, 2007b).

1304

1305 In addition to landform preservation potential, spatial and temporal scales will be key determinants in
1306 the approaches used in mapping of ice-marginal landscapes, with studies in such settings often
1307 focused on the formation of small features (<3 m in height) on recent, short-term timescales (0–30
1308 years) (e.g. Beedle et al., 2009; Lukas, 2012; Bradwell et al., 2013; Reinardy et al., 2013; Chandler et
1309 al., 2016b) and/or evolution of the glacier foreland over a given time period (e.g. Bennett et al., 2010;
1310 Bennett and Evans, 2012; Ewertowski, 2014; Jamieson et al., 2015; Chandler et al., 2016a, b; Evans et
1311 al., 2016a). Thus, the approach to geomorphological mapping discussed in Section 5.2 require some
1312 modification, as discussed below. It is also worth noting that geomorphological mapping usually
1313 forms part of process-oriented studies in modern glacial settings (Figure 16), often with the intention
1314 of providing modern analogues for palaeo-ice masses and their geomorphological imprints (e.g. Evans
1315 et al., 1999; Evans, 2011; Schomacker et al., 2014; Benediktsson et al., 2016).

1316

1317 Geophysical surveying methods can also strengthen links between modern and ancient landform
1318 records through surveying of the internal architecture of landforms that can be directly linked to
1319 depositional processes, as well as glaciological and climatic conditions (e.g. Bennett et al., 2004;
1320 Benediktsson et al., 2009, 2010; Lukas and Sass, 2011; Midgley et al., 2013, 2018). Recent advances
1321 in geophysical imaging of sub-ice geomorphology has allowed links to be made between modern and
1322 palaeo-ice sheets (see Section 3.2.2.3), and we expect this to a growth area going forward (see also
1323 Stokes, 2018). More broadly, geophysical methods can also be used to identify the extent of buried
1324 ice, allowing an assessment of the geomorphological stability of contemporary glacier forelands (e.g.
1325 Everest and Bradwell, 2003).

1326

1327 *5.3.1 Remote mapping of modern glacial settings*

1328 The spatial resolution of remotely-sensed data is of critical importance in modern glacial settings:
1329 spatial resolutions commensurate with the size of the landforms being mapped and the scope of the
1330 research are required. Typically, aerial photographs or satellite imagery with GSDs of <0.5 m are used
1331 in modern glacial settings to enable mapping of small features (e.g. Benediktsson et al., 2010; Lukas,
1332 2012; Bradwell et al., 2013; Brynjólfsson et al., 2014; Lovell, 2014; Schomacker et al., 2014;
1333 Chandler et al., 2016a; Ewertowski et al., 2016; Lovell et al., 2018). LiDAR or UAV-derived DEMs
1334 are also becoming increasingly used for mapping in modern glacial environments (e.g. Brynjólfsson et
1335 al., 2014, 2016; Jónsson et al. 2014, 2016; Benediktsson et al., 2016; Chandler et al., 2016a;
1336 Ewertowski et al., 2016; Everest et al., 2017; Lovell et al., 2018). Despite the high-resolution of the
1337 imagery, some compromise on the level of detail may be necessary, such as deciding on a maximum
1338 mapping scale (e.g. 1:500–1:1000, Schomacker et al., 2014) to prevent too detailed mapping or by
1339 simplifying the mapping of certain features. In studies of low-amplitude (annual) moraines, the
1340 crestlines rather than the planforms are typically mapped, reflecting a combination of image
1341 resolution and data requirements: annual moraine sequences are often used to calculate ice-margin
1342 retreat rates and mapping of crestlines is sufficient detail for this purpose (Figure 17; Krüger, 1995;
1343 Beedle et al., 2009; Lukas, 2012; Bradwell et al., 2013; Chandler et al., 2016a, b). Moreover, this
1344 approach can actually ‘normalise’ the data for subsequent analyses, removing the variability of, for
1345 example, moraine-base widths that result from gravitational processes during or after moraine
1346 formation.

1347

1348 The temporality (both month and year) of imagery takes on greater significance in modern glacial
1349 environments. Depending on the purpose of the research, either the most recent high resolution
1350 remotely-sensed dataset available or a series of images from a number of intervals during a given time
1351 period are commonly required (e.g. Benediktsson et al., 2010; Bennett et al., 2010; Bradwell et al.,
1352 2013; Reinardy et al., 2013; Chandler et al., 2016a; Evans et al., 2016b; Ewertowski et al., 2016). In
1353 exceptional circumstances, the research may require an annual temporal resolution; for example,
1354 aerial photographs are commonly captured annually at the beginning and end of the ablation season in
1355 many forelands of the European Alps (cf. Lukas, 2012; Zemp et al., 2015). The burgeoning use of
1356 UAVs provides very high-resolution imagery (<0.1 m GSD) of contemporary glacier forelands and
1357 the option to capture up-to-date imagery during every visit to the site, circumventing issues relating to
1358 temporal resolution. This approach is likely to come into greater usage for studies examining short-
1359 term ice-marginal landscape evolution and preservation potential.

1360

1361 Photogrammetric image processing (see Section 3.3) is arguably of most importance in contemporary
1362 glacial environments, particularly where the purpose of the mapping is to investigate small variations
1363 of the order of metres to tens of metres at short-term (0–30 years) timescales (cf. Evans, 2009).
1364 However, such constraints are not necessarily applicable where broader landsystem mapping is

1365 conducted (e.g. Evans, 2009; Evans and Orton, 2015; Evans et al., 2016a). Ideally, digital aerial
1366 photographs should be processed using stereoscopic photogrammetry techniques using GCPs
1367 collected during topographic surveys to enable the production of DEMs and orthorectified imagery
1368 with low error values (RMSEs <2 m; see Section 3.3). It is preferable to survey GCPs and capture
1369 imagery contemporaneously, with surveyed GCPs appearing in the captured aerial imagery (e.g.
1370 Evans and Twigg, 2002; Evans et al., 2006, 2012; Schomacker et al., 2014), but imagery often pre-
1371 dates the geomorphological investigations and topographic surveys (e.g. Bennett et al., 2010;
1372 Bradwell et al., 2013; Chandler et al., 2016b). Alternatively, the digital aerial photographs could be
1373 processed using SfM photogrammetry methods (see Section 3.3.1.2).

1374

1375 *5.3.2 Field mapping in modern glacial settings*

1376 The rapidly-changing nature of modern glacier forelands presents a number of challenges when using
1377 topographic base maps (see Section 2). Firstly, in relation to spatial limitations, topographic maps
1378 available in many settings (typically at scales of 1: 25,000 or 1: 50,000) may offer insufficient spatial
1379 resolution for mapping: (i) the relief of the small geomorphological features ubiquitous in
1380 contemporary glacial environments is often less than the contour intervals depicted on the maps; and
1381 (ii) many forelands, such as those of southeast Iceland, have limited elevation changes across the
1382 foreland (cf. Evans and Twigg, 2002; Evans et al., 2016a).

1383

1384 Publicly-available topographic maps are rarely updated frequently enough to be useful for mapping
1385 the often rapid (annual to decadal-scale) changes exhibited by modern glacier margins and proglacial
1386 landscapes. Instead, it is desirable to undertake geodetic-grade surveying (i.e. using an RTK-GPS) of
1387 landforms and measurement of high-resolution topographic profiles, where conditions allow a safe
1388 approach towards the glacier margin (e.g. Benediktsson et al., 2008; Bradwell et al., 2013). Indeed,
1389 conducting detailed surveying with geodetic-grade equipment is essential for quantifying small
1390 changes in ice-marginal/proglacial landscapes (e.g. Schomacker and Kjær, 2008; Ewertowski and
1391 Tomczyk, 2015; Korsgaard et al., 2015) and obtaining metre-scale ice-margin retreat rates from the
1392 geomorphological record (e.g. Bradwell et al., 2013; Chandler et al., 2016a). This level of detail and
1393 accuracy may be unnecessary for some glacial geomorphological studies (e.g. those focused on the
1394 overall glacial landsystem), and annotation of aerial photograph extracts may be sufficient. There are
1395 still potential temporal limitations with these approaches, namely (a) limitations imposed by the
1396 date/year of image capture when mapping on print-outs and (b) difficulties with correlating survey
1397 data with imagery, depending on the time difference and rapidity of landscape changes. In localities
1398 where (parts of) the ice-marginal/proglacial landscape cannot be satisfactorily or safely traversed,
1399 imagery and elevation control from remotely-sensed sources will be necessary (e.g. Evans et al.,
1400 2016e).

1401

1402 **6. Frameworks for best practice**

1403

1404 Based on our review of the various mapping approaches, we here synthesise *idealised* frameworks for
1405 mapping palaeo-ice sheet geomorphological imprints (Section 6.1) and alpine and plateau-style ice
1406 mass (cirque glaciers, valley glaciers, ice-fields and ice-caps) geomorphological imprints (Section
1407 6.2). The aim is to provide frameworks for best practice in glacial geomorphological mapping,
1408 ensuring robust and systematic geomorphological mapping programmes. The templates outlined can
1409 be modified as necessary, depending on the study area size and project scope, along with the datasets,
1410 software and time available.

1411

1412 Before outlining the idealised frameworks, we offer four general recommendations for undertaking
1413 and reporting glacial geomorphological mapping that are applicable at all scales of investigation:

1414

1415 (1) The methods, datasets and equipment employed in mapping should be clearly stated,
1416 including the resolution and format of remotely-sensed data.

1417 (2) Any processing methods and imagery rectification errors (RMSEs) should be reported, as
1418 well as mapping uncertainties (both in terms of the location of the landforms and their
1419 identification/classification). Where remotely-sensed datasets are obtained as pre-processed,
1420 georeferenced products, this should also be stated.

1421 (3) Establishing and reporting criteria for identifying and mapping different landforms is
1422 desirable (e.g. Barrell et al., 2011; Darvill et al., 2014; Bendle et al., 2017a; Lovell and
1423 Boston, 2017). As a minimum, this could take the form of a brief definition of the mapped
1424 landform (e.g. Storrar and Livingstone, 2017).

1425 (4) GIS software (e.g. *ArcGIS*, *QGIS*) should be used for geomorphological mapping and
1426 digitisation to provide georeferenced geomorphological data.

1427

1428 Following the above general recommendations will provide transparency about how the mapping was
1429 compiled and what considerations were made during the process, aiding accuracy assessment,
1430 comparison and integration of geomorphological data. This is particularly valuable for the
1431 incorporation of the geomorphological mapping in large compilations (Bickerdike et al., 2016;
1432 Stroeven et al., 2016; Clark et al., 2017a) and subsequently using the data for palaeoglaciological
1433 reconstruction and/or testing numerical ice sheet models (Stokes et al., 2015; Margold et al., 2018).

1434

1435 In relation to software (recommendation 4), some practitioners may prefer to use graphics software
1436 packages (e.g. *Adobe Illustrator*, *Canvas X*, *CorelDRAW*) for producing final glacial
1437 geomorphological maps (e.g. Brynjólfsson et al., 2014; Darvill et al., 2014; Chandler et al., 2016a;
1438 Bendle et al., 2017a; Norris et al., 2017). Such graphics software can provide greater functionality

1439 than current GIS packages for fine adjustments of the final cartographic design. However, any
1440 modification in graphics software should be kept to a minimum in order to avoid compromising the
1441 transferability of the data for other users (e.g. as shapefiles), with the focus instead on adjustments to
1442 the map symbology and ensuring optimal map presentation.

1443

1444 *6.1 Palaeo-ice sheet geomorphological imprints*

1445

1446 For mapping of palaeo-ice sheet geomorphological imprints we recommend the use of multiple
1447 remotely-sensed datasets in a synergistic and systematic process, subject to data availability and
1448 coverage (Figure 18). As a minimum, remote-sensing investigations should involve reconnaissance-
1449 level mapping using multiple remotely-sensed datasets to establish the most suitable dataset (e.g.
1450 Stokes et al., 2016a). However, mapping often benefits from utilising a range of imagery types and
1451 resolutions, enabling the advantages of each respective method/dataset to be integrated to produce an
1452 accurate geomorphological map (see below). At the outset of the mapping, a decision should be made
1453 on the level of mapping detail required for particular landforms (i.e. polyline or polygon mapping), in
1454 line with the aims and requirements of the study (see Section 5.1.1).

1455

1456 Initially, mapping should involve an assessment of the study area using remotely-sensed data in
1457 conjunction with existing maps and literature to identify gaps in the mapping record and localities for
1458 focused mapping. Following this reconnaissance stage, the mapper may proceed with mapping from
1459 both DEMs and satellite imagery, adding increasing levels of detail with increasingly higher
1460 resolution datasets. Recommended techniques for processing the satellite images and DEMs are
1461 outlined in Sections 3.3.2 and 3.3.3, including the generation of false-colour composites with different
1462 spectral band combinations to aid landform identification (e.g. Jansson and Glasser, 2005; Lovell et
1463 al., 2011; Storrar and Livingstone, 2017).

1464

1465 DEMs may provide a superior source of imagery as they directly record the shape of landforms, rather
1466 than the interaction of reflected radiation and topography, and therefore allow for more accurate and
1467 intuitive mapping. For example, DEMs are often particularly useful for identifying and mapping
1468 meltwater channels (e.g. Greenwood et al., 2007; Storrar and Livingstone, 2017). Specific features
1469 may also only be identifiable on satellite imagery, such as low-relief corridors of glaciofluvial
1470 deposits, due to their distinctive spectral signatures (e.g. Storrar and Livingstone, 2017). Moreover,
1471 the typically superior resolution of satellite imagery may enhance landform detectability and allow for
1472 more detailed mapping. Many glacial landforms are also clearly distinguishable in one or more sets of
1473 remotely-sensed data (or through using a combination of datasets).

1474

1475 To ensure that all landforms are mapped from remotely-sensed data, the datasets should be viewed at
1476 a variety of scales and mapping conducted through multiple passes of the area, enabling the addition
1477 of increasing levels of detail to and/or refinement of initial mapping with each pass (Norris et al.,
1478 2017). It may be advantageous to perform a final check at a small cartographic scale (e.g. 1:500,000)
1479 to ensure there are no errors in the mapping, such as duplication of landforms at image overlaps (e.g.
1480 De Angelis, 2007). The mapping should be iterative, with repeated consultations of various remotely-
1481 sensed datasets throughout the process recommended.

1482

1483 In this contribution, we have focused on the use of satellite imagery and DEMs for mapping palaeo-
1484 ice sheet geomorphological imprints, since these are the most widely used for practical reasons.
1485 However, aerial photograph interpretation and fieldwork should not be abandoned altogether in
1486 palaeo-ice sheet settings. Aerial photographs, where available, can be used to add further detail and
1487 refine the mapping, whilst fieldwork enables ground-truthing of remote mapping (e.g. Hättestrand and
1488 Clark, 2006; Kleman et al., 2010; Darvill et al., 2014; Evans et al., 2014). Furthermore, mapping from
1489 satellite imagery and DEMs can direct fieldwork, highlighting areas for sedimentological and
1490 stratigraphic investigations. Such studies can provide invaluable data on landform genesis, subglacial
1491 processes and ice dynamics (e.g. Livingstone et al., 2010; Evans et al., 2015; Spagnolo et al., 2016;
1492 Phillips et al., 2017; Norris et al., 2018). Remote mapping of palaeo-ice sheet geomorphology also
1493 guides targeted dating for chronological investigations and should be an essential first phase in such
1494 studies (e.g. Darvill et al., 2014, 2015).

1495

1496 *6.2 Alpine and plateau-style ice mass geomorphological imprints*

1497

1498 Our idealised framework for mapping alpine and plateau-style ice mass geomorphological imprints is
1499 an iterative process involving several consultations of remotely-sensed data and field mapping
1500 (Figures 19 and 20). This methodology provides a robust approach to mapping that has been broadly
1501 used in previous studies (e.g. Benn and Ballantyne, 2005; Lukas and Lukas, 2006; Kjær et al., 2008;
1502 Boston, 2012a, b; Brynjólfsson et al., 2014; Jónsson et al., 2014; Pearce et al., 2014; Schomacker et
1503 al., 2014; Chandler et al., 2016a; Chandler and Lukas, 2017). This framework is also applicable to
1504 modern glacial settings as the overarching methods do not differ fundamentally, but practitioners
1505 should be aware of issues relating to the temporal resolution of remotely-sensed data (see Section
1506 5.3).

1507

1508 In the initial preparatory stage, the mapper should consult topographic, geological and extant
1509 geomorphological maps (where available), and ideally undertake mapping of the study area using
1510 remotely-sensed data, at least at a reconnaissance level. This essential phase familiarises the mapper
1511 with the study area prior to fieldwork and enables the identification of significant areas for targeted,

1512 detailed field mapping (or ground verification) and sedimentological investigations of specific
1513 landforms. Conversely, the reconnaissance investigations may also clarify which areas are less
1514 important for a field visit and aid route planning. Importantly, this enables a systematic approach to
1515 mapping, and is particularly important in previously-unmapped areas (e.g. Boston, 2012a, b). During
1516 the initial stage, it may also be desirable to establish a legend/mapping system in readiness for
1517 subsequent field mapping (Otto and Smith, 2013).

1518
1519 Following the preparatory/reconnaissance stage, detailed field mapping, or at a minimum some
1520 ground verification, should ideally be conducted to avoid overlooking (subtle) landforms and
1521 misinterpreting others. Depending on the nature of the project and accessibility limitations, ground
1522 verification may be done during a single (and relatively short) field visit (e.g. Lukas, 2012; Chandler
1523 et al., 2016a), whilst detailed field mapping would usually require longer field visits or even repeated,
1524 long-term field campaigns (e.g. Kjær et al. 2008; Boston, 2012a, b; Schomacker et al., 2014; Evans et
1525 al., 2016a). During field surveys, consultation of initial remote mapping helps to ensure accurate
1526 representation of landforms on field maps and allows verification of all features identified remotely
1527 (e.g. Boston, 2012a, b; Pearce et al., 2014).

1528
1529 Following field mapping, which may be an intermittent and ongoing process in the case of large study
1530 areas and long-term research projects, it is ideal to finalise the geomorphological mapping using high-
1531 resolution imagery (i.e. aerial photographs, satellite imagery, LiDAR DEMs, UAV-derived imagery).
1532 This allows complex patterns of landforms, such as Scottish ‘hummocky moraine’ (e.g. Lukas and
1533 Lukas, 2006; Boston, 2012b), crevasse-squeeze ridges (e.g. Kjær et al., 2008), drumlin fields (e.g.
1534 Benediktsson et al., 2016), and sawtooth ‘annual’ moraines (e.g. Chandler et al., 2016a; Evans et al.,
1535 2016a), to be mapped with high spatial accuracy, following landform identification and interpretation
1536 in the field. Again, during this stage, previous mapping from DEMs and field maps should be
1537 consulted. As highlighted in the scale-appropriate examples, the procurement of remotely-sensed data
1538 with appropriate spatial and temporal resolution is important (see Sections 5.2 and 5.3).

1539
1540 Depending on the type of imagery used (hard-copy or digital), the rectification of imagery/overlays
1541 may precede or follow aerial photograph mapping: where digital format aerial photographs are used,
1542 rectification will be undertaken before mapping (Figure 19), whilst acetate overlays will be corrected
1543 *after* mapping from hard-copy aerial photographs (Figure 20) (see also Supplementary Material).
1544 Subsequently, acetate overlays can be checked against digital imagery (if available) before being
1545 digitised, either in a GIS software package (e.g. *ArcMap*, *QGIS*) or in a graphics software package.

1546
1547 In our view, geomorphological mapping in cirque glacier, valley glacier and icefield/ice-cap outlet
1548 settings should not be reliant solely on the morphological characteristics of features and should ideally

1549 be combined with detailed sedimentological investigations of available exposures as part of an
1550 inductive-deductive process, using standard procedures (cf. Evans and Benn, 2004; Lukas et al., 2013,
1551 and references therein). This reflects the fact that these glacier systems occupy more manageable
1552 study areas and therefore sedimentological analyses can be more readily applied. By combining
1553 geomorphological mapping and sedimentology, issues relating to equifinality (Chorley, 1962; Möller
1554 and Dowling, 2018) will be avoided, which is important when attempting to establish the wider
1555 palaeoglaciological and palaeoclimatic significance of the geomorphological evidence (cf. Benn and
1556 Lukas, 2006). This multi-proxy, process-form approach ensures accurate genetic interpretations on
1557 geomorphological maps.

1558

1559 **7. Conclusions**

1560

1561 Geomorphological mapping forms the basis of a wide range of process-oriented, glacial chronological
1562 and palaeoglaciological studies. As such, it is imperative that effective approaches are used to ensure
1563 robust assimilation of data and that errors and uncertainties are explicitly reported. This is particularly
1564 the case where field mapping and analogue data are transferred to digital format and combined with
1565 digital remotely-sensed data.

1566

1567 In general, specific methods and datasets are often applied to particular glacial settings: (i) a mixture
1568 of satellite imagery (e.g. Landsat) and DEMs (e.g. ASTER GDEM, SRTM) are typically used for
1569 mapping in palaeo-ice sheet settings; and (ii) a combination of aerial photographs and field mapping
1570 are widely employed for mapping alpine and plateau-style ice mass geomorphological imprints.
1571 Increasingly, UAV-captured aerial imagery and high resolution DEMs (derived from UAV-captured
1572 imagery and LiDAR) are being utilised for mapping of modern glacial environments and are likely to
1573 be a growth area in future geomorphological mapping studies, enabling high resolution, multi-
1574 temporal remotely-sensed datasets to be obtained at relatively low cost. The usage of particular
1575 methods reflects the spatial and temporal resolution of remotely-sensed datasets, along with the
1576 practicality of their application (both in terms of time and finance).

1577

1578 In this contribution, we have highlighted that compromises and pragmatic solutions are often
1579 necessary in glacial geomorphological mapping, particularly with respect to processing techniques
1580 and the level of mapping detail. For example, detailed GNSS surveys using geodetic-grade equipment
1581 are desirable for photogrammetric processing of aerial photographs, but this is impractical for the
1582 large areas covered by icefields, ice-caps and ice sheets. Thus, pragmatic approaches may be used,
1583 such as georeferencing analogue-derived mapping to existing (coarser) georeferenced datasets (e.g.
1584 satellite imagery, DEMs or orthophotographs). In relation to the level of mapping detail, it is often

1585 necessary to map particular landforms as linear features (e.g. subglacial bedforms, moraines) or define
1586 a maximum scale during mapping, due to image resolution and/or study requirements.

1587

1588 Based on our review, we have outlined idealised frameworks and general recommendations to ensure
1589 best practice in future studies. In particular, we emphasise the importance of utilising multiple
1590 datasets or mapping approaches in synergy, akin to multi-proxy/-method approaches used in many
1591 Earth Science disciplines; multiple remotely-sensed datasets in the case of ice sheet-scale
1592 geomorphology and a combination of remote sensing and field mapping for cirque glaciers to ice-
1593 caps. Further key recommendations are the clear reporting of (i) the methods, datasets and equipment
1594 employed in mapping, (ii) any processing methods employed and imagery rectification errors
1595 (RMSEs) associated with imagery, along with mapping uncertainties, (iii) the criteria for identifying
1596 and mapping different landforms. We also recommend that mapping is conducted in GIS software to
1597 provide georeferenced geomorphological data. Finally, we advocate sedimentological investigations
1598 of available exposures as part of an inductive-deductive process during fieldwork to ensure accurate
1599 genetic interpretations of the geomorphological record as part of a holistic approach. Following these
1600 recommendations will aid in comparison, integration and accuracy assessment of geomorphological
1601 data, particularly where geomorphological data are incorporated in large compilations and
1602 subsequently used for palaeoglaciological reconstruction.

1603

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1621

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Figure captions

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

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

Figure 3. Satellite image (A) and geomorphological mapping (B) showing suites of moraines formed by the Lago General Carrera–Buenos Aires ice lobe of the former Patagonian Ice Sheet, located to the east of the present-day Northern Patagonian Icefield. A combination of remotely-sensed datasets and field mapping were used to circumvent issues of localised cloud cover, as visible in A. Where areas were obscured, SPOT-5 and DigitalGlobe images available in *Google Earth* were used. Note the extensive outwash development between moraine suites. The geomorphological map extract is taken from Bendle et al. (2017a).

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

2847

2848 **Figure 5.** Geomorphology of the Finsterwalderbreen foreland, Svalbard, mapped in the field and from
2849 a digital aerial photograph captured in 2004. Photograph provided by the NERC Earth Observation
2850 Data Centre. Modified from Lovell et al. (2018).

2851

2852 **Figure 6.** Views at various points along the length of the 1890 surge end moraine at Eyjabakkajökull,
2853 Iceland, visualised in *ESRI ArcScene* (Benediktsson et al., 2010). Aerial orthophotographs from 2008
2854 are draped over a 3 m grid DEM with 1.5x vertical exaggeration.

2855

2856 **Figure 7.** High-resolution geomorphological mapping of part of the Fláajökull foreland, Iceland,
2857 based on UAV-derived imagery (Evans et al., 2016a). A 1:350 scale version of this map is freely
2858 available for download from *Journal of Maps*: <http://dx.doi.org/10.1080/17445647.2015.1073185>.

2859

2860 **Figure 8.** Geomorphological mapping of lineations in northwest Saskatchewan, Canada, from SRTM
2861 imagery (modified from Norris et al., 2017). (A) and (B) Densely spaced drumlins displaying low
2862 length to width ratios. (C) and (D) Highly elongated fluting orientated NE–SW east of the Grizzly
2863 Bear Hills. Geomorphological map extracts in (C) and (D) show lineations (black lines), eskers (red
2864 lines) and meltwater channels (dashed blue lines).

2865

2866 **Figure 9.** Examples of landforms in relief-shaded DEMs. Red indicates higher elevations and blue
2867 lower elevations. (A) Lineations in N Canada shown in 16 m resolution CDED data. (B) De Geer
2868 moraines in SW Finland shown in 2 m resolution LiDAR data. (C) Lineations of the Dubawnt Lake
2869 Ice Stream shown in 5 m resolution ArcticDEM mosaic data. (D) Esker-fed ice-contact outwash fan in
2870 SW Finland shown in 2 m resolution LiDAR data. See Table 2 for DEM data sources.

2871

2872 **Figure 10.** Conceptual diagrams illustrating the distinction between ground sampled distance (B and
2873 E) and pixel size (C and F). The ground distances between two measurements by the detector (i.e. the
2874 ground sampled distances) are 30 m and 50 m in (B) and (E), respectively. These ground sample
2875 distances are then assigned to pixels in the resulting 30 x 30 m (C) and 50 x 50 m (F) digital images.
2876 Note, resultant images may fail to represent accurately the shape of the objects (upper row) or even
2877 may fail to reproduce them (lower row), even where the size of the object is the same or larger than
2878 the sampling distance.

2879

2880 **Figure 11.** Geometric artefacts that may be present in space- and air-borne radar captured imagery,
2881 resulting from the effects of relief. (A) **Foreshortening**, occurring where the slope of the local terrain
2882 is less than the incidence angle (γ). The facing slope, $a - b$, becomes compressed to $a_l - b_l$ in the
2883 resulting image. (B) **Layover**, occurring in steep terrain when the slope angle is greater than the

2884 incidence angle. As a mountain-top, b , is closer to the sensor than the base, a , this causes layover in
2885 the imagery (an incorrect positioning of b_l relative to a_l). (C) **Radar shadow** in areas of rugged
2886 terrain as the illumination is from an oblique source. No data is recorded for the region $b_l - d_l$. (D) In
2887 regions of varying topography, a **combination of artefacts** may be present: points b and c will be
2888 impacted by layover and will be positioned incorrectly relative to a ; no data will be recorded for the
2889 region between c and d due to radar shadow; foreshortening occurs at slope facet $d - e$; further radar
2890 shadow occurs at $e - f$; and foreshortening at f and g . After Clark (1997).

2891

2892 **Figure 12.** Extracts from hillshaded relief models of Ben More Coigach, NW Scottish Highlands,
2893 showing the effect of geometric artefacts on the models. The hillshades were generated with azimuths
2894 of 45° (A) and 315° (B). Stretching of upland terrain during processing of the DEM data results in
2895 blurred regions on the hillshaded relief models. NEXTMap DSM from Intermap Technologies Inc.
2896 provided by NERC via the NERC Earth Observation Data Centre.

2897

2898 **Figure 13.** Example mapping of subglacial bedforms from the Strait of Magellan, Patagonia (A–C),
2899 and the Dubawnt Lake Ice Stream (D–F). The bedforms are mapped as polylines along landform
2900 crests in B and E, and mapped as polygons delineating lower-break-of-slope in C and F. The Dubawnt
2901 Lake Ice Stream polylines (Stokes and Clark, 2003) and polygons (Dunstone, 2014) were mapped by
2902 different mappers at different times, which may account for small inconsistencies. For further details
2903 on the bedform examples from the Strait of Magellan, see Lovell et al. (2011) and Darvill et al.
2904 (2014).

2905

2906 **Figure 14.** Geomorphological mapping of Coire Easgainn, Monadhliath, Scotland, using a
2907 combination of NEXTMap DSMs, analogue aerial photographs and field mapping. Modified from
2908 Boston (2012a, b).

2909

2910 **Figure 15.** Examples of landforms in icefield and valley glacier settings mapped on medium to coarse
2911 resolution imagery. Landforms observed in the Chagan Uzun Valley, Russian Altai, displayed on (A)
2912 SPOT image and (B) Landsat 7 ETM+ image. (C) Associated geomorphological map extract from
2913 Gribenski et al. (2016). Moraines in the Anadyr Lowlands, Far NE Russia, displayed on (D) semi-
2914 transparent shaded ViewFinder Panorama (VFP) DEM data (NE solar azimuth) draped over the raw
2915 VFP DEM. (E) Associated mapping of moraines (black polygons) from Barr and Clark (2012).

2916

2917 **Figure 16.** Geomorphological mapping (A) from the Múljökull foreland, Iceland, completed as part
2918 of a process-oriented study examining the internal architecture and structural evolution of a Little Ice
2919 Age terminal moraine at this surge-type glacier (Benediktsson et al., 2015). The mapping was

2920 combined with sedimentological investigations (B) to produce a process-form model of moraine
2921 formation and evolution (C).

2922

2923 **Figure 17.** Geomorphological mapping of the foreland of Skálafellsjökull, an active temperate outlet
2924 of Vatnajökull, SE Iceland. (A) Digital aerial photographs (2006; 0.41 m GSD; *Loftmyndir ehf*), pan-
2925 sharpened WorldView-2 multi-spectral satellite imagery (2012; 0.5 m GSD; *European Space*
2926 *Imaging*), a UAV-derived DEM (2013; 0.09 m GSD) and field mapping were employed to produce
2927 the mapping extract (B). A compromise on the level of detail was made, with annual moraines
2928 mapped along crestlines due to image resolution and map readability. This mapping detail was
2929 sufficient for calculating crest-to-crest moraine spacing (ice-margin retreat rates) shown in (C), which
2930 was the principal purpose of the study. Modified from Chandler et al. (2016a, b).

2931

2932 **Figure 18.** Idealised workflow for mapping palaeo-ice sheet geomorphology. Some pathways in the
2933 workflow are optional (grey dashed lines) depending on data availability and the feasibility and
2934 applicability of particular methods. Note, where analogue (hard-copy) aerial photographs are used for
2935 mapping, processing of acetate overlays would be undertaken *after* mapping from the aerial
2936 photographs. Further details on image processing are shown on the processing workflow available as
2937 supplementary material.

2938

2939 **Figure 19.** Idealised workflow for mapping alpine- and plateau-style ice mass geomorphology. In this
2940 scenario, digital remotely-sensed datasets are used and this necessitates image processing *before*
2941 mapping is undertaken. Ideally, GNSS surveys would be conducted in order to process digital aerial
2942 photographs, as depicted in the workflow. Some pathways are optional (grey dashed lines) depending
2943 on data availability and the feasibility and applicability of particular methods. Although
2944 sedimentology is shown as ‘optional’, it is highly desirable to undertake sedimentological
2945 investigations, wherever possible. Alternative image processing solutions are available and readers
2946 should consult with the detailed processing workflow which is available as supplementary material.

2947

2948 **Figure 20.** Idealised workflow for mapping alpine- and plateau-style ice mass geomorphology. In this
2949 scenario, analogue (hard-copy) aerial photographs are used and this necessitates image processing
2950 *after* mapping is undertaken. Some pathways are optional (grey dashed lines) depending on data
2951 availability and the feasibility and applicability of particular methods. Although sedimentology is
2952 shown as ‘optional’, it is highly desirable to undertake sedimentological investigations, wherever
2953 possible. Alternative image processing solutions are available and readers should consult with the
2954 detailed processing workflow which is available as supplementary material.

2955

Table 1. Primary satellite imagery types used in glacial geomorphological mapping and example applications. Broadly ordered in terms of spatial resolution.

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. (2016b); 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	1986–2009	3 1 1	20 20 10	Airbus Defence and Space (intelligence-airbusds.com)	Smith et al. (2000); Coronato et al. (2009)
SPOT 4	HRVIR	1998–2013	1 3 1	10 20 20		Trommelen and Ross (2010, 2014); Ercolano et al. (2016) [viewed in Google Earth™]; McHenry and Dunlop (2016); Principato et al. (2016)
SPOT 5	HRG/HRS	2002–2015	1 3 1	2.5, 5 10 20		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)
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–	1	0.61	DigitalGlobe	da Rosa et al. (2011, 2013b); May et al (2011);
GeoEye-1		2008–	1	0.46	(digitalglobe.com)	Lovell et al. (2011)
WorldView-2		2009–	1	0.46	European Space Imaging (euspaceimaging.com)	Westoby et al. (2014)
Google Earth™ (specific image details not given)	n/a	n/a	n/a	n/a	Google Earth	Jamieson et al. (2015); Chandler et al. (2016a); Evans et al. (2016e); Ewertowski et al (2016) Margold and Jansson (2011); Margold et al. (2011); Kassab et al (2013); Stroeven et al. (2013); Darvill et al (2014); Blomdin et al. (2016b); 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); Stroeven 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			●	✓	✓	✓	✓