



Deposited via The University of Leeds.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/81772/>

Version: Accepted Version

Article:

Carrivick, JL and Tweed, FS (2013) Proglacial Lakes: character, behaviour and geological importance. *Quaternary Science Reviews*, 78. 34 - 52. ISSN: 0277-3791

<https://doi.org/10.1016/j.quascirev.2013.07.028>

Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

1
2
3
4

Proglacial lakes: character, behaviour and geological importance

Jonathan L. Carrivick¹ and Fiona S. Tweed²

¹School of Geography, University of Leeds, Woodhouse Lane, Leeds, West Yorkshire, LS2 9JT, UK

²Geography, Staffordshire University, Leek Road, Stoke-on-Trent, Staffordshire, ST4 2DF, UK

5
6
7
8
9
10
11
12

Correspondence to:

Dr. Jonathan Carrivick,

Email: j.l.carrivick@leeds.ac.uk

Tel.:(0)113 343 3324

13

Abstract

14 Proglacial lakes are ubiquitous within the Quaternary record and can provide exceptional breadth and
15 depth of palaeoenvironmental information. Present deglaciation is increasing the number and size of
16 proglacial lakes around the world. This study provides a synthesis of knowledge on proglacial lake
17 character and behaviour and critically evaluates the importance of proglacial lakes from a geological
18 perspective. We show how ‘ice-marginal’ or ‘ice-contact’ lakes and other distal proglacial lakes can
19 be distinguished from each other by geomorphological, sedimentological, chemical and biological
20 characteristics. The key controls on proglacial lake geomorphology and sedimentology are outlined
21 and discussed. Proglacial lakes can exacerbate mountain glacier and ice sheet margin ablation via
22 mechanical and thermal stresses, but very large lakes can moderate summer air temperatures and
23 relatively retard summer ice ablation. Proglacial lakes interrupt meltwater flux and are very efficient
24 sediment traps. Hydrological routing and consequent geomorphological activity can be radically
25 modified by sudden drainage of proglacial lakes and resultant glacial lake outburst floods;
26 exceptionally large proglacial lake drainages affected global ocean circulation and global climate
27 during the Quaternary. Overall, analyses of proglacial lakes can provide a valuable insight into (i)
28 patterns, character and behaviour of mountain glaciers, ice sheets and glaciations, and (ii) the
29 impacts of past, present and future deglaciation.

30
31 **Key words:** glacial lake; ice-dammed; moraine-dammed; ice-marginal; ice-contact; deglaciation
32
33

34 **1. Introduction and rationale**

35 This study provides a synthesis of knowledge on proglacial lakes with an emphasis on local, regional
36 and global effects on geological systems. Proglacial lakes are masses of water impounded at the edge
37 of a glacier or at the margin of an ice sheet. The term ‘proglacial lake’ has been used to refer to ice-
38 contact or ice-marginal lakes, which are physically attached to an ice margin, as well as lakes
39 detached from, or immediately beyond, a contemporary ice margin. In this paper, the term proglacial
40 lake therefore includes all lakes that are or have been directly influenced by (i) a glacier ice margin
41 or (ii) subaerial glacial meltwater.

42
43 Proglacial lakes are very significant within the Quaternary record. The character and behaviour of
44 proglacial lakes is intrinsically linked to climate through the surface energy balance and to wider
45 geological systems through glacier dynamics, glacial meltwater and sediment fluxes (e.g. Larsen et
46 al., 2011). Proglacial lakes can affect the stability of ice-sheet margins and mountain glaciers and can
47 disengage glacier behaviour from climatic perturbations. Proglacial lakes interrupt the delivery of
48 meltwater and sediment to proglacial zones and ultimately to oceans. Sedimentation within
49 proglacial lakes is an exceptionally important geochronological archive recording short-term inter-
50 seasonal patterns, inter-annual patterns, and long-term patterns of glacier-derived meltwater
51 fluctuation. Thus proglacial lake records are used by proxy to reconstruct glacier mass balance (e.g.
52 Phillips et al., 2006; Larsen et al., 2011), although that can be highly variable between catchments
53 and through time (e.g. Carrivick and Chase, 2011). In practical terms, knowledge of proglacial lakes
54 has application in assessments of sites vulnerable to glacier outburst floods, aquatic ecosystem
55 monitoring and hydro-electric power generation, for example. Therefore, it is now critically
56 important to (i) better understand the Quaternary record by using recent quantitative studies of
57 modern analogues, and (ii) assess the potential geological importance of the observed evolution and
58 development of proglacial lakes around the world. The major motivations for this study are that;

59 (i) Proglacial lakes are pervasive within worldwide geological records of Quaternary
60 deglaciation (e.g. Teller, 2001; Jansson, 2003; Mangerud et al., 2004; Larsen et al., 2006;
61 Livingstone et al., 2010; Fiore et al., 2011; Murton and Murton, 2012) and in most cases offer
62 exceptional breadth and depth of palaeo-environmental information (e.g. Thomas and Briner, 2009).

63 (ii) Present deglaciation is producing an increased number and size of proglacial lakes around the
64 world; for example, as recently documented in the European Alps (e.g. Paul et al., 2007), the

65 Caucasus (e.g. Stokes et al., 2007), Iceland (e.g. Schomacker, 2010), South America (e.g. Loriaux
66 and Cassasa, 2012; Thompson et al., 2011) and across the Himalaya (e.g. Gardelle et al., 2011) and
67 specifically within the Mt Everest region (Tartari et al., 2008), in Bhutan (Komori, 2008) and Tibet
68 (Chen et al., 2007; Wang et al., 2011). It is very important to understand the effects that these lakes
69 could have on modern and future geological and environmental systems.

70 (iii) Glacial lake outburst floods (GLOFS), which are a type of jökulhlaup, are ubiquitous within
71 the Quaternary record of deglaciation (e.g. Baker, 2007), and also have a modern geological imprint
72 and are modern natural hazards.

73

74 The aims of this study are to provide a review of the character and behaviour of proglacial lakes,
75 emphasising recent developments in knowledge and understanding and critically evaluating the
76 importance of proglacial lakes from a geological perspective. Specifically, we focus on; (i) recent
77 advances in understanding the formation and evolution of proglacial lakes; (ii) criteria for
78 distinguishing proglacial lakes from other freshwater lakes, from marine glacier margins and from
79 subglacial lakes in the Quaternary record; and (iii) identification of the linkages between proglacial
80 lakes and glacier dynamics, meltwater and sediment fluxes and weather and climate, as determined
81 from the Quaternary record and from modern measurements.

82

83 **2. Proglacial lake character and behaviour**

84 In this section, key attributes of proglacial lakes that shape their geological significance are
85 discussed. Consideration is given to past and present locations and distributions of proglacial lakes
86 before a discussion of controls on proglacial lake formation and evolution. Physical characteristics of
87 proglacial lakes are subsequently described with emphasis on key geomorphological and
88 sedimentary characteristics that are of use for (i) determining past glacial and hence palaeo-
89 environmental patterns, and (ii) distinguishing proglacial lakes from other freshwater lakes, from
90 marine glacier margins and from subglacial lakes in the Quaternary record. Whilst proglacial lakes
91 occur worldwide, we note that the literature on proglacial lakes is dominated by studies within
92 (temperate) high mountain and high latitude regions.

93

94 ***2a. Location and distribution of proglacial lakes***

95 Proglacial lakes can be situated in front and at the sides of mountain glaciers, at the front and sides of
96 ice sheet outlet glaciers and at the edge of nunataks and are most commonly dammed by ice,
97 bedrock, moraine debris or landslide debris (Fig. 1). Less commonly, proglacial lakes can be
98 dammed by other sediments; for example as a glacier retreats and thins behind the ice-contact slope
99 of a glacifluvial fan or apron (Carrivick and Russell, 2013). Previous reviews have compiled data on
100 natural dams (e.g. Costa and Schuster, 1988) and have discussed the formation and catastrophic
101 drainage of ice-dammed lakes (e.g. Tweed and Russell, 1999), moraine-dammed lakes (e.g.
102 Richardson & Reynolds, 2000) and landslide dams (e.g. Korup, 2002). Proglacial lakes exist in all
103 currently glaciated regions of the world and the legacy of proglacial lakes is frequently evident in
104 formerly glaciated areas. Table 1 provides examples of modern proglacial lakes from around the
105 world. Table 2 provides examples of major palaeo-proglacial lakes, particularly those lakes
106 associated with Late Pleistocene ice sheet deglaciation from which sudden drainage generated some
107 of the largest floods on Earth and affected ocean currents and offshore sediment fluxes.

108

109 ***2b. Proglacial lake formation***

110 Proglacial lakes can be impounded by ice, moraine, landslide debris or bedrock (Costa and Schuster,
111 1988). The formation, evolution and persistence of proglacial lakes are strongly linked to glacier
112 dynamics and the nature of the surrounding environment. There are clear associations between both
113 of these factors and changing climatic conditions, but factors independent of climate can influence
114 proglacial lake behaviour. The type of dam has implications for lake character, lake evolution and
115 lake drainage. Failure or overtopping of the impounding material frequently leads to glacier lake
116 outburst floods (GLOFS) or jökulhlaups (e.g. Walder and Costa, 1996; Tweed and Russell, 1999;
117 Richardson and Reynolds, 2000; Clague and Evans, 2000; Nayar, 2009), which can be powerful
118 agents of landscape change through erosion and sediment deposition (e.g. Carling, 1996; Carling et
119 al., 2002; Carrivick and Twigg, 2005, Carrivick et al., 2004a, b, 2007; Carrivick, 2007, Alho et al.,
120 2007, Russell et al., 2006).

121

122 Formation of ice-dammed lakes is a consequence of local topography and favourable hydraulic
123 pressure gradients (Tweed and Russell, 1999; Roberts, 2005) and is usually associated with ice
124 margin advance or thickening, which permits the impounding of water. In most settings, ice-dammed
125 lake formation is a gradual, quasi-periodic to episodic process, linked to glacier mass balance and,

126 ultimately, climate forcing (Evans and Clague, 1994). However, sudden glacial advance during
127 surging can block drainage channels and create ice-dammed lakes independently of climate (e.g.
128 Clarke and Mathews, 1981; Mayo, 1989). The rate of lake formation may be linked to glacier surface
129 gradient and velocity (Quincey et al., 2007) and the behaviour of ice-dammed lakes, along with their
130 drainage triggers, is intimately connected to and influenced by, the nature of the damming ice.

131

132 Formation of moraine-dammed lakes is quasi-periodic and is usually associated with periods of
133 glacier retreat or down-wasting following previous ice advance (Clague and Evans, 2000; Korup and
134 Tweed, 2007). However, the development of large terminal moraines can result from a variety of
135 processes some of which are independent of climate; for example changes in supraglacial debris
136 fluxes controlled by sediment input from valley sides (Benn and Owen, 2002). Moraine-dammed
137 lakes expand into topographic lows formerly occupied by ice or major meltwater channels and lakes
138 can grow rapidly, fed by both precipitation and glacial meltwater (Yao et al., 2010; Wang et al.
139 2011). Moraine-dammed lakes often develop on debris-covered glaciers as debris-charged glacier
140 snouts can become separated from more rapidly ablating ice up-glacier and eventually stagnate; in
141 these circumstances, ice-cored and non-ice cored moraine then serves as an effective barrier to
142 meltwater runoff leading to proglacial lake development (e.g. Ageta et al., 2000; Stokes et al., 2007).
143 Moraine-dammed lakes also grow in depressions formed by large masses of buried ice (e.g. Howarth
144 and Price, 1969; Kääb and Haeberli, 2001). In many settings, moraine-dammed lakes gradually
145 evolve to become separated from any ice mass and can persist beyond regional deglaciation
146 (Krivonogov et al., 2005; Pasquini et al., 2008).

147

148 Formation of landslide-dammed lakes in glacial environments is stochastic and is usually associated
149 with slope de-buttressing on glacier retreat (Korup, 2002; Korup and Tweed, 2007). Increases in
150 slope angle and relief coupled with the loss of internal friction and cohesion of slope materials
151 prepare slopes for failure. River-damming landslides can be triggered by rainstorms and snowmelt
152 leading to elevated pore-water pressures, by seismic vibration or by undercutting (Korup, 2002).
153 Repeated landslides at particular sites can form stacked dams (e.g. Chigira et al., 2003). Landslide-
154 dammed lakes are often ephemeral as firstly, the damming material frequently lacks cohesion and
155 secondly, they generally form in steep mountain terrain with high denudation rates and consequently
156 lakes decrease in size due to sediment infill (Hicks et al., 1990; Korup et al., 2006). Bedrock-

157 dammed lakes require a glacial over-deepening (Cook and Swift, 2012) in which to form and are
158 therefore common in mountainous regions, where reigels form effective dams, on ice cap fringes and
159 in ice sheet outlet troughs. In some locations, proglacial lakes are impounded by a combination of
160 dam types, or evolve through a sequence of different lake/dam configurations (see section 2c).

161

162 ***2c. Proglacial lake evolution***

163 Once formed, proglacial lakes can be persistent elements of a landscape, but they can also be
164 transitory and dynamic. The type of dam and the environmental setting exert key controls on
165 proglacial lake growth, contraction, filling, emptying and persistence, all of which are important for
166 understanding the landform and sedimentary record, for the reconstruction of past environmental
167 conditions and for the prediction of future environmental change.

168

169 Evolution of ice-contact lakes is strongly influenced by their proximity to ice and the dynamic nature
170 of their relationship with it. Ice-dammed lakes fill and empty, their drainage frequently resulting in
171 jökulhlaups (Walder and Costa, 1996; Tweed and Russell, 1999; Russell et al., 2011). Evans and
172 Clague (1994) first described the ‘jökulhlaup cycle’ and further discussions of lake formation,
173 drainage, re-filling and re-emptying in response to glacier fluctuations and associated ice-dammed
174 lake drainage trigger mechanisms have been provided by Tweed and Russell (1999). More recently,
175 rates of lake level rise and lake water temperature as a control on a jökulhlaup cycle have been
176 modelled by Ng and Liu (2009). The magnitude and frequency of jökulhlaups from ice-dammed lake
177 drainage is connected to different phases of the jökulhlaup cycle. Thinner ice dams consequent on
178 glacier retreat impound progressively decreasing levels of lake water, causing more frequent low
179 magnitude floods (e.g. Roberts et al., 2005). Conversely, thickening ice dams created by glacier
180 advance have the capacity to impound larger bodies of water, generating less frequent jökulhlaups of
181 greater magnitude (e.g. Clague and Evans, 1997). Cycles of filling and emptying can persist on
182 annual (e.g. Mathews and Clague, 1993; Walder et al., 2006), one to five years (e.g. Sturm and
183 Benson, 1985), decadal (e.g. Waite, 1985) and centennial (e.g. Teller and Leverington, 2004)
184 timescales and have implications for rates of erosion, sediment transfer and deposition. Proglacial
185 lake cycles are discussed more fully in [section 2e](#).

186

187 Moraine-dammed lakes (e.g. Fig. 2A) evolve as a consequence of their environmental setting,
188 particularly their proximity to ice. Identification and monitoring of moraine-dammed lakes in
189 mountainous terrain has become increasingly important chiefly due to the occurrence of GLOFs as
190 moraine-dammed lakes expand on glacial retreat (Vuichard and Zimmerman, 1987; Watanabe and
191 Rothacher, 1996; Ageta et al., 2000; Richardson and Reynolds, 2000; Sakai et al., 2000; Aniya and
192 Naruse, 2001; Kattelmann, 2003; Shresta and Shresta, 2004; Harrison et al., 2006; Quincey et al.,
193 2007; Bajracharya et al., 2007; Komori, 2008). There has been widespread documentation of the
194 evolution of moraine-dammed lakes associated with debris-covered glaciers (e.g. Bolch et al., 2008;
195 Wang et al., 2011); the enlargement and deepening of moraine-dammed lakes on and adjacent to
196 debris-charged glacier snouts is linked to the melting and subsidence of dead ice beneath and
197 adjacent to them (e.g. Stokes et al., 2007; Kääb and Haeberli, 2001). These environments are often
198 highly dynamic and the changes within them can create complex and interdependent processes and
199 impacts; for example, an outburst flood from a moraine-dammed lake at Chamdo in the Boschula
200 mountain range of Tibet triggered a large landslide that led to the formation of a landslide-dammed
201 lake (Wang et al., 2011), which in turn could generate further floods.

202

203 Proglacial lakes can expand, coalesce, decrease in size (e.g. Fig. 2B), disappear, or become detached
204 from an ice margin (Carrivick, 2011; Fig. 3). The evolution and persistence of proglacial lakes
205 exhibit strong links to glacier behaviour and therefore to climate change. When a glacier is
206 advancing, it is coupled with the sandur and meltwater can freely disperse onto it. On glacier
207 recession, an over-deepened glacier basin, either in bedrock (Fig. 2C) or within sediments, is
208 frequently revealed, creating a depression in the proglacial zone which forms a gap between the ice
209 front and proglacial rivers (e.g. Marren, 2002). If a glacier continues to retreat, ice eventually
210 decouples from the sandur (e.g. Fig. 2D), resulting in the ponding of meltwater and the trapping and
211 storage of sediment within proglacial lakes (Syverson, 1998; Schomacker and Kjaer, 2008); for
212 example, Liermann et al. (2012) report that 85 % of sediment from the Bødalén catchment in western
213 Norway is retained by a proglacial lake. Meltwater exits a proglacial lake system via a few outlets
214 onto a sandur as glacier retreat continues (e.g. Gomez et al., 2002; Fig. 2E). Glacier retreat into over-
215 deepened glacier basins often accelerates due to enhanced calving, which in turn causes lake
216 expansion and further calving and retreat. Such positive feedbacks between proglacial lakes and ice
217 dynamics are complicated and have been suggested to cause (i) rapid disintegration of ice sheet

218 margins, or (ii) rapid advance or surges, by encouraging low effective pressures at an ice margin (e.g.
219 Fyfe, 1990; Stokes and Clark, 2003). Proglacial lakes usually grow rapidly following the transition to
220 the calving phase, as this increases meltwater input over that of glacier ice melting alone (Kirkbride,
221 1993; Röhl, 2006; Fujita et al., 2009; Sakai et al., 2009; Schomacker, 2010). It is possible to infer
222 meltwater generation volumes and rates from proglacial lake growth (e.g. Teller, 1995; Clark et al.,
223 1999; Marshall and Clarke, 1999), which, alongside their hazard potential, strengthens the case for
224 monitoring of proglacial lakes.

225

226 The worldwide retreat of many ice sheet margins and glacier termini is currently giving rise to the
227 formation of new proglacial lakes and the enlargement of existing proglacial lakes (e.g. references in
228 [Table 3](#); [Fig. 3](#)). Recent formation and expansion of proglacial lakes is particularly well-documented
229 in the Himalaya and other high mountain regions of the world ([Table 3](#)), but to-date has not been
230 fully recognised at ice sheet margins (Carrivick, 2011; [Fig. 3](#))

231

232 Glacier fluctuations exert a strong influence on the development and evolution of proglacial lakes.
233 Cycles of draining and refilling of both ice-dammed and moraine-dammed lakes are profound
234 controls on their sedimentary impact. As glaciers retreat, ice-dammed lakes may drain completely
235 and fail to reform as a consequence of thinning ice dams, but moraine-dammed lakes begin to
236 develop and expand, particularly at the frontal margins of glaciers and ice sheets. It is possible for
237 ice-dammed lakes to evolve into moraine-dammed lakes, as they gradually separate from glacial ice.
238 Some such lakes may survive over centennial or millennial timescales, depending on the coherence
239 of the moraine dam; some modern proglacial lakes are the remnants of ancient lakes (e.g.
240 Krivonogov et al., 2005).

241

242 ***2d. Multiple lake development***

243 There are marked differences in the evolution, behaviour and geological significance of individual
244 proglacial lakes as compared to the development of a suite of lakes along an ice-margin and their
245 eventual coalescence. The Quaternary landform and sedimentary record provides numerous
246 examples of the development and drainage of complex proglacial lake systems associated with the
247 advance and retreat of large ice masses, especially during the late Pleistocene. Several investigations
248 have revealed evidence of multiple lake growth and coalescence, the development of lake drainage

249 routeways and their re-use and subsequent abandonment as these lakes evolved and drained. For
250 example, the complex history and impacts of proglacial lake evolution and drainage associated with
251 the deglaciation of the Cordilleran ice sheet; e.g. Glacial Lake Missoula and Glacial Lake Columbia;
252 Fig. 4) and the Laurentide ice sheet; e.g. Glacial Lake Agassiz; Fig. 4) have been comprehensively
253 researched (e.g. Baker and Bunker, 1985; Teller, 1987; O'Connor and Baker, 1992; Benito and
254 O'Connor, 1993; Kehew and Teller, 1994; Teller et al., 2002; Clarke et al., 2003; Jansson, 2003).
255 The Quaternary ice sheet margins of northern Eurasia and central Asia dammed huge proglacial
256 lakes (Fig.4); Baker (2007) highlights the glacially diverted drainage system of central Asia in which
257 lakes were connected by a series of spillways. Larsen et al. (2006) provide a synthesis of the glacier
258 and lake history of north-west Russia, which links glacier dynamics to the evolution and behaviour
259 of ice-dammed lakes and reveals a complex lake history with ice-dammed lakes forming at different
260 locations along ice margins at different times. Rudoy and Baker (1993), Baker et al. (1993) Carling
261 et al., (2002), Herget (2005) and Komatsu et al., (2009) present geomorphological and
262 sedimentological evidence for cataclysmic floods in the Altai Mountains of southern Siberia, due to
263 the emptying of multiple palaeolakes impounded by ice, moraine and lava flows. Current glacier and
264 ice sheet recession is also giving rise to complex patterns of proglacial lake development (e.g. Fig. 3)
265 and behaviour as lakes grow, coalesce and drain (e.g. Ageta et al, 2000; Stokes et al, 2007; Carrivick,
266 2011). This complex behaviour of proglacial lakes in space and time has a range of impacts on the
267 landform and sedimentary record, which will be discussed in sections 2f v, vii.

268

269 ***2e. Proglacial lake cycles***

270 Observation and measurement of proglacial lake cycles is very rare. In general, research into
271 proglacial lake evolution takes one of two approaches. The first approach is to model the behaviour
272 of modern lakes using historical documentation of events and climatic conditions as a basis (e.g. Ng
273 et al., 2007). This approach has severe limitations, principally because the historical recorded
274 observations upon which these models are often based are limited to the last fifty years or less and
275 are often incomplete. The second approach uses the Quaternary record and is usually based on
276 geomorphological indicators and sedimentary evidence (e.g. Fiore et al., 2011), but also employs
277 geo-chronological data, such as the analysis of tree-rings (e.g. Capps et al., 2011) and pollen or other
278 organics within strata immediately above or below glacial units (e.g. Astakhov, 2008) to produce

279 models of lake evolution (e.g. Etienne et al., 2006). However, this approach is hampered by a lack of
280 modern analogue studies.

281

282 ***2f. Physical characteristics of proglacial lakes***

283 Observations and measurements of geomorphology and sedimentology permit process-based
284 interpretations and reconstructions of past environments and processes. Therefore understanding of
285 the physical characteristics of proglacial lakes is crucial for targeted sampling for both (i) direct
286 reconstruction of proglacial lake processes; and by proxy glacial activity, and (ii) recognising
287 proglacial lakes in the Quaternary record and thereby indirect reconstruction of past environmental
288 conditions. Furthermore, proglacial lake sediments and simultaneously deposited organic material
289 provide some of the best uninterrupted geochronological archives; alongside tree rings, speleothems
290 and ice cores. Indeed, the stratigraphic record of proglacial lakes is one of the most continuous
291 continental records of climate change through the Holocene to the present day (e.g. Hicks et al.,
292 1990; Leonard and Reasoner, 1999; Charlet et al., 2008; Rayburn et al., 2011).

293

294 ‘Ice-marginal’ or ‘ice-contact’ lakes and distal proglacial lakes are distinct from each other in terms
295 of both geomorphology and sedimentology. Ice-marginal lakes have a unique lacustrine character
296 that reflects both a close proximity to an ice margin and also the rapidly changing nature of this
297 situation. Teller (1987) and more recently Rubensdotter and Rosquist (2009) have summarised the
298 main factors controlling the geomorphological and sedimentary characteristics of ice-contact lakes
299 as; location of a glacier margin, elevation and topography of surrounding landscape, location and
300 elevation of the lake overflow channel, and volume and nature of sediment supply. Each of these
301 factors is discussed below for ice-contact and for distal proglacial lakes by considering the key
302 controls and effects of water depth, bathymetry, hydrography / limnology and specifically thermal
303 regime and suspended sediment density stratification, chemical and biological characteristics and
304 sedimentation. It is important to recognise the importance of spatio-temporal scale (e.g. lake area,
305 lake depth, catchment size, time period) when considering proglacial processes.

306

307 ***i) Water depth***

308 Water depth in ice-marginal lakes is prone to sudden changes due to (i) opening and closing of
309 outlets by glacier margin position changes and by changes in glacier thickness, (ii) periodic or

310 episodic outburst floods or ‘jökulhlaups’, and iii) recharge events. Fluctuating water level is one key
311 characteristic of ice-marginal lakes that discriminates them from subglacial lakes (Livingstone et al.,
312 2012). Fluctuating proglacial lake water levels has impacts on (i) glacier character and dynamics
313 (Table 4), and (ii) landform development (e.g. Sturm, 1986; Winsemann et al., 2011), and thus has
314 important implications for environmental reconstruction. Water depth rather than climate appears to
315 have controlled moraine systems deposited along the Wisconsinian ice margin (Hillaire-Marcel et al.,
316 1981; Vincent, 1989). Water depth has also been inferred to control subglacial drainage
317 configuration and hence the style and pattern of sedimentation along the ice/lake interface (e.g. Fyfe,
318 1990; Winsemann et al., 2011). Specifically, Fyfe (1990) reports that large deltas were the product of
319 conduit-focused sedimentation, whilst lower, narrower coalescing fans of finer material formed from
320 a distributed drainage system. Furthermore, Fyfe (1990) suggested that subglacial conduit systems
321 are unstable where marginal water depths are greatest, thereby favouring development of a
322 distributed drainage system. Perhaps it is important to note that water depth does not control
323 sediment thickness (Gilbert, 2003) but that it is critical for preserving fine-laminated sediments
324 (something like mm-scale) versus more massive and mixed sediments. In this latter respect, water
325 depth must be carefully considered in the context of numerous other controls when discussing
326 sedimentation; water depth controls oxygen and thermal stratification that in turn affect the mixing
327 potential of the water and sediments. Other factors to consider as a control on sediment preservation
328 include alkalinity, dissolved oxygen, diagenesis and fetch.

329

330 *ii) Bathymetry*

331 Bathymetry strongly determines sediment dispersal within proglacial lakes. Turbid density/gravity
332 currents or ‘underflows’, which are particularly prominent in ice-contact lakes, are directed by into
333 low points on a lake floor (Gustavson, 1975; Smith et al., 1982; Ashley, 1995). Common bathymetric
334 elements include submerged bedrock hills and depositional landforms such as moraines, subaqueous
335 channels and enclosed basins that are created by erosional over-deepening or uneven sedimentation.
336 Knowledge of lake bathymetry is also important for geological investigations because submerged
337 topographic barriers or ‘sills’ can act as barriers to the transfer of water and sediment and to the
338 transport of icebergs. Ice-rafted debris (IRD) can become grounded in water that is shallower than
339 the critical depth required for flotation.

340

341 The vast majority of proglacial lake basins have flat floors produced by voluminous sedimentation.
342 Terrain that was previously glacially subdued and smoothed can become draped and obscured by
343 thin beds and laminae of silts and clays. Pleistocene proglacial lake basins, such as those in the
344 Hudson Bay area and on the Canadian Shield (Dredge and Cowan, 1989), can be recognised today as
345 very extensive areas of peatlands that have accumulated due to relatively impermeable sediments and
346 poor drainage. These palaeo-lake areas are usually further distinguished by encircling wave-cut cliffs
347 or by coarser sediment that was deposited in shallower water, such as beaches and lags of wave-
348 washed sediment (Teller, 2003).

349

350 On a large scale, bathymetry of proglacial lakes is dependent on regional topography. Very large
351 Pleistocene proglacial lakes across North America developed at least partly because the continental
352 land surface slope trended northwards towards the Arctic Ocean (Teller, 1987). This slope, which
353 was inverse to the direction of ice motion, was accentuated by isostatic depression and thus a
354 considerable accommodation space for meltwater was created in the landscape. To quantify this
355 effect, in North America and also in Scandinavia the isostatic depression from south to north as
356 measured by (now deformed) lake shorelines or ‘beaches’ is ~ 200 m (e.g. Lemmen et al., 1994).
357 Today, many proglacial lakes are developing along the western margins of the Greenland ice sheet
358 not just due to enhanced meltwater generation, but also because accommodation space for meltwater
359 to accumulate in the landscape is created as the ice sheet retreats on an adverse bed slope.

360

361 *iii) Hydrography / Limnology*

362 Very little hydrographic / limnological data exist for modern proglacial and particularly for ice-
363 contact lakes; work by Francus et al (2008) and Schiefer and Gilbert (2008) are notable exceptions.
364 In general, proglacial lakes experience pronounced, frequent and regular fluctuations in thermal (e.g.
365 Richards et al., 2012) and sediment load inputs and generally develop some sort of density
366 stratification. Density stratification makes proglacial lakes, especially ice-contact lakes, distinct from
367 other ‘river-fed’ lakes (e.g. Gustavson, 1975; Weirich, 1985, 1986) and distinct from subglacial lakes
368 (Livingstone et al., 2012). Density stratification is important geologically because it controls
369 circulation (currents) of water and thus determines sediment distribution within the lake and the
370 overall architecture and detailed structure of sedimentary deposits (Fig. 5). Both density stratification
371 and circulation patterns are controlled by specific physical forcing within the glacial system (e.g.

372 Josberger et al., 2010). A summary of particular differences in physicochemical properties between
373 ice-contact and other (distal) proglacial lakes is provided in [Table 5](#). Note that studies listed in [Table](#)
374 [5](#) are predominantly within (temperate) high mountain and high latitude regions and that seasonality
375 in thermal stratification is very different in the tropics.

376

377 Water temperature-density relationships in proglacial lakes are complicated, not least due to spatio-
378 temporal scales and external (catchment, climate) and internal factors (lake geometry and physic-
379 chemical attributes). However, glacial meltwater entering a proglacial lake will be generally near 0°C
380 in temperature. In contrast, hillslope or groundwater streams can be at least 10°C warmer. In
381 response to these temperature differences and to seasonally changing water sources and meltwater
382 volumes, proglacial lakes typically develop a well-mixed layer of warmer and thus lower density
383 water at the top of the water column; in high latitude and (temperate) high mountain proglacial lakes
384 this occurs during summer. There can be an accompanying sharp decrease in temperature at the base
385 of the lake. In the autumn, high latitude and (temperate) high mountain proglacial lake surface waters
386 that are usually cool, become denser and consequently sink. Eventually the vertical temperature
387 profile of such a typical proglacial lake can overturn, perhaps twice a year for lakes that are distal
388 from an ice margin (Ashley, 1995; Richards et al., 2012).

389

390 Density stratification in proglacial lakes, and especially in ice-contact lakes, is due not only to water
391 temperature differences, but also to suspended sediment concentration ([Table 6](#)). Meltwater streams
392 with high sediment loads ($> 1 \text{ g l}^{-1}$) can develop density stratification where density increases with
393 depth. This vertical density gradient will likely be more gradual than that of temperature (Ashley,
394 1995). Ashley (1995) lists published suspended sediment concentrations of over 200 mg l^{-1} for
395 proglacial lakes; although more recent publications suggest much lower values (e.g. Geilhausen et
396 al., 2012; Liermann et al., 2012).

397

398 Overall, if there is a significant difference in density, as is typical for ice-contact lakes due to
399 summer inputs of sediment laden meltwater, inflows will likely maintain integrity as a plume and
400 being denser than ambient lake water will sink as an underflow current, or a gravity, density or
401 turbidity current (e.g. Gilbert and Crookshanks, 2009). Such density currents produce graded,
402 rhythmically-stratified sediments that infill depressions on a lake basin floor. In contrast, distal

403 proglacial lakes can receive lower-density water from a glacial, groundwater or a hillslope source.
404 This lower-density water rises to the surface as an overflow. Water entering a distal proglacial lake
405 with the same density as that of the lake will circulate as an interflow (e.g. Smith et al., 1982;
406 Francus et al., 2008). Overflow-interflow circulation is typical of distal proglacial lakes and produces
407 rhythmically-laminated thin bottom sediments that drape topography.

408

409 *iv) Chemical and biological characteristics*

410 Chemical processes within proglacial lakes are very under-studied, perhaps because of the over-
411 riding importance of physical processes. This lack of study is perhaps surprising because chemical
412 characteristics and biological material within proglacial lake sediments are important for providing
413 both relative and absolute geochronological dates as well as proxy evidence for environmental
414 conditions at the time of sedimentation (e.g. Lamoureux and Gilbert, 2004; Etienne et al., 2006). For
415 example, Fortner et al., (2005) showed that chemical budgets can identify changing water source
416 contributions through time.

417

418 Biological disturbance of sediment by surface or near-surface lacustrine (or marine) dwelling
419 organisms i.e. ‘bioturbation’ in distal proglacial lakes is usually well-developed since sedimentation
420 rates are very low due to fast mixing; incoming flows are of a similar temperature and suspended
421 sediment concentration as lake water (Table 6; Smith et al., 1982). The wide range of structures
422 produced by bioturbation processes are trace fossils. The range of species of these fossils permits
423 reconstruction of environmental conditions such as water depth, water temperature, turbidity and
424 salinity, and the organic component of the fossils permits absolute geochronological dating
425 (Andrews et al., 1996; Bujalesky et al., 1997; Uchman et al., 2009).

426

427 *v) Sedimentation*

428 It is absolutely crucial to understand sedimentation within proglacial lakes (Table 7) for (i)
429 deciphering the Quaternary record of glaciation and glacier dynamics and (ii) distinguishing
430 proglacial lakes from other water bodies. Sedimentation within proglacial lakes is primarily
431 controlled by proximity to the ice-margin and by lake water density stratification. However, most
432 mountain regions are subject to seismic activity, paraglacial processes and other geomorphological
433 controls that also affect sediment dynamics within lakes. Specifically, sediment concentration within

434 input streams and the vertical position of input streams relative to the total water depth are key
435 controlling factors on sedimentation. To a lesser extent; and usually only in very large lakes, winds
436 can set up epilimnial currents, the Coriolis force can direct currents, and the duration of ice cover on
437 a lake can affect circulation patterns and strength via thermal stratification development (Ashley,
438 1995; Richards et al., 2012). This exposure of proglacial lakes to atmospheric conditions sets those
439 sediments apart in compositional character from subglacial lakes (Livingstone et al., 2012). In all
440 proglacial lakes, the spatial and temporal pattern of sedimentation (Table 7) can be interrupted due to
441 cyclical and episodic or abrupt water level changes (e.g. Hicks et al., 1990; Lewis et al., 2002).

442
443 Sedimentation within all proglacial lakes tends to be dominated in volume and in areal extent by that
444 from suspension settling (Table 7). However, sedimentation within ice-contact lakes can be
445 dominated by the action of jets, where both bedload and suspended load are of very high volume, or
446 from hyperconcentrated flows, or from traction carpets similar to those in turbid subaerial rivers
447 (Francus et al., 2008; Fanetti et al., 2008; Benn and Evans, 2010). Ice rafting can be a very effective
448 mechanism for dispersing sediment over large distances in ice-contact lakes. Ice-contact
449 sedimentation is dominated by ice-contact deltas, subaqueous fans and submerged ramps (Tables 6,
450 7) but perhaps also by mass movement processes. Ice-cliff margins and submerged ice ramps are
451 unlikely to be preserved in any coherent state. With distance from the ice margin, rhythmically
452 laminated bottom sediments will develop (Ashley, 1995). Diamict ‘moraine’ material is likely to be
453 deposited on the up-ice side of grounding line fans and ice-contact deltas. The apex of an ice-contact
454 delta marks the position of a discrete and sustained input of meltwater, but multiple apexes could
455 either reflect multiple inputs or else a single source that moved. The thickness of topset (subaerial)
456 sediments on a delta is closely related to the vertical range of meltwater inputs; the difference
457 between maximum lake level and the depth of fluvial scour by input streams.

458
459 Distal glaciallacustrine sedimentation is far more likely to be preserved in the geological record and
460 thus is far more useful as a palaeo-environmental archive than ice-contact sediments (e.g. Leonard
461 and Reasoner, 1999; Francus et al., 2008). The physical separation of a distal proglacial lake from a
462 glacier or ice sheet margin means that there is no moraine, minimal if any ice-rafted debris (IRD),
463 decreased suspended load and decreased clast sizes in comparison to that within ice-contact lakes.
464 Distal glaciallacustrine sediments are characterised by deltaic sediments; fine-grained, prograding and

465 gently-dipping foresets, and by rhythmic bottom sediments and sand, silt and clay (e.g. Loso et al.,
466 2004). Following deglaciation, sedimentation in proglacial lakes can be dominated by paraglacial
467 activity (Ballantyne, 2003) or hillslope processes (e.g. Gilbert and Desloges, 2005). This progression
468 of sedimentation style is especially evident within small lake basins and in mountainous areas will
469 predominantly comprise slumping of valley-side glacial deposits to generate large subaqueous
470 debris flows (Desloges, 1994; Martini and Brookfield, 1995; Dirszowsky and Desloges, 1997;
471 Johnsen and Brennand, 2006). Rapidly-altered sedimentation styles or rates and thus regional (non
472 ice-contact) ice retreat or advance can be inferred by abrupt changes or unconformities in the
473 sequence of grain size, mineralogy and biological composition (e.g. Schiefer and Gilbert, 2008). It
474 should be noted that turbidity/gravity/density currents in proglacial lakes may only last a few
475 minutes, but can deposit several centimetres of sediment, whereas suspension settling of fine-grained
476 material may only deposit a few millimetres or less over many months (Palmer et al., 2007). Gilbert
477 and Crookshanks (2009) have demonstrated and quantified the spatial and temporal variability in
478 sedimentation rates from turbidity currents. It is clear that laminated sediments can represent
479 depositional cycles on many timescales and the term 'varve' is best restricted to where a seasonal
480 cycle can be demonstrated (c.f. Leemann and Niessen, 2004).

481

482 Identification of the vertical succession of deposits related to ice-contact, ice-distal and paraglacial
483 conditions has enabled inference of very rapid sedimentation during glacier retreat (e.g. Leonard and
484 Reasoner, 1999; Loso et al., 2004), slowed depositional rates after deglaciation, and subsequent
485 sedimentation of substantial volumes of sediment through fluvial influx of reworked glacial
486 sediment (Ballantyne, 2003; Etienne et al., 2006; Schiefer and Gilbert, 2008). This overall pattern is
487 the same as those reconstructed for Late Pleistocene ice sheets (e.g. Mullins et al., 1990; Desloges
488 and Gilbert, 1991; Gilbert and Desloges, 1992; Seltzer, 2008; Murton and Murton, 2012), and as
489 reconstructed for past ice sheet margins, outlet glaciers (e.g. Anderson and Archer, 1999; Charlet et
490 al., 2008) and for mountain glaciers (e.g. Gilbert et al., 1997; Lamoureux, 1999; Lewis et al., 2002;
491 Blass et al., 2003, 2005; Loso et al., 2004; McCulloch et al., 2005; Thomas et al., 2010). There are
492 very few studies of contemporary sedimentation within proglacial lakes, but a few selected examples
493 are given [Table 1](#).

494

495 Several specific sedimentary units and structures are very important to describe and understand
496 because they can be used to both indicate and to diagnose glaci-lacustrine processes and

497 environmental conditions. Sedimentary evidence of proglacial lakes most obviously includes
498 rhythmites, which may include varves; however, IRD is unequivocal, or diagnostic, of a
499 glaciallacustrine (or glacialmarine) environment. IRD can be identified in both massive and laminated
500 sediments, which in proglacial lakes may only be a few tens of centimetres thick and in the latter
501 case by the deformation or penetration of underlying laminae. Individual clasts of IRD are termed
502 ‘dropstones’ and where significant numbers of dropstones are deposited in space a ‘dropstone
503 diamicton’ can be recognised. The rate of deposition of IRD is a function of the debris content of the
504 ice and the frequency of iceberg passage, which reflects the calving rate and the distance from the ice
505 margin. Thus clast-rich dropstone diamictons are usually associated with proximal environments
506 (Hambrey, 1994). Dropstone clast morphology is inherited from the parent glacial material; i.e. it
507 depends on the glacial transport pathway and mechanism; active subglacial transport versus inactive
508 supraglacial transport. Thus no systematic differences in dropstone clast morphology are evident
509 between proximal and distal glaciallacustrine environments (Hambrey, 1994). Dropstone clast
510 orientation is preferentially vertical, due to its passage vertically through the water column, but the
511 preservation of this orientation depends on the bottom sediment characteristics.

512

513 Iceberg grounding structures and sediments are also diagnostic of glaciallacustrine (and glacialmarine)
514 environments. A key piece of diagnostic evidence of a palaeo proglacial lake is the presence of linear
515 and curved grooves within the sediments that have ridges immediately alongside them. These iceberg
516 keel scours and plough marks may be entirely in parallel, or may cross over each other and can
517 therefore be used to infer the number of glacial advances and the direction of those advances. Iceberg
518 scouring can be so intense that all primary depositional structures are destroyed leaving a chaotic
519 massive structureless diamicton. However, more commonly distinctive folding and faulting
520 structures can create erosional grooves and constructional berms by single iceberg grounding or
521 ploughing events (Woodworth-Lynas and Guigné, 1990; Eyles et al., 2005).

522

523 Sedimentation volumes and rates, as obtained by the thickness of deposits and by the relative and
524 absolute dating of deposits (usually varves) respectively, are used to infer i) water sources and
525 dynamics, ii) proximity to an ice margin and hence glacier advances and retreats, iii) climatic
526 conditions driving these glacier margin changes. Since the work of Jopling and McDonald (1975), it
527 has been clear that, away from the point of influx, glaciallacustrine sediment thins as accumulation
528 rates are much reduced. It is also clear that ice-contact lakes have higher sedimentation rates than

529 distal proglacial lakes. The rate at which sediment is delivered from a glacier into an ice-contact lake
530 is a function of ice melt rate, glacier type and of sediment concentration within the ice.

531

532

533 *vi) Landforms*

534 Glacilacustrine landforms (Table 7) permit reconstructions of glacier margin position, glacier margin
535 thickness, glacial meltwater conduit positions and types, glacier behaviour and, by inference, glacier
536 mass balance and climate. Glacier margins in large and deep proglacial lakes are less stable than
537 those on land because calving and surging processes mean that it is difficult for a glacier or an ice
538 sheet to establish a fixed boundary of equilibrium. This ice margin instability, alongside the high
539 potential for wave erosion, means that well-defined moraine ridges are unlikely to be preserved in
540 proglacial lake basins. Thus the history of ice retreat across very large and deep proglacial basins is
541 not very well known (e.g. Murton and Murton, 2012). Subaqueous moraines may have linear or
542 sinuous crests and particularly in the case of DeGeer moraines occur in fields of relatively narrow
543 sub-parallel ridges (e.g. Golledge et al., 2008). Subaqueous moraine ridges frequently display
544 heavily glacitectonised sediment structures that are indicative of compression; i.e. ice margin
545 pushing during advance (e.g. Bennett et al., 2000). DeGeer moraines can more simply formed by
546 intermittent glacier margin retreat (e.g. Lindén, and Möller, 2005) as well as by brief ice margin still-
547 stands or minor advances, and thus they have considerable implications for understanding
548 deglaciation (Larsen et al., 2006). Subaqueous moraines can mainly consist of coalescing grounding
549 line fans, as is the case for the Salpausselka Moraines in southern Finland (Fyfe, 1990), the eastern
550 Maine moraines (Ashley et al., 1991) and the Oak Ridges Moraine in Ontario, for example (Russell
551 and Arnott, 2003; Sharpe et al., 2007).

552

553 Grounding line fans are fed by flows entering a lake basin at the base of the water column, rather
554 than at the top, as is the case for deltas. Grounding line fans can thus be used to infer ice thickness.
555 Grounding line fans are also therefore commonly associated with specific points along esker systems
556 where they mark former glacier margin positions. If a glacier advances, till deposition may occur as
557 well as glacitectonic thrusts and folds.

558

559 Deltas form by a combination of fluvial aggradation above water level and progradation on the delta
560 front where bedload is rapidly deposited when the incoming stream decelerates with still lake water

561 interaction. Delta-front profiles are usually concave, reflecting decreasing sediment clast size due to
562 reduced flow competence and reduced sedimentation rate. Deltas can be used to reconstruct water
563 levels and ice margin configurations. However, most importantly quantification of delta volumes can
564 provide valuable estimates of erosion rates within glaciated catchments (e.g. Østrem et al., 2005). It
565 is usual to distinguish between ice-contact deltas formed within ice-contact lakes and glacier-fed
566 deltas formed within distal proglacial lakes. This is not least because the morphology and
567 sedimentology of deltas reflects the gradient of the feeder river and the water depth, but also possibly
568 temporal changes in glacier coverage within the catchment (e.g. Dirszowsky and Desloges, 2004).
569 Rising water depth can produce stacked delta sequences or else deltas can become incised in the case
570 of falling levels. Changing water depth can also be recorded within the internal sedimentology of
571 lake deltas (e.g. Østrem et al., 2005; Russell, 2007), as can climatic-catchment processes, glacial
572 processes and associated water and sediment loading (e.g. Brandes et al., 2011), or lake drainage.

573

574

575 **3. Quaternary importance of proglacial lakes**

576 Proglacial lake evolution, character and behaviour, glacier and ice sheet growth and decay, meltwater
577 and sediment fluxes directly affect geological systems and these interactions are summarised in
578 [Table 6](#). Furthermore, proglacial lakes demonstrate complex system interdependencies and feedback
579 mechanisms on global to local scales ([Fig. 6](#)). These interdependencies are discussed in the following
580 sections in order to (i) better understand the Quaternary record by using recent quantitative studies of
581 modern analogues, and (ii) enable future studies to make a judgement of the geological importance
582 of the evolution and development of contemporary proglacial lakes around the world.

583

584 ***3a) Proglacial lake influences on ice dynamics***

585 Glacier margin morphology ([section 2a](#)), physical stability and dynamics ([section 2b](#)) are affected by
586 the presence, character and behaviour of an ice-marginal lake. Indeed, the growth of an ice-marginal
587 lake ([section 2c](#)) can affect the longitudinal stress balance of a glacier and therefore glacier velocity
588 and mass balance ([Fig. 7](#)). This interaction between ice-marginal lakes and glacier ice dynamics has
589 been measured for modern mountain glaciers (e.g. Kirkbride and Warren, 1999; Diolaiuti et al.,
590 2006; Röhl, 2006) and has been modelled for Quaternary ice sheet margins (e.g. Cutler et al., 2001).
591 Although Price et al., (2008) did not explicitly consider ice-marginal lakes, they have shown in a

592 modelling study of a modern part of the western Greenland ice sheet that ice sheet margin conditions
593 fundamentally affect ice sheet dynamics up to the equilibrium line. Overall, ice-marginal lakes can
594 control glacier ice dynamics via eight mechanisms; (i) raising the water table, (ii) raising water
595 temperature, (iii) raising subglacial water pressure, (iv) increasing ice surface gradient, (v) promoting
596 flotation, (vi) promoting calving, (vii) intense ice flexure and fracture during rapid draining or filling,
597 (viii) intense flushing of sediment from beneath a glacier and intense aggradation of sediment at a
598 glacier terminus during rapid draining (Fig. 7). The Quaternary record has been used to suggest that
599 it is also possible that ice-marginal lakes can encourage development of ice-streams (e.g. Stokes and
600 Clark, 2003, 2004; Demidov et al., 2006).

601
602 Water at the base of a glacier is fundamental to controlling processes of ice motion via the
603 longitudinal stress balance and specifically via decreased friction, enhanced basal sliding and
604 saturation of underlying sediments promoting deformation, for example. The depth of water at an
605 ice-margin determines (i) the distance ‘up-ice’ that water propagates, (ii) vertical extension of a basal
606 hydrological system (Harper et al., 2010) via basal water pressure (e.g. Tsutaki et al., 2011) and (iii)
607 calving rates (e.g. Pelto and Warren, 1991) and these factors encourage faster ice velocity and
608 heighten mass loss (Table 6; Fig. 7). It is also plausible that where large volumes persist at the bed of
609 a glacier; and perhaps up into a glacier (Harper et al., 2010), basal water pressures not only promote
610 sliding if they approach the overburden pressure (Tsutaki et al., 2011), but could result in hydro-
611 fracturing and basal crevasse development and propagation (c.f. van der Veen, 1998). As an ice-
612 marginal lake increases in size and mass loss from a glacier snout progresses, a glacier ice surface
613 must steepen thus increasing driving stresses and glacier velocity in a positive feedback loop (Fig. 7).

614
615 Glacier mass loss and glacier velocity are also augmented by an ice-marginal lake because lake water
616 delivers heat to a glacier and thus causes thermally-induced melting. Thermal melting can cause
617 notches to develop at the water line and this thermal undercutting can apparently control calving (e.g.
618 Kirkbride and Warren, 1999; Diolaiuti et al., 2006; Röhl, 2006), especially for glaciers with
619 velocities, low calving rates and low surface gradients (Röhl, 2006). Quantification of such thermal
620 melting is very rare, but subaqueous melting of 9 m.yr^{-1} has been recorded by Hochstein et al.,
621 (1998), for example. Furthermore, heat delivered from ice-marginal lakes to glaciers controls thermal
622 erosion far beyond the immediate extent of the ice-marginal lake itself by producing ponded
623 meltwater beneath and within a glacier, particularly in crevasses (Fig. 7). An ice-marginal lake will

624 therefore cause glacier margin fluctuations, glacier velocity and glacier mass balance to be at least
625 partially decoupled from climate (Kirkbride, 1993). In New Zealand, for example, glaciers
626 terminating in lakes have termini that have retreated the farthest and moved at the fastest speeds in
627 comparison to all other types of glaciers (Chinn, 1999) and over the last century have shown more
628 variability in recession and far lower mean elevation changes (Chinn, 1996). In contrast, the relative
629 stability of the margin of the Moreno glacier in Patagonia has in part been attributed to calving
630 processes and to the bottom topography of a proglacial lake (Rott et al., 1998).

631

632 Where ice-marginal lake water is sufficiently deep, relative to the ice thickness, buoyancy will cause
633 flotation of an ice margin and rapid calving, snout retreat and surface lowering (e.g. Naruse and
634 Skvarca, 2000; Boyce et al., 2007; Tsutaki et al., 2011), or sudden glacier lake drainage, i.e. a
635 ‘jökulhlaup’ (e.g. Huss et al., 2007). If calving generates ice bergs at a rate greater than iceberg melt,
636 the resultant accumulation of ice on a lake surface can buttress an ice-margin and stabilise a glacier
637 snout (Geirsdóttir et al., 2008). In contrast, when glacier ice is grounded with lake water, that ice is
638 often in tension and near fracture and consequently unstable (e.g. Pelto and Warren, 1991; Kirkbride
639 and Warren, 1999; Diolaiuti et al., 2006; Röhl, 2006).

640

641 Whenever ice-marginal lakes drain rapidly or fill rapidly, which often occurs in cycles (Evans and
642 Clague, 1994; Russell et al., 2011), the water mass releases/exerts stress on the ice margin that is
643 manifest in ice flexure (e.g. Walder et al., 2006) or fracture. Jökulhlaups that drain along the front of
644 an ice-margin can cause mechanical erosion of that ice margin (e.g. Sugden et al., 1985) causing
645 temporarily unstable ice cliffs. Jökulhlaups that drain subglacially can temporarily increase basal
646 water pressure over a broad region; promoting sliding, inhibiting cavity closure and blocking
647 drainage (e.g. Anderson et al., 2005), producing glacier velocity changes (e.g. Anderson et al., 2005;
648 Huss et al., 2007; Sugiyama et al., 2007). The Quaternary record suggests that glacier velocity can
649 accelerate due to the drainage of ice-dammed lakes (Meinsen et al., 2011; Lovell et al., 2012) and
650 thus for glacier dynamics to be decoupled, at least temporarily, from climatic perturbations.

651

652 Modern subglacial jökulhlaups have been noted to be highly effective in flushing sediment from a
653 glacier bed (Russell et al., 2006) and at redistributing it to glacier margins. Sediment aggradation at a
654 glacier meltwater portal will promote ice-contact delta and braid-plain formation ([section 2fv](#);

655 Fleisher et al., 2003) and thereby alter the grounding-line dynamics for water-terminating glaciers
656 (Lindén and Möller, 2005; Benn, 2008). Enhanced sediment accumulation in water at glacier termini
657 has the potential to physically buttress those glacier termini and thus to remove them from both the
658 immediate effects of both lake level change and climate change.

659

660 Quaternary ice-marginal lakes have been highlighted as key factors in the location and initiation of
661 ice streams (e.g. Stokes and Clark, 2003, 2004; Demidov et al., 2006) and hence in the onset and
662 progression of ice sheet deglaciation. The mechanisms by which a proglacial lake could control ice
663 streams are rather the same as already discussed for ice-marginal lakes controlling glacier dynamics;
664 specifically that if an ice sheet with a steep surface gradient and consequent high driving stresses
665 entered a proglacial lake, that was deep relative to ice thickness, then an increase in velocity through
666 calving would propagate fast ice flow up-glacier by altering the longitudinal stress balance through a
667 series of thermo-mechanical feedback mechanisms (Stokes and Clark, 2003).

668

669 ***3b) Proglacial lake influences on meltwater, sediment fluxes and landforms***

670 Proglacial lakes interrupt the passage of meltwater from a glacier through a proglacial zone and
671 reduce flow velocities sufficiently to cause sedimentation. They therefore act as a trap for sediments
672 which would otherwise be transported into a proglacial zone and beyond. This trapping and storage
673 is well-recognised and there is a plethora of work on both Quaternary and modern lake sedimentation
674 (e.g. Hicks et al., 1990; Kirkbride, 1993; Marshall and Clarke, 1999; Hasholt et al., 2000; Lewis et
675 al., 2002; Schomacker and Kjaer, 2008; Fujita et al., 2009; Liermann et al., 2012). Such sediment
676 sinks have great potential to record relatively high-resolution evidence of sediment delivery from the
677 catchments in which they are situated; they can provide information on medium to long-term
678 sediment yields on a catchment scale (e.g. Liermann et al., 2012) and chronologies of lake sediments
679 can be used as proxy evidence for regional hydrological changes and climate variability (Desloges
680 and Gilbert, 1998). Sediment fluxes in glacial environments are usually considered to be highest
681 immediately following deglaciation due to over-steepened relief and paraglacial slope readjustment
682 (e.g. Hallet et al., 1996; Leonard, 1997; Ballantyne, 2000; Orwin and Smart, 2004). However, there
683 is potential for larger glaciers to produce higher sediment yields than smaller glaciers or retreating
684 glaciers. This complication as to whether higher sediment yields represent deglaciation or increases
685 in the size of ice masses has important implications for using sediment records in the context of

686 glacier and climate reconstructions. Recent observations of the southern outlets of Vatnajökull in
687 Iceland indicate that proglacial lakes are acting fluvial sediment traps, reducing sediment input into
688 the Atlantic coastal system (Syverson, 1998; Schomacker and Kjær, 2008). Proglacial lakes are also
689 traps for aeolian sediment. For example, development of proglacial lakes at the margins of the
690 Patagonian ice field resulted in the trapping of fine-grained aeolian sediment in those lakes in the
691 early phases of the last glacial retreat and thus stopped the ice age dust flux to Antarctica (e.g.
692 Ackert, 2009).

693

694 Proglacial lakes can act as sediment stores as a consequence of episodic processes that are seemingly
695 independent of climate change. For example, the eruption of Eyjafjallajökull in 2010 caused rapid
696 melting of glacier ice resulting in debris-rich jökulhlaups, which completely infilled a moraine-
697 dammed lake at the snout of the glacier Gígjökull. This sediment has the potential to be re-mobilised
698 by further high-magnitude jökulhlaups triggered by future eruptions of Eyjafjallajökull. In such
699 cases, proglacial lake evolution and sediment flux are linked to cycles of volcanic activity rather than
700 glacier retreat, although ultimately climate change may be implicated in intensification of subglacial
701 eruptive activity (e.g. Carrivick et al., 2009; Tuffen, 2012; McGuire, 2013).

702

703 Episodic events exert profound control on meltwater and sediment fluxes in glaciated catchments
704 over very short time periods. For example, hydrological diversion or re-routing and even reversal of
705 rivers, and consequent geomorphological activity including gorge incision, valley formation and
706 sedimentation has been attributed to GLOFS or jökulhlaups soon after the Last Glacial Maximum
707 (LGM). Global examples are given by Baker (2003); examples in northern Russia are explained by
708 Astakhov et al. (1999), Mangerud et al. (2001) and Krinner et al. (2004); and Murton and Murton
709 (2012) give many examples from the Quaternary in the UK. Some of these proglacial lake drainages
710 produced jökulhlaups so large that the resultant influx of freshwater and sediment affected ocean
711 circulation and climate; this is addressed in [section 3c.ii](#). Modern outburst floods from ice-, moraine-
712 and landslide-dammed lakes in the Himalayas, Canada, New Zealand and Tien Shan have caused
713 similar hydrological and geomorphological impacts(e.g. Desloges and Gilbert, 1998; Cenderelli and
714 Wohl, 2003; Korup et al., 2006).

715

716 Quantification of the contribution of such episodic sediment pulses to long-term sediment budgets is
717 difficult because of problems in obtaining direct measurements (e.g. Korup et al., 2004). However,
718 this quantification needs addressing, because glacifluvial, aeolian and marine sediment transfer
719 systems will be increasingly affected by formation and drainage of moraine- and rockslide-dammed
720 lakes that is predicted to accompany deglaciation due to climate change (e.g. Richardson and
721 Reynolds, 2000; Chikita and Yamada, 2005). The Quaternary record might offer help in this
722 quantification; (i) it should be possible to infer meltwater volumes and meltwater generation rates
723 from the spatial and temporal patterns in proglacial lake evolution; regional contrasts in lake
724 evolution have been attributed to describe climatic variability (e.g. Gardelle et al., 2011); (ii)
725 sedimentation rates in neighbouring catchments with and without a history of outburst floods could
726 be compared. We note that identification of storage elements within catchments such as proglacial
727 lakes is critical to the effective study of sediment budgets (Reid and Dunne, 1996).

728
729 Proglacial lakes most obviously influence terrestrial geomorphology within very large continental
730 basins, which were occupied by exceptionally large Quaternary proglacial lakes (Fig. 1). These lake
731 basins received and retained large volumes of glacial and glacifluvial sediment during deglaciation
732 from the LGM. The sediments, still well-preserved, are an invaluable (i) geochronological archive
733 (section f) and (ii) support modern-day Arctic and sub-Arctic peatlands that are very important for
734 the global carbon balance. Glacilacustrine sediments can dominate moraine facies, for example as for
735 the Salpausselkä moraines that in part determined by lake water depth (Fyfe, 1990). Furthermore,
736 whilst lake water level dynamics, and in particular lake ‘transgressions’ (c.f. Teller, 2001) controls
737 beach development and character, it is these palaeo-lake shorelines that have a geological importance
738 because they can be used to measure regional isostatic uplift (Teller, 2001). Quaternary proglacial
739 lakes influenced terrestrial geomorphology more widely by promoting continental hydrological
740 drainage reversals; examples have been reported in Siberia and mainland Europe (e.g. Mangerud et
741 al., 2004; Svendsen et al., 2004) and in the UK (e.g. Murton and Murton, 2012).

742
743 Quaternary GLOFs or jökulhlaups have indirectly extended the geomorphological influence of
744 proglacial lakes to marine settings. Terrestrial canyons (e.g. Baker and Bunker, 1985; Herget, 2002)
745 and submarine canyons (e.g. Thieler et al., 2007; Elliot and Parson, 2008) have been excavated by
746 drainages of Quaternary proglacial lakes. In terms of deposition, Quaternary jökulhlaups have
747 emplaced giant submarine fans onto continental shelves (e.g. Brown and Kennett, 1998; Geirsdóttir

748 et al., 2002). Sedimentological analyses in Alaskan fjords have suggested that marine impacts of
749 Quaternary jökulhlaups may be more widespread than previously thought, because many deposits
750 previously interpreted as ‘glacial’ could in fact be products of jökulhlaups (Willems et al., 2011).

751

752 ***3c) Proglacial lake and climate interactions***

753 The relationships between proglacial lakes and climate have been researched extensively; it is
754 therefore our intention to only outline the most salient elements of these relationships. Proglacial
755 lakes are intrinsically linked to wider geological and environmental systems; namely weather and
756 climate, meltwater and sediment fluxes and glacier and ice sheet dynamics. These interactions are
757 briefly discussed below, highlighting interdependencies and feedback mechanisms.

758

759 ***i) Proglacial lake influences on local and regional weather***

760 In comparison to bedrock, soil or vegetation covered land and glacier ice, (unfrozen) proglacial lakes
761 have a lower albedo (e.g. Sakai et al., 2000) and a higher thermal heat capacity. Proglacial lakes
762 thereby affect the local surface energy balance and in particular summer ablation, which is the major
763 component of annual mass balance for most alpine glaciers (Oerlemans and Reichert, 2000).
764 Specifically, on a local scale ice-marginal lakes can absorb relatively high amounts of incoming
765 shortwave radiation during summer, freeze in winter and hence reflect most incoming shortwave
766 radiation (Björnsson et al., 2001), retain relatively cold meltwater and have a thermal heat capacity
767 greater than that of surrounding land, which combined lead to relatively cool summer air
768 temperatures and relatively warm autumnal air temperatures.

769

770 On a regional scale, substantial lakes can directly influence weather patterns (e.g. Long et al., 2007
771 Brown and Duguay, 2010). Krinner et al., (2004) and Mangerud et al. (2004) discuss the feedback
772 effects between ice-dammed lakes, climate and glacier fluctuations in northern Eurasia during the
773 earliest stages of the last glaciation there (90 - 80 ka). Ice sheet growth over the Barents and Kara
774 seas expanded south onto the Russian mainland and led to the damming of north flowing rivers
775 forming ice-dammed lakes. Modelling results suggest that these lakes remained cool in summer, not
776 only because they were in receipt of large quantities of water from the ice sheet margin but also as a
777 consequence of the thermal heat capacity of water being far greater than that of land. The resultant
778 summer cooling, which was strong over the lakes themselves, also extended onto the ablation zone

779 of the ice sheet (Mangerud et al., 2004), and in turn reduced summer melt across the margin of the
780 ice sheet and increased ice mass balance. It is thought that such ‘coupled lake-ice sheet systems’
781 could be self-sustaining and play an important role in climate modification (Krinner et al., 2004).
782 This relationship is finely balanced; if ice sheet decay triggers ice-dammed lake drainage, de-
783 coupling occurs. Numerical modelling by Peyaud et al. (2007) that was designed to further illuminate
784 the impacts of Quaternary ice-dammed lakes on ice sheets also supports these findings. It is clear that
785 further work on the relationships between proglacial lakes, ice sheet and climate will assist in
786 environmental change reconstruction and the prediction of the impacts of current global deglaciation.
787 If proglacial lakes modify regional climate, then indirectly they may assist in the preservation or
788 degradation of ice sheets (Fig. 6). For example, work by Hostetler et al. (2000) simulated the effects
789 of Lake Agassiz on the climate of central North America at 11 ka using a high-resolution regional
790 climate model nested within a general circulation model and demonstrated that the lake cooled the
791 climate at the southern edge of the Laurentide Ice Sheet.

792

793 *ii) Proglacial lake influences on global climate*

794 There is well-established evidence that the drainage of large Quaternary proglacial lakes affected
795 ocean circulation and thereby changed climate due to the sudden influx of very large ($\sim 1 \text{ M m}^3 \text{ s}^{-1}$)
796 meltwater pulses into the oceans and there is a substantial body of work on these events and their
797 implications (e.g. Barber et al., 1999; Marshall and Clarke, 1999; Clarke, et al., 2001; Mangerud et
798 al., 2001; Teller et al., 2001; Fisher et al., 2002; Teller et al., 2002; Clarke, et al., 2003; 2004, 2009;
799 Rayburn et al., 2011). Late Pleistocene megafloods from the margins of the Laurentide ice sheet in
800 Canada and North America have been extensively studied; the fluctuations of the ice sheet resulted
801 in the complex evolution and drainage of the basins that now contain the Great Lakes (e.g. Kehew
802 and Lord, 1987; Teller and Kehew, 1995). Particular attention has been paid to the outflow of large
803 quantities of freshwater into Arctic Ocean from the subglacial drainage of ‘superlake’ Agassiz. The
804 timing, routing and duration of catastrophic meltwater discharges from Lake Agassiz and other
805 proglacial lakes has been debated at length (e.g. Broecker, 2006; Lowell et al., 2005; Tarasov and
806 Peltier, 2005; Lepper et al., 2007; Fisher et al., 2008; Murton et al., 2010; Rayburn et al., 2011), not
807 least because the final drainage of Lake Agassiz into Hudson Bay could have triggered the Younger
808 Dryas cold event - a millennial-scale reversal to glacial conditions during the last glaciation - as a

809 consequence of the disruption of the salinity gradient that drives meridional overturning circulation
810 (c.f. Teller, 2012).

811

812 Development and drainage of huge proglacial lakes in Eurasia could also have perturbed regional
813 hydrological conditions and thereby indirectly affected global climate. For example, in Russia, ice
814 sheets developing in the north blocked large northwards flowing rivers creating Lake Komi, the
815 Baltic lake and lakes in the White Sea Basin and the West Siberian Plain (Astakhov et al., 1999;
816 Mangerud et al., 2001; Krinner et al., 2004; Margold et al., 2011); these lakes would have drained
817 into the Arctic Ocean, influencing sea ice formation and oceanic circulation (Mangerud et al., 2001).
818 Margold et al., (2011) have proposed that flooding from Glacial Lake Vitim in Siberia caused
819 climatic and environmental impacts as a consequence of large freshwater influx into the Arctic
820 Ocean, further suggesting that the drainage of Lake Vitim was responsible for a freshwater spike at -
821 13 ka inferred from Arctic Ocean sediments (Speilhagen et al., 2005).

822

823 It is clear that further research on the sensitivity of ocean circulation to freshwater inputs and the
824 extent to which the drainage of large proglacial lakes can modify the behaviour of ocean circulation
825 and trigger climate oscillations will be increasingly important, given the development of proglacial
826 lakes concomitant with current deglaciation.

827

828

829 **4. Summary and conclusions**

830 In summary, geological evidence from the Quaternary shows that proglacial lakes were a major
831 component of deglaciation. At present, proglacial lakes are increasing in number and size around the
832 world. Ice-marginal or ‘ice-contact’ lakes exert a control on mountain glacier and ice sheet margin
833 dynamics via the longitudinal stress balance. Glacier margin morphology, physical stability and ice
834 dynamics are all affected by the presence, character and behaviour of an ice-marginal lake. Growth
835 of an ice-marginal lake can have a positive feedback with glacier dynamics and glacier mass loss,
836 due to the controls of; (i) raising an englacial water table, (ii) raising englacial water temperature,
837 (iii) raising subglacial water pressure, (iv) increasing ice surface gradient, (v) promoting ice margin
838 flotation, (vi) promoting calving, (vii) intense ice flexure and fracture during rapid draining or filling,
839 (viii) intense flushing of sediment from beneath a glacier and intense aggradation of sediment at a

840 glacier terminus during rapid draining. Proglacial lakes interrupt routing of ablation-fed meltwater,
841 episodically released meltwater and sediment from a glacier system to a proglacial zone.
842 Sedimentation in proglacial lakes is one of the most important; continuous and high-resolution
843 geochronological archives. Proglacial lakes have been documented to impact continental
844 hydrological drainage, and via jökulhlaups can create spectacular terrestrial and submarine landforms
845 including canyons and extensive fans. Proglacial lakes can affect weather and climate via albedo and
846 thermal heat capacity controls, and via sudden drainage to produce jökulhlaups that abruptly deliver
847 freshwater and sediment in sufficient quantity to modify ocean circulation and climate.

848

849 Scientific advances in understanding of the Quaternary can be brought about by (i) drawing
850 terrestrial and marine records together, and (ii) considering a range of approaches and methodologies
851 across multiple scientific disciplines. However, there are hitherto untapped opportunities for utilising
852 emerging technologies to understand proglacial lake processes and to revisit or extend proglacial
853 lake geochronological archives. For example, autonomous underwater vehicles (AUVs) with
854 capability to simultaneously measure bathymetry, water currents and water quality parameters in
855 three-dimensions and at high repeatability could offer great insights to modern processes of
856 sedimentation, water circulation and indeed subglacial water routing and discharge regimes. Water
857 surface-deployed acoustic systems such as ‘sediment echo-sounders’ or ‘sub-bottom profilers’ that
858 are capable of imaging sediment stratigraphy through a water column should offer unprecedented
859 information on both modern Quaternary sedimentation styles and rates.

860

861 In conclusion, our knowledge of the character, behaviour and geological importance of proglacial
862 lakes has improved markedly over the past few decades at least in part due to a shift from mono-
863 disciplinary studies to more integrated studies. However, whilst there is much more holistic work to
864 be done, and this study is a start, it is abundantly clear that proglacial lakes are intrinsically linked to
865 climate change and to wider geological systems through glacier mass balance and hence glacial
866 meltwater and sediment fluxes. Proglacial lakes could be an integral part of deglaciation by affecting
867 the stability and character of glacier margins. They can disengage glacier behaviour from climatic
868 perturbations. Proglacial lakes interrupt the delivery of meltwater and sediment to proglacial zones
869 and ultimately to oceans. Sedimentation within proglacial lakes is a very important geochronological
870 archive recording short-term inter-seasonal patterns, inter-annual patterns, and long-term patterns of

871 glacier-derived meltwater fluctuation and hence, by proxy, glacier mass balance. Overall, proglacial
872 lakes are exceptionally useful for understanding (i) patterns, character and behaviour of mountain
873 glaciers and glaciations, (ii) ice sheet dynamics and driving processes, (iii) past deglaciation, (iv) the
874 geological importance of present-day proglacial lakes, and (v) future deglaciation in both mountain
875 and ice sheet environments. Looking forwards, proglacial lakes will continue to increase in number
876 size due to mountain glacier and ice sheet mass loss. Ice-marginal lakes will de-couple mountain
877 glacier and ice sheet margin changes from climate and will accelerate glacier mass loss in the short-
878 term. Outburst floods from proglacial lakes will therefore also increase in frequency and perhaps also
879 in magnitude, thereby constituting a persistent hazard.

880

881 **Acknowledgements**

882 The School of Geography, University of Leeds is thanked for supporting fieldwork in west
883 Greenland. Sam Shires is thanked for the photograph in figure 2D.

884

885 **References**

886

887 Ackert Jr, R.P., 2009. Palaeoclimate: Patagonian dust machine. *Nature Geoscience* 2, 244-245.

888 Ageta, Y., Iwata, S., Yabuki, H., Naito, N., Sakai, A., Narama, C., Karma, T., 2000. Expansion of glacier lakes in recent
889 decades in the Bhutan Himalayas. *IAHS Publication* 165-176.

890 Alho, P., Russell, A.J., Carrivick, J.L and Käyhkö, J. 2005. Reconstruction of the largest jökulhlaup within Jökulsá á
891 Fjöllum river, NE Iceland during Holocene. *Quaternary Science Reviews* 24, 2319-2334.

892 Ames, A., 1998. A documentation of glacier tongue variations and lake development in the Cordillera Blanca,
893 Peru. *Zeitschrift für Gletscherkunde und Glazialgeologie* 34, 1– 36.

894 Anderson, D.M., Archer, R.B., 1999. Preliminary evidence of early deglaciation in southern Chile. *Palaeogeography*
895 *Palaeoclimatology Palaeoecology* 146, 295-301.

896 Anderson, R.S., Walder, J.S., Anderson, S.P., Trabant, D.C., Fountain, A.G., 2005. The dynamic response of Kennicott
897 Glacier, Alaska, USA, to the Hidden Creek Lake outburst flood. *Annals of Glaciology* 40, 237-242.

898 Andrews, J.T., Austin, W.E.N., Bergsten, H., Jennings, A.E., (Eds.), 1996. Late Quaternary Palaeoceanography of the
899 North Atlantic Margins. Geological Survey, London, Special Publication 111.

900 Aniya, M., Naruse, R. 2001. Overview of glaciological research projects in Patagonia in 1998 and 1999: Holocene
901 glacier variations and their mechanisms. *Bulletin of Glaciological Research* 18, 71-78.

902 Arkhipov, S.A., Ehlers, J., Johnson, R.G., Wright Jr, H.E., 1995. Glacial drainage towards the Mediterranean during the
903 Middle and Late Pleistocene. *Boreas* 24, 196-206.

904 Ashley, G.M., 1995. Glaciolacustrine environments. In: Menzies, J., (Ed.), *Modern Glacial Environments: Processes,*
905 *Dynamics and Sediments.* Butterworth-Heinemann. Oxford, pp. 417-444.

906 Ashley, G.M., Boothroyd, J.C., and Borns, H.W., 1991. Sedimentology of late Pleistocene (Laurentide) deglacial-phase
907 deposits, eastern Maine: an example of a temperate marine grounded ice sheet margin. In: Anderson, J.B., and Ashley,
908 G.M., (Eds.), *Glacial Marine Sedimentation: Palaeoclimatic Significance.* Geological Society of America, Special Paper
909 261, 107-125.

- 910 Astakhov, V.I., 2008. Evidence of Late Pleistocene ice-dammed lakes in West Siberia. *Boreas* 35, 607-621.
- 911 Bajracharya, B., Shrestha, A.B., Rajbhandari, L., 2007. Glacial lake outburst floods in the Sagarmatha region. *Mountain*
912 *Research and Development* 27, 336-344.
- 913 Baker, V.R., 2007. Greatest floods - largest rivers. *Large Rivers: Geomorphology and Management*, 65-74.
- 914 Baker, V.R., Bunker, R.C., 1985. Cataclysmic late Pleistocene flooding from glacial Lake Missoula: A review.
915 *Quaternary Science Reviews* 4, 1-41.
- 916 Baker, V.R., Benito, G., Rudoy, A.N., 1993. Paleohydrology of late Pleistocene superflooding, Altay mountains, Siberia.
917 *Science* 259, 348-350.
- 918 Ballantyne, C.K., 2003. Paraglacial landystems. In: Evans, D.J.A., (Ed.), *Glacial Landystems*. Arnold, London. 432-46.
- 919 Benito, G., O'Connor, J.E., 2003. Number and size of last-glacial Missoula floods in the Columbia River valley between
920 the Pasco Basin, Washington, and Portland, Oregon. *Geological Society of America Bulletin* 115, 624-638.
- 921 Benn, D.I., 2008. Subglacial and subaqueous processes near a glacier grounding line: sedimentological evidence from a
922 former ice-dammed lake, Achnasheen Scotland. *Boreas* 25, 23-36.
- 923 Benn, D.I., Owen, L.A., 2002. Himalayan glacial sedimentary environments: a framework for reconstructing and dating
924 the former extent of glaciers in high mountains. *Quaternary International* 97, 3-25.
- 925 Benn, D.I., Evans, D.J.A., 2010. *Glaciers and Glaciation*. Hodder Education, London, pp. 802.
- 926 Bennett, M.R., Huddart, D., McCormick, T., 2000. The glaciolacustrine landform-sediment assemblage at
927 Heinabergsjökull, Iceland. *Geografiska Annaler* 82A, 1-16.
- 928 Blass, A., Anselmetti, F.S., Ariztegui, D., 2003. 60 years of glaciolacustrine sedimentation in Steinsee (Sustenpass,
929 Switzerland) compared with historic events and instrumental meteorological data. *Eclogae Geologicae Helvetiae* 96,
930 S59-S71.
- 931 Blass, A., Anselmetti, F.S., Grosjean, M., Sturm, M., 2005. The last 1300 years of environmental history recorded in the
932 sediments of Lake Sils (Engadine, Switzerland). *Eclogae Geologicae Helvetiae* 98, 319-332.
- 933 Brown, L.C., Duguay, C.R., 2010. The response and role of ice cover in lake-climate interactions. *Progress in Physical*
934 *Geography* 34, 671-704.
- 935 Bodén, P., Fairbanks, R.G., Wright, J.D., Burckle, L.H., 1997. High-resolution stable isotope records from southwest
936 Sweden: The drainage of the Baltic Ice Lake and Younger Dryas ice margin oscillations. *Paleoceanography*, 12, 39-49.
- 937 Bolch, T., Buchroithner, M.F., Peters, J., Baessler, M., Bajracharya, S. 2008. Identification of glacier motion and
938 potentially dangerous glacial lakes in the Mt. Everest region, Nepal using spaceborne imagery. *Natural Hazards and*
939 *Earth System Science* 8, 1329-1340.
- 940 Bonan G.B., 1995. Sensitivity of a GCM simulation to inclusion of inland water surfaces. *Journal of Climate* 8, 2691-
941 2704.
- 942 Boyce, E.S., Motyka, R.J., Truffer, M., 2007. Flotation and retreat of a lake-calving terminus, Mendenhall Glacier,
943 southeast Alaska, USA. *Journal of Glaciology* 53, 211-224.
- 944 Brandes, C., Polom, U., Winsemann, J., 2011. Reactivation of basement faults: interplay of ice-sheet advance, glacial
945 lake formation and sediment loading. *Basin Research* 23, 53-64.
- 946 Brown, P.A., Kennett, J.P., 1998. Megaflood erosion and meltwater plumbing changes during last North American
947 deglaciation recorded in Gulf of Mexico sediments. *Geology* 26, 599-602.
- 948 Bujalesky, G.G., Heusser, C.J., Coronato, A.M., Roig, C.E., Rabassa, J.O., 1997. Pleistocene glaciolacustrine
949 sedimentation at Lago Fagnano, Andes of Tierra del Fuego, southernmost South America. *Quaternary Science Reviews*
950 16, 767-778.
- 951 Capps, D.M., Wiles, G.C., Clague, J.J., Luckman, B.H., 2011. Tree-ring dating of the nineteenth-century advance of
952 Brady Glacier and the evolution of two ice-marginal lakes, Alaska. *The Holocene* 21, 641-649.
- 953 Carling, P.A., 1996. Morphology, sedimentology and palaeohydraulic significance of large gravel dunes, Altai
954 Mountains, Siberia. *Sedimentology* 43, 647-664.

- 955 Carling, P.A., Kirkbride, A.D., Parnachov, S., Borodavki, P.S., Berger, G.W., 2002. Late Quaternary catastrophic
956 flooding in the Altai Mountains of south-central Siberia: a synoptic overview and an introduction to flood deposit
957 sedimentology. *Spec. Publs Int. Ass. Sediment.*, 32. 17–35
- 958 Carrivick, J.L., 2011. Jökulhlaups: geological importance, deglacial association and hazard management. *Geology Today*
959 27, 133-140.
- 960 Carrivick, J.L. 2007. Modelling coupled hydraulics and sediment transport of a high-magnitude flood and associated
961 landscape change. *Annals of Glaciology* 45, 143-154.
- 962 Carrivick, J.L., Chase, S.E., 2011. Spatial and temporal variability in the net mass balance of glaciers in the Southern
963 Alps, New Zealand. *New Zealand Journal of Geography and Geophysics* 54, 415-429
- 964 Carrivick J.L., Russell A.J., 2013. Glaciofluvial Landforms of Deposition. In: Elias S.A. (Ed.), *The Encyclopedia of*
965 *Quaternary Science* 2, 6-17. Amsterdam: Elsevier.
- 966 Carrivick, J.L., Russell, A.J., Rushmer, E.L., Tweed, F.S., Marren, P.M., Deeming, H., Lowe, O.J., 2009.
967 Geomorphological evidence towards a deglacial control on volcanism. *Earth Surface Processes and Landforms* 34, 1164–
968 1178.
- 969 Carrivick, J.L., Pringle, J.K., Russell, A.J., Cassidy, N.J., 2007. Sedimentary architecture and stratigraphy of outburst
970 flood sedimentation within a bedrock valley system, Hraundalur, Iceland. *Journal of Environmental and Engineering*
971 *Geophysics* 12, 127-143.
- 972 Carrivick, J.L., Twigg, D. 2005. Jökulhlaup-influenced topography and geomorphology at Kverkfjöll, Iceland. *Journal of*
973 *Maps* 2005, 17-27
- 974 Carrivick, J.L., Russell, A.J., Tweed, F.S., Twigg, D., 2004. Palaeohydrology and sedimentology of jökulhlaups from
975 Kverkfjöll, Iceland. *Sedimentary Geology* 172, 19-40.
- 976 Carrivick, J.L., Russell, A.J., Tweed, F.S., 2004. Geomorphological evidence for jökulhlaups from Kverkfjöll volcano,
977 Iceland. *Geomorphology* 63, 81-102.
- 978 Charlet, F., De Batist, M., Chapron, E., Bertrand, S., Pino, M., Urrutia, R., 2008. Seismic stratigraphy of Lago Puyehue
979 (Chilean Lake District): new views on its deglacial and Holocene evolution. *Journal of Paleolimnology* 39, 163-177.
- 980 Chen, X.Q., Cui, P., Li, Y., Yang, Z., Qi, Y.Q., 2007. Changes in glacial lakes and glaciers of post-1986 in the Poiqu
981 River basin, Nyalam, Xizang (Tibet). *Geomorphology* 88, 298-311.
- 982 Chigira, M., Wang, W.N., Furuya, T., Kamai, T., 2003. Geological causes and geomorphological precursors of the
983 Tsaoling landslide triggered by the 1999, Chi-Chi earthquake Taiwan. *Engineering Geology* 68, 259–273.
- 984 Chikita, K.A., Yamada, T., 2005. The expansion of Himalayan glacial lakes due to global warming: field observations
985 and numerical simulation. *IAHS-AISH Publication* 295, 111-119.
- 986 Chinn, T.J., 1996. New Zealand glacier responses to climate change of the past century. *New Zealand Journal of Geology*
987 *and Geophysics* 39, 415-428.
- 988 Chinn, T.J., 1999. New Zealand glacier response to climate change of the past 2 decades. *Global and Planetary Change*
989 22, 155-168.
- 990 Clague, J.J., Evans, S.G., 1997. The 1994 jökulhlaup at Farrow Creek, British Columbia, Canada. *Geomorphology* 19, 77-
991 87.
- 992 Clague, J.J., Evans, S.G., 2000. A review of catastrophic drainage of moraine-dammed lakes in British Columbia.
993 *Quaternary Science Reviews* 19, 1763-1783.
- 994 Clark, P.U., Alley, R.B., Pollard, D., 1999. Northern Hemisphere ice-sheet influences on global climate change. *Science*
995 286, 1104-1111.
- 996 Clarke, G.K.C., Mathews, W.H., 1981. Estimates of the magnitude of glacier outburst floods from Lake Donjek, Yukon
997 Territory, Canada. *Canadian Journal of Earth Sciences* 18, 1452-1463.
- 998 Clarke, G., Leverington, D., Teller, J., Dyke, A., 2003. Superlakes, megafloods, and abrupt climate change. *Science*
999 301(5635), 922-923.

- 1000 Clarke, G. K., Bush, A. B., & Bush, J. W. (2009). Freshwater discharge, sediment transport, and modeled climate
1001 impacts of the final drainage of glacial Lake Agassiz. *Journal of Climate*, 22(8), 2161-2180.
- 1002 Cook, S.J., Swift, D.A., 2012. Subglacial basins: their origin and importance in glacial systems and landscapes. *Earth
1003 Science Reviews* 115, 332-372.
- 1004 Costa, J.E., Schuster, R.L., 1988. The formation and failure of natural dams. *Geological Society of America Bulletin*, 100,
1005 1054-1068.
- 1006 Cutler, P.M., Mickelson, D.M., Colgan, P.M., MacAyeal, D.R., Parizek, B.R., 2001. Influence of the Great Lakes on the
1007 dynamics of the southern Laurentide Ice Sheet: numerical experiments. *Geology* 29, 1039-1042.
- 1008 Demidov, I.N., Houmark-Nielsen, M., Kjær, K.H., Larsen, E., 2006. The last Scandinavian Ice Sheet in northwestern
1009 Russia: ice flow patterns and decay dynamics. *Boreas* 35, 425-443.
- 1010 Desloges, J.R., 1994. Varve deposition and sediment yield record at three small lakes of the southern Canadian
1011 Cordillera. *Arctic and Alpine Research* 26, 130-140.
- 1012 Desloges, J.R., Gilbert, R.E., 1991. Sedimentary record of Harrison Lake: implications for deglaciation in southwestern
1013 British Columbia. *Canadian Journal of Earth Sciences* 28, 800-815.
- 1014 Diolaiuti, G., Citterio, M., Carnielli, T., D'Agata, C., Kirkbride, M., Smiraglia, C., 2006. Rates, processes and
1015 morphology of freshwater calving at Miage Glacier (Italian Alps). *Hydrological Processes* 20, 2233-2244.
- 1016 Dirszowsky, R., Desloges, J.R., 2004. Evolution of the Moose Lake delta, British Columbia: implications for holocene
1017 environmental change in the Canadian Rocky Mountains. *Geomorphology* 57, 75-93.
- 1018 Dirszowsky, R.W., Desloges, J.R., 1997. Glaciolacustrine sediments and neoglacial history of the Chephren Lake Basin,
1019 Banff National Park, Alberta. *Géographie Physique et Quaternaire* 51, 41-53.
- 1020 Dredge, L.A., Cowan, W.R., 1989. Quaternary Geology of the southwestern Canadian Shield. In: Fulton, R.G. (Ed.),
1021 Quaternary Geology of Canada and Greenland Geological Survey of Canada, Geology of Canada 1. 214-235.
- 1022 Elliott, G.M., Parson, L.M., 2008. Influence of sediment drift accumulation on the passage of gravity-driven sediment
1023 flows in the Iceland Basin, NE Atlantic. *Marine and Petroleum Geology* 25, 219-233.
- 1024 Etienne, J.L., Jansson, K.N., Glasser, N.F., Hambrey, M.J., Davies, J.R., Waters, R.A., Maltman, A.J., Wilby, P.R., 2006.
1025 Palaeoenvironmental interpretation of an ice-contact glacial lake succession: an example from the late Devensian of
1026 southwest Wales, UK. *Quaternary Science Reviews* 25, 739-762.
- 1027 Evans, S.G., Clague, J.J., 1994. Recent climatic change and catastrophic geomorphic processes in mountain
1028 environments. *Geomorphology* 10, 107-128.
- 1029 Eyles, N., Eyles, C.H., Woodworth-Lynas, C.M.T., Randall, T.A., 2005. The sedimentary record of drifting ice (early
1030 Wisconsin Sunnybrook deposit) in an ancestral ice-dammed Lake Ontario, Canada. *Quaternary Research* 63, 171-181.
- 1031 Fanetti, D., Anselmetti, F.S., Chapron, E., Sturm, M., Vezzoli, L., 2008. Megaturbidite deposits in the Holocene basin fill
1032 of Lake Como (Southern Alps, Italy). *Palaeogeography Palaeoclimatology Palaeoecology* 259, 323-340.
- 1033 Fiore, J., Girardclos, S., Pugin, A., Gorin, G., Wildi, W., 2011. Würmian deglaciation of western Lake Geneva
1034 (Switzerland) based on seismic stratigraphy. *Quaternary Science Reviews* 30, 377-393.
- 1035 Fleisher, P.J., Bailey, P.K., Cadwell, D.H., 2003. A decade of sedimentation in ice-contact, proglacial lakes, Bering
1036 Glacier, AK. *Sedimentary Geology* 160, 309-324.
- 1037 Fleisher, P.J., Bailey, P.K., Cadwell, D.H., 2003. A decade of sedimentation in ice-contact, proglacial lakes, Bering
1038 Glacier, AK. *Sedimentary Geology* 160, 309-324.
- 1039 Fortner, S.K., Tranter, M., Fountain, A., Lyons, W.B., Welch, K.A., 2005. The geochemistry of supraglacial streams of
1040 Canada Glacier, Taylor Valley (Antarctica), and their evolution into proglacial waters. *Aquatic Geochemistry* 11, 391-
1041 412.
- 1042 Francus, P., Bradley, R.S., Lewis, T., Abbott, M., Retelle, M., Stoner, J.S., 2008. Limnological and sedimentary processes
1043 at Sawtooth Lake, Canadian High Arctic, and their influence on varve formation. *Journal of Paleolimnology* 40, 963-985.

- 1044 Fujita, K., Sakai, A., Nuimura, T., Yamaguchi, S., Sharma, R.R., 2009. Recent changes in ImjaGlacialLake and its
1045 damming moraine in the Nepal Himalaya revealed by in situ surveys and multi-temporal ASTER imagery.
1046 *Environmental Research Letters* 4, 045205.
- 1047 Fyfe, G.J., 1990. The effect of water depth on ice-proximal glaciolacustrine sedimentation: Salpausselkä I, southern
1048 Finland. *Boreas* 19, 147-164.
- 1049 Gardelle, J., Arnaud, Y., Berthier, E., 2011. Contrasted evolution of glacial lakes along the Hindu Kush Himalaya
1050 mountain range between 1990 and 2009. *Global and Planetary Change* 75, 47-55.
- 1051 Geilhausen, M., Morche, D., Otto, J.C., Schrott, L., 2012. Assessment of suspended and solute load in the proglacial
1052 Obersulzbach stream (Hohe Tauern, Austria). In: EGU General Assembly Conference Abstracts 14, 12696.
- 1053 Geirsdóttir, Á., Andrews, J.T., Ólafsdóttir, S., Helgadóttir, G., Hardardóttir, J., 2002. A 36 Ky record of iceberg rafting
1054 and sedimentation from north-west Iceland. *Polar Research* 21, 291-298.
- 1055 Geirsdóttir, Á., Miller, G.H., Wattrus, N.J., Björnsson, H., Thors, K., 2008. Stabilization of glaciers terminating in closed
1056 water bodies: Evidence and broader implications, *Geophysical Research Letters* 35, L17502.
- 1057 Gilbert, R., 2003. Spatially irregular sedimentation in a small, morphologically complex lake: implications for
1058 paleoenvironmental studies. *Journal of Paleolimnology* 29, 209-220.
- 1059 Gilbert, R., Desloges, J.R., 1992. The late Quaternary sedimentary record of Stave Lake, southwestern British Columbia.
1060 *Canadian Journal of Earth Sciences* 29, 1997-2006.
- 1061 Gilbert, R., Crookshanks, S., 2009. Sediment waves in a modern high-energy glaciolacustrine environment.
1062 *Sedimentology* 56, 645-659.
- 1063 Gilbert, R., Desloges, J.R., 2005. The record of Glacial Lake Champagne in Kusawa Lake, southwestern Yukon
1064 Territory. *Canadian Journal of Earth Sciences* 42, 2127-2140.
- 1065 Gilbert, R., Desloges, J.R., Clague, J.J., 1997. The glaciolacustrine sedimentary environment of Bowser Lake in the
1066 northern Coast Mountains of British Columbia, Canada. *Journal of Paleolimnology* 17, 331-346.
- 1067 Gollidge, N.R., Phillips, E., 2008. Sedimentology and architecture of De Geer moraines in the western Scottish
1068 Highlands, and implications for grounding-line glacier dynamics. *Sedimentary Geology* 208, 1-14.
- 1069 Gomez, B., Smith, L.C., Magilligan, F.J., Mertes, L.A.K., Smith, N.D., 2002. Glacier outburst floods and outwash plain
1070 development: Skeiðarársandur, Iceland. *Terra Nova* 12, 126-131.
- 1071 Grosswald, M.G., 1998. Late-Weichselian ice sheets in Arctic and Pacific Siberia. *Quaternary International* 45, 3-18.
- 1072 Grosswald, M.G., Rudoy, A.N., 1996. Quaternary glacier-dammed lakes in the mountains of Siberia. *Polar Geography*
1073 20, 180-198.
- 1074 Gustavson, T.C., 1975. Bathymetry and sediment distribution in proglacial Malaspina Lake, Alaska. *Journal of*
1075 *Sedimentary Petrology* 45, 450-461.
- 1076 Hambrey, M.J., 1994. *Glacial Environments*. University of British Columbia Press. Vancouver, 296pp.
- 1077 Harper, J.T., Bradford, J.H., Humphrey, N.F., Meierbachtol, T.W., 2010. Vertical extension of the subglacial drainage
1078 system into basal crevasses. *Nature* 467, 579-582.
- 1079 Harrison, S., Glasser, N., Winchester, V., Haresign, E., Warren, C., Jansson, K. 2006. A glacial lake outburst flood
1080 associated with recent mountain glacier retreat, Patagonian Andes. *The Holocene* 16, 611-620.
- 1081 Hasholt, B., 1993. Late autumn runoff and sediment transport in a proglacial drainage system, Sermilik, East Greenland.
1082 *Geografisk Tidsskrift-Danish Journal of Geography* 93, 1-5.
- 1083 Hawarth, P.J., Price, R.J. 1969. The Proglacial Lakes of Breiðamerkurjökull and Fjallsjökull, Iceland. *The Geographical*
1084 *Journal* 135, 573-581.
- 1085 Hasholt, B., Walling, D.E., Owens, P.N., 2000. Sedimentation in arctic proglacial lakes: Mittivakkat Glacier, south-east
1086 Greenland. *Hydrological Processes* 14, 679-699.
- 1087 Hergert, J., 2005. Reconstruction of Pleistocene ice-dammed lake outburst floods in the Altai Mountains, Siberia.
1088 *Geological Society of America Special Publications* 386.

- 1089 Hicks, D.M., McSaveney, M.J., Chinn, T.J.H., 1990. Sedimentation in Proglacial Ivory Lake, Southern Alps, New
1090 Zealand. *Arctic and Alpine Research* 22, 26-42.
- 1091 Hillaire-Marcel, C., Occhietti, S., Vincent, J.-S., 1981. Sakami Moraine, Quebec; A 500 km long moraine without
1092 climatic control. *Geology* 9, 210-214.
- 1093 Hochstein, M.P., Watson, M.I., Malengreau, B., Nobes, D.C., Owens, I., 1998. Rapid melting of the terminal section of
1094 the Hooker Glacier (Mt Cook National Park, New Zealand). *New Zealand Journal of Geology and Geophysics* 4, 203-
1095 218.
- 1096 Hubbard, A., Hein, A.; Kaplan, M.R.; Hulton, N.R.J., 2005. A modelling reconstruction of the Last Glacial Maximum
1097 Ice Sheet and its deglaciation in the vicinity of the Northern Patagonian Icefield, South America, *Geografiska Annaler*,
1098 Series A: Physical Geography 87, 375-39.
- 1099 Huggel, C., Käab, A., Haeberli, W., Teysseire, P., Paul, F., 2002. Remote sensing based assessment of hazards from
1100 glacier lake outbursts: a case study in the Swiss Alps. *Canadian Geotechnical Journal* 39, 316-330.
- 1101 Huss, M., Bauder, A., Werder, M., Funk, M., Hock, R., 2007. Glacier-dammed lake outburst events of Gornensee,
1102 Switzerland. *Journal of Glaciology* 53, 189-200.
- 1103 Jansson, K.N. 2003. Early Holocene glacial lakes and ice marginal retreat pattern in Labrador/Ungava, Canada.
1104 *Palaeogeography, Palaeoclimatology, Palaeoecology* 193, 473-501.
- 1105 Johnsen, T.F., Brennand, T.A., 2006. The environment in and around ice-dammed lakes in the moderately high relief
1106 setting of the southern Canadian Cordillera. *Boreas* 35, 106-125.
- 1107 Jopling, A.V., MacDonald, B.C., (Eds.), 1975. Glaciofluvial and glaciolacustrine sedimentation. *SEPM Special*
1108 *Publication* 23.
- 1109 Josberger, J.G., Shuchman, R.A., Meadows, G.A., Savage, S., Payne, J., 2010. Hydrography and circulation of ice-
1110 contact lakes at Bering Glacier, Alaska, U.S.A. *Arctic, Antarctic, and Alpine Research* 38, 547-560.
- 1111 Käab, A., Haeberli, W., 2001. Evolution of a high-mountain thermokarst lake in the Swiss Alps. *Arctic, Antarctic and*
1112 *Alpine Research* 33, 385-390.
- 1113 Kattelmann, R., 2003. Glacial lake outburst floods in the Nepal Himalaya: a manageable hazard? *Natural Hazards* 28,
1114 145-154.
- 1115 Kehew, A.E., Teller, J.T., 1994. History of late glacial runoff along the southwestern margin of the Laurentide ice sheet.
1116 *Quaternary Science Reviews* 13, 859-877.
- 1117 Kirkbride, M.P., 1993. The temporal significance of transitions from melting to calving termini at glaciers in the central
1118 Southern Alps of New Zealand. *The Holocene* 3, 232-240.
- 1119 Kirkbride, M.P., Warren, C.R., 1999. Tasman Glacier, New Zealand: 20th-century thinning and predicted calving retreat.
1120 *Global and Planetary Change* 22, 11-28.
- 1121 Komatsu, G., Baker, V.R., 2007. Formation of valleys and cataclysmic flood channels on Earth and Mars. *The Geology*
1122 *of Mars: Evidence from Earth-Based Analog*, 1, 297.
- 1123 Komatsu, G., Arzhannikov, S.G., Gillespie, A.R., Burke, R.M., Miyamoto, H., Baker, V.R., 2009. Quaternary paleolake
1124 formation and cataclysmic flooding along the upper Yenisei River. *Geomorphology* 104, 143-164.
- 1125 Komori, J., 2008. Recent expansions of glacial lakes in the Bhutan Himalayas. *Quaternary International* 184, 177-186.
- 1126 Korup, O., 2002. Recent research on landslide dams-a literature review with special attention to New Zealand. *Progress*
1127 *in Physical Geography* 26, 206-235.
- 1128 Korup, O., Tweed, F., 2007. Ice, moraine, and landslide dams in mountainous terrain. *Quaternary Science Reviews* 26,
1129 3406-3422.
- 1130 Korup, O., Strom, A.L., Weidinger, J.T., 2006. Fluvial response to large rock-slope failures-examples from the
1131 Himalayas, the Tien Shan, and the Southern Alps in New Zealand. *Geomorphology* 78, 3-21.
- 1132 Krivonogov, S.K., Sheinkman, V.S., Mistryukov, A.A., 2005. Stages in the development of the Darhad dammed lake
1133 (Northern Mongolia) during the Late Pleistocene and Holocene. *Quaternary International* 136, 83-94.

- 1134 Lamoureux, S.F., 1999. Catchment and lake controls over the formation of varves in monomictic Nicolay Lake,
1135 Cornwall Island, Nunavut. *Canadian Journal of Earth Sciences* 36, 1533-1546.
- 1136 Lamoureux, S.F., Gilbert, R., 2004. A 750-yr record of autumn snowfall and temperature variability and winter
1137 storminess recorded in the varved sediments of Bear Lake, Devon Island, Arctic Canada. *Quaternary Research* 61, 134-
1138 147.
- 1139 Larsen, E., Longva, O., Follestad, B.A., 2006. Formation of De Geer moraines and implications for deglaciation
1140 dynamics. *Journal of Quaternary Science* 6, 263-277.
- 1141 Larsen, D.J., Miller, G.H., Geirsdóttir, Á., Thordarson, T., 2011. A 3000-year varved record of glacier activity and
1142 climate change from the proglacial lake Hvítárvatn, Iceland. *Quaternary Science Reviews* 30, 2715-2731.
- 1143 Larsen, E., Kjaer, K., Demidov, I.N., Funder, S., Grøsfjeld, K., Houmark-Nielsen, M., Jensen, M., Linge, H., Lyså, A.,
1144 2006. Late Pleistocene glacial and lake history of northwestern Russia. *Boreas* 35, 394-424.
- 1145 Leemann, A., Niessen, F., 2004. Varve formation and the climatic record in an Alpine proglacial lake: calibrating
1146 annually-laminated sediments against hydrological and meteorological data. *The Holocene* 4, 1-8.
- 1147 Lemmen, D.S., Aitkin, A.E., Gilbert, R., 1994. Early Holocene deglaciation of Expedition and Strand Fiords, Canadian
1148 High Arctic. *Canadian Journal of Earth Sciences* 31, 943-958.
- 1149 Leonard, E.M., Reasoner, M.A., 1999. A continuous Holocene glacial record inferred from proglacial lake sediments in
1150 Banff National Park, Alberta, Canada. *Quaternary Research* 51, 1-13.
- 1151 Lewis, T., Gilbert, R., Lamoureux, S.F., 2002. Spatial and temporal changes in sedimentary processes at proglacial Bear
1152 Lake, Devon Island, Nunavut, Canada. *Arctic Antarctic and Alpine Research* 34, 119-129.
- 1153 Liermann, S., Beylich, A.A., van Welden, A., 2012. Contemporary suspended sediment transfer and accumulation
1154 processes in the small proglacial Sætrevatnet sub-catchment, Bødalen, western Norway. *Geomorphology* 167, 91-101.
- 1155 Lindén, M., Möller, P., 2005. Marginal formation of De Geer moraines and their implications to the dynamics of
1156 grounding-line recession. *Journal of Quaternary Science* 20, 113-133.
- 1157 Livingstone, S.J., Ó Cofaigh, C., Evans, D.J., Palmer, A., 2010. Sedimentary evidence for a major glacial oscillation and
1158 proglacial lake formation in the Solway Lowlands (Cumbria, UK) during Late Devensian deglaciation. *Boreas* 39, 505-
1159 527.
- 1160 Livingstone, S.J., Clark, C.D., Piotrowski, J.A., Tranter, M., Bentley, M.J., Hodson, A., Swift, D.A., Woodward, J.,
1161 2012. Theoretical framework and diagnostic criteria for the identification of palaeo-subglacial lakes. *Quaternary Science*
1162 *Reviews* 53, 88-110.
- 1163 Long, Z., Perrie, W., Gyakum, J., Caya, D., Laprise, R., 2007. Northern lake impacts on local seasonal climate. *Journal*
1164 *of Hydrometeorology* 8, 881-896.
- 1165 Loriaux, T., Casassa, G., 2012. Evolution of glacial lakes from the Northern Patagonia Icefield and terrestrial water
1166 storage in a sea-level rise context. *Global and Planetary Change* 102, 33-40.
- 1167 Loso, M.G., Anderson, R.S., Anderson, S.P., 2004. Post-Little Ice Age record of coarse and fine clastic sedimentation in
1168 an Alaskan proglacial lake. *Geology* 32, 1065-1068.
- 1169 Lovell, H., Stokes, C.R., Bentley, M.J., Benn, D.I., 2012. Evidence for rapid ice flow and proglacial lake evolution
1170 around the central Strait of Magellan region, southernmost Patagonia. *Journal of Quaternary Science* 27, 625-638.
- 1171 Mangerud, J., Jakobsson, M., Alexanderson, H., Astakhov, V., Clarke, G.K.C., Henriksen, M., Hjort, C., Krinner, G.,
1172 Lunkka, J.-P., Möller, P., Murray, A., Nikolskaya, O., Saarnisto, M., Svendsen, J.I., 2004. Ice-dammed lakes and
1173 rerouting of the drainage of northern Eurasia during the last glaciation. *Quaternary Science Reviews* 23, 1313-1332.
- 1174 Margold, M., Jansson, K.N., Stroeven, A.P., Jansen, J.D., 2011. Glacial Lake Vitim, a 3000-km³ outburst flood from
1175 Siberia to the Arctic Ocean. *Quaternary Research* 76, 393-396.
- 1176 Marren, P.M., 2002. Glacier margin fluctuations, Skaftafellsjökull, Iceland: implications for sandur evolution. *Boreas* 31,
1177 75-81.
- 1178 Martini, I.P., Brookfield, M.E., 1995. Sequence analysis of upper Pleistocene (Wisconsinan) glaciolacustrine deposits of
1179 the north-shore bluffs of Lake Ontario, Canada. *Journal of Sedimentary Research* B65, 388-400.

- 1180 Mathews, W.H., Clague, J.J., 1993. The record of jökulhlaups from Summit Lake, northwestern British Columbia.
1181 Canadian Journal of Earth Sciences 30, 499-508.
- 1182 Mayo, L.R., 1989. Advance of Hubbard glacier and 1986 outburst of Russell Fiord, Alaska, USA. Annals of Glaciology
1183 13, 189-194.
- 1184 McCulloch, R.D., Bentley, M.J., Tipping, R.M., Clapperton, C.M., 2005. Evidence for late-glacial ice dammed lakes in
1185 the central Strait of Magellan and Bahía Inútil, southernmost south America. Geografiska Annaler: Series A, Physical
1186 Geography 87, 335-362.
- 1187 McGuire, B., 2013. Hazardous responses of the solid Earth to a changing climate. Climate Forcing of Geological
1188 Hazards, 1-33.
- 1189 Meinsen, J., Winsemann, J., Weitkamp, A., Landmeyer, N., Lenz, A., Dölling, M., 2011. Middle Pleistocene (Saalian)
1190 lake outburst floods in the Münsterland Embayment (NW Germany): impacts and magnitudes. Quaternary Science
1191 Reviews 30, 2597-2625.
- 1192 Mullins, H.T., Eyles, N., Hinchley, E.J., 1990. Seismic reflection investigation of Kalamalka Lake: a 'fiord lake' on the
1193 interior plateau of southern British Columbia. Canadian Journal of Earth Sciences 27, 1225-1235.
- 1194 Murton, D.K., Murton, J.B., 2012. Middle and Late Pleistocene glacial lakes of lowland Britain and the southern North
1195 Sea Basin. Quaternary International 260, 115-142.
- 1196 Murton, J.B., Bateman, M.D., Dallimore, S.R., Teller, J.T., Yang, Z., 2010. Identification of Younger Dryas outburst
1197 flood path from Lake Agassiz to the Arctic Ocean. Nature 464, 740-743.
- 1198 Naruse, R., Skvarca, P., 2000. Dynamic features of thinning and retreating Glaciar Upsala, a lacustrine calving glacier in
1199 southern Patagonia. Arctic, Antarctic, and Alpine Research 32, 485-491.
- 1200 Nayar, A., 2009. When the ice melts. Nature 461, 1042-1046.
- 1201 Ng, F., Liu, S., 2009. Temporal dynamics of a jökulhlaup system. Journal of Glaciology 55, 651-665.
- 1202 Ng, F.S.L., Liu, S., Mavlyudov, B., Wang, Y., 2007. Climatic control on the peak discharge of glacier outburst floods.
1203 Geophysical Research Letters 34, L21503.
- 1204 O'Connor, J.E., 1993. Hydrology, hydraulics, and geomorphology of the Bonneville flood. Geological Society of
1205 America Special Paper 274, 83pp.
- 1206 O'Connor, J.E., Baker, V.R., 1992. Magnitudes and implications of peak discharges from glacial Lake Missoula.
1207 Geological Society of America Bulletin 104(3), 267-279.
- 1208 O'Connor, J.E., Costa, J.E., 1993. Geologic and hydrologic hazards in glacierized basins in North America resulting from
1209 19th and 20th century global warming. Natural Hazards 8, 121-140.
- 1210 Østrem, G., Haakensen, N., Olsen, H.C., 2005. Sediment transport, delta growth and sedimentation in Lake Nigardsvatn,
1211 Norway. Geografiska Annaler 87A, 243-258.
- 1212 Palmer, A.P., Rose, J., Lowe, J.J., Walker, M.J.C., 2007. The pre-Holocene succession of glaciolacustrine sediments
1213 within Llangorse basin. In: Carr, S.J., Coleman, S.G., Humpage, A.J., Shakesby, R.A., (Eds.), Quaternary of the Brecon
1214 Beacons – Field Guide. Quaternary Research Association, London, 220-229.
- 1215 Paul, F., Kääh, A., Haeberli, W., 2007. Recent glacier changes in the Alps observed by satellite: Consequences for future
1216 monitoring strategies. Global and Planetary Change 56, 111-122.
- 1217 Pelto, M.S., Warren, C.R., 1991. Relationship between tidewater glacier calving velocity and water depth at the calving
1218 front. Annals of Glaciology 15, 115-118.
- 1219 Phillips, F.M., Zreda, M.G., Benson, L.V., Plummer, M.A., Elmore, D., Sharma, P., 1996. Chronology for fluctuations in
1220 Late Pleistocene Sierra Nevada glaciers and lakes. Science 274, 749-751.
- 1221 Pasquini, A.I., Lecomte, K.L., Depetris, P.J. 2008. Climate change and recent water level variability in Patagonian
1222 proglacial lakes, Argentina. Global and Planetary Change 63, 290-298.
- 1223 Price, S.F., Payne, A.J., Catania, G.A., Neumann, T.A., 2008. Seasonal acceleration of inland ice via longitudinal
1224 coupling to marginal ice. Journal of Glaciology 54, 213-219.

- 1225 Quincey, D.J., Richardson, S.D., Luckman, A., Lucas, R.M., Reynolds, J.M., Hambrey, M.J., Glasser, N.F., 2007. Early
1226 recognition of glacial lake hazards in the Himalaya using remote sensing datasets. *Global and Planetary Change* 56, 137-
1227 152.
- 1228 Rayburn, J.A., Cronin, T.M., Franzi, D.A., Knuepfer, P.L.K., Willard, D.A., 2011. Timing and duration of North
1229 American glacial lake discharges and the Younger Dryas climate reversal. *Quaternary Research* 75, 541-551.
- 1230 Reid, L.M., Dunne, T., 1996. *Rapid evaluation of sediment budgets*. Catena Verlag.
- 1231 Reuther, A.U., Herget, J., Ivy-Ochs, S., Borodavko, P., Kubik, P.W., Heine, K., 2006. Constraining the timing of the
1232 most recent cataclysmic flood event from ice-dammed lakes in the Russian Altai Mountains, Siberia, using cosmogenic
1233 in situ ¹⁰Be. *Geology* 34, 913-916.
- 1234 Richards, J., Moore, R.D., Forrest, A.L., 2012. Late-summer thermal regime of a small proglacial lake. *Hydrological
1235 Processes* 26, 2687–2695.
- 1236 Richardson, S.D., Reynolds, J.M., 2000. An overview of glacial hazards in the Himalayas. *Quaternary International* 65,
1237 31-47.
- 1238 Roberts, M.J., 2005. Jökulhlaups: a reassessment of floodwater flow through glaciers. *Reviews of Geophysics* 43,
1239 RG1002.
- 1240 Roberts, M.J., Pálsson, F., Gudmundsson, M.T., Björnsson, H., & Tweed, F.S., 2005. Ice-water interactions during floods
1241 from Grænalón glacier-dammed lake, Iceland. *Annals of Glaciology* 40, 133-138.
- 1242 Röhl, K., 2006. Thermo-erosional notch development at fresh-water-calving Tasman Glacier, New Zealand. *Journal of
1243 Glaciology* 52, 203-213.
- 1244 Rott, H., Stuefer, M., Siegel, A., Skvarca, P., Eckstaller, A., 1998. Mass fluxes and dynamics of Moreno glacier, southern
1245 Patagonia icefield. *Geophysical Research Letters* 25, 1407-1410.
- 1246 Rubensdotter, L., Rosqvist, G., 2009. Influence of geomorphological setting, fluvial-, glaciofluvial- and mass-movement
1247 processes on sedimentation in alpine lakes. *Holocene* 19, 665-678.
- 1248 Rudoy, A. N., Baker, V.R., 1993. Sedimentary effects of cataclysmic late Pleistocene glacial outburst flooding, Altay
1249 Mountains, Siberia. *Sedimentary Geology* 85, 53-62.
- 1250 Russell, A.J., 2007. Controls of the sedimentology of an ice-contact jökulhlaup-dominated delta, Kangerlussuaq, west
1251 Greenland. *Sedimentary Geology* 193, 131-148.
- 1252 Russell, A.J., Aitken, J.F., de Jong, C., 1990. Observations on the drainage of an ice-dammed lake in West Greenland.
1253 *Journal of Glaciology* 36, 72-74.
- 1254 Russell, A.J., Roberts, M.J., Fay, H., Marren, P.M., Cassidy, N.J., Tweed, F.S., Harris, T., 2006. Icelandic jökulhlaup
1255 impacts: implications for ice-sheet hydrology, sediment transfer and geomorphology. *Geomorphology* 75, 33-64.
- 1256 Russell, A.J., Carrivick, J.L., Ingeman-Nielsen, T., Yde, J.C., Williams, M., 2011. A new cycle of jökulhlaups at Russell
1257 Glacier, Kangerlussuaq, West Greenland. *Journal of Glaciology* 57, 238-246.
- 1258 Russell, H.A.J., Arnott, R.W.C., 2003. Hydraulic-jump and hyperconcentrated-flow deposits of a glacial subaqueous
1259 fan: Oak Ridges Moraine, southern Ontario, Canada. *Journal of Sedimentary Research* 73, 887-905.
- 1260 Sakai, A., Chikita, K., Yamada, T., 2000. Expansion of a moraine-dammed glacial lake, Tsho Rolpa, in Rolwaling
1261 Himal, Nepal Himalaya. *Limnology and Oceanography* 45, 1401-1408.
- 1262 Sakai, A., Nishimura, K., Kadota, T., Takeuchi, N., 2009. Onset of calving at supraglacial lakes on debris-covered
1263 glaciers of the Nepal Himalaya. *Journal of Glaciology* 55, 909-917.
- 1264 Schiefer, E., Gilbert, R., 2008. Proglacial sediment trapping in recently formed Silt Lake, upper Lillooet Valley, Coast
1265 Mountains, British Columbia. *Earth Surface Processes and Landforms* 33, 1542-1556.
- 1266 Schomacker, A., 2010. Expansion of ice-marginal lakes at the Vatnajökull ice cap, Iceland, from 1999 to 2009.
1267 *Geomorphology* 119, 232-236.
- 1268 Schomacker, A., Kjær, K.H., 2008. Quantification of dead-ice melting in ice-cored moraines at the high-Arctic glacier
1269 Holmströmbreen, Svalbard. *Boreas* 37, 211-225.

- 1270 Seltzer, G.O., 2008. A lacustrine record of late Pleistocene climatic change in the subtropical Andes. *Boreas* 23, 105-111.
- 1271 Sharpe, D.R., Russell, H.A.J., Logan, C., 2007. A 3-dimensional geological model of the Oak Ridges Moraine area,
1272 Ontario, Canada. *Journal of Maps* 2007, 239-253.
- 1273 Shresta, M.L., Shresta, A.B., 2004. Recent trends and potential climatic change impacts on glacier retreat/glacier lakes in
1274 Nepal and potential adaptation measures. In: OECD Global Forum on Sustainable Development, Paris, France, 21pp.
- 1275 Smith, N.D., Vendl, M.A., Kennedy, S.K., 1982. Comparison of sedimentation regimes in four glacier-fed lakes of
1276 western Alberta. In: Davidson-Arnott, R., Nickling, W., Fahey, B.D., (Eds.), *Research in Glacial, Glacio-fluvial, and*
1277 *Glacio-lacustrine Systems*, GeoBooks, Norwich. pp. 203-238.
- 1278 Spielhagen, R.F., Baumann, K.H., Erlenkeuser, H., Nowaczyk, N.R., Nørgaard-Pedersen, N., Vogt, C., Weiel, D., 2004.
1279 Arctic Ocean deep-sea record of northern Eurasian ice sheet history. *Quaternary Science Reviews* 23, 1455-1483.
- 1280 Stokes, C.R., Clark, C.D., 2003. The Dubawnt Lake palaeo-ice stream: evidence for dynamic ice sheet behaviour on the
1281 Canadian Shield and insights regarding the controls on ice-stream location and vigour. *Boreas* 32, 263-279.
- 1282 Stokes, C.R., Clark, C.D., 2004. Evolution of late glacial ice-marginal lakes on the northwestern Canadian Shield and
1283 their influence on the location of the Dubawnt Lake palaeo-ice stream. *Palaeogeography, Palaeoclimatology,*
1284 *Palaeoecology* 215, 155-171.
- 1285 Stokes, C.R., Popovnin, V., Aleynikov, A., Gurney, S.D., Shahgedanova, M., 2007. Recent glacier retreat in the Caucasus
1286 Mountains, Russia, and associated increase in supraglacial debris cover and supra-/proglacial lake development. *Annals*
1287 *of Glaciology* 46, 195-203.
- 1288 Sturm, M. 1986. Formation of a strandline during the 1984 jökulhlaup of Strandline Lake. *Arctic* 39, 267-269.
- 1289 Sturm, M., Benson, C.S., 1985. A history of jökulhlaups from Strandline Lake, Alaska, USA. *Journal of Glaciology* 31,
1290 272-280.
- 1291 Sugden, D.E., Clapperton, C.M., Knight, P.G., 1985. A jökulhlaup near Søndre Strømfjord, west Greenland, and some
1292 effects on the ice-sheet margin. *Journal of Glaciology* 31, 366-368.
- 1293 Sugiyama, S., Bauder, A., Weiss, P., Funk, M., 2007. Reversal of ice motion during the outburst of a glacier-dammed
1294 lake on Gornergletscher, Switzerland. *Journal of Glaciology* 53, 172-180.
- 1295 Svendsen, J.I., Alexanderson, H., Astakhov, V.I., Demidov, I., Dowdeswell, J.A., Funder, S., Gataullin, V., Henriksen,
1296 M., Hjort, C., Houmark-Nielsen, M., Hubberten, H.W., Ingólfsson, Ó., Jakobsson, M., Kjær, K.H., Larsen, E., Lokrantz,
1297 H., Lunkka, J.P., Lyså, A., Mangerud, J., Matiouchkov, A., Murray, A., Möller, P., Niessen, F., Nikolskaya, O., Polyak,
1298 L., Saarnisto, M., Siegert, C., Siegert, M.J., Spielhagen, R.F., Stein, R., 2004. Late Quaternary ice sheet history of
1299 northern Eurasia. *Quaternary Science Reviews* 23, 1229-1271.
- 1300 Syverson, K.M., 1998. Sediment record of short-lived ice-contact lakes, Burroughs Glacier, Alaska. *Boreas* 27, 44-54.
- 1301 Tartari, G., Salerno, F., Buraschi, E., Bruccoleri, G., Smiraglia, C., 2008. Lake surface area variations in the North-
1302 Eastern sector of Sagarmatha National Park (Nepal) at the end of the 20th Century by comparison of historical maps.
1303 *Journal of Limnology* 67, 139-154.
- 1304 Teller, J.T., 1987. Proglacial lakes and the southern margin of the Laurentide Ice Sheet. In: Ruddiman, W.F., Wright,
1305 H.E., (Eds.), *North America and Adjacent Oceans During the Last Deglaciation. The Decade of North American*
1306 *Geology*. Geological Society of America, Boulder, CO, K3. pp. 39-69.
- 1307 Teller, J.T. 1995. The impact of large ice sheets on continental paleohydrology. In: Gregory, J., Baker, V. Starkel, L.
1308 (Eds.), *Global Continental Paleohydrology*. Wiley, New York, 109-129.
- 1309 Teller, J.T., 2001. Formation of large beaches in an area of rapid differential isostatic rebound: the three-outlet control of
1310 Lake Agassiz. *Quaternary Science Reviews* 20, 1649-1659.
- 1311 Teller, J.T., 2012. Importance of freshwater injections into the Arctic Ocean in triggering the Younger Dryas cooling.
1312 *Proceedings of the National Academy of Sciences* 109, 19880-19881.
- 1313 Teller, J.T., Leverington, D.W., 2004. Glacial Lake Agassiz: A 5000 yr history of change and its relationship to the $\delta^{18}O$
1314 record of Greenland. *Geological Society of America Bulletin* 116, 729-742.

- 1315 Teller, J.T., 2003. Subaquatic landsystems: large proglacial lakes. In: Evans, D.A., (Ed.), *Glacial Landsystems* Edwin
1316 Arnold, London. pp. 348–371.
- 1317 Teller, J.T., Leverington, D.W., Mann, J.D., 2002. Freshwater outbursts to the oceans from glacial Lake Agassiz and their
1318 role in climate change during the last deglaciation. *Quaternary Science Reviews* 21, 879-887.
- 1319 Thielert, E.R., Butman, B., Schwab, W.C., Allison, M.A., Driscoll, N.W., Donnelly, J.P., Uchupi, E., 2007. A
1320 catastrophic meltwater flood event and the formation of the Hudson Shelf Valley. *Palaeogeography, Palaeoclimatology,
1321 Palaeoecology* 246, 120-136.
- 1322 Thomas, E.K., Briner, J.P., 2009. Climate of the past millennium inferred from varved proglacial lake sediments on
1323 northeast Baffin Island, Arctic Canada. *Journal of Paleolimnology* 41, 209-224.
- 1324 Thomas, E.K., Szymanski, J., Briner, J.P., 2010. Holocene alpine glaciation inferred from lacustrine sediments on
1325 northeastern Baffin Island, Arctic Canada. *Journal of Quaternary Science* 25, 146-161.
- 1326 Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Brecher, H.H. 2011. Tropical glaciers, recorders and indicators of
1327 climate change, are disappearing globally. *Annals of Glaciology* 52, 23-34.
- 1328 Tsutaki, S., Nishimura, D., Yoshizawa, T., Sugiyama, S., 2011. Changes in glacier dynamics under the influence of
1329 proglacial lake formation in Rhonegletscher, Switzerland. *Annals of Glaciology* 52, 31-36.
- 1330 Tuffen, H., 2010. How will melting of ice affect volcanic hazards in the twenty-first century? *Philosophical Transactions
1331 of the Royal Society A: Mathematical, Physical and Engineering Sciences* 368, 2535-2558.
- 1332 Tweed, F.S., Russell, A.J., 1999. Controls on the formation and sudden drainage of glacier-impounded lakes:
1333 implications for jökulhlaup characteristics. *Progress in Physical Geography* 23, 79-110.
- 1334 Uchman, A., Kazakauskas, V., Gaigalas, A., 2009. Trace fossils from Late Pleistocene varved lacustrine sediments in
1335 eastern Lithuania. *Palaeogeography Palaeoclimatology Palaeoecology* 272, 199-211.
- 1336 van der Veen, C.J., 1998. Fracture mechanics approach to penetration of bottom crevasses on glaciers. *Cold Regions
1337 Science and Technology* 27, 213–223.
- 1338 Vincent, J.S., 1989. Quaternary geology of the southeastern Canadian Shield. In: Fulton, R.J. (Ed.), *Quaternary Geology
1339 of Canada and Greenland*. Geological Society of Canada, *Geology of Canada* 1, 249-275.
- 1340 Vuichard, D., Zimmermann, M., 1987. The 1985 catastrophic drainage of a moraine-dammed lake, Khumbu Himal,
1341 Nepal: cause and consequences. *Mountain Research and Development* 7, 91-110.
- 1342 Waitt, R.B., 1985. Case for periodic, colossal jökulhlaups from Pleistocene glacial Lake Missoula. *Geological Society of
1343 America Bulletin* 96, 1271-1286.
- 1344 Walder, J.S., Costa, J.E., 1996. Outburst floods from glacier-dammed lakes: effect of mode of lake drainage on flood
1345 magnitude. *Earth Surface Processes and Landforms* 21, 701-723.
- 1346 Walder, J.S., Trabant, D.C., Cunico, M., Anderson, S.P., Anderson, R.S., Fountain, A.G., Malm, A., 2005. Fault-
1347 dominated deformation in an ice dam during annual filling and drainage of a marginal lake. *Annals of Glaciology* 40,
1348 174-178.
- 1349 Walder, J.S., Trabant, D.C., Cunico, M., Fountain, A.G., Anderson, S.P., Anderson, R.S., Malm, A., 2006. Local response
1350 of a glacier to annual filling and drainage of an ice-marginal lake. *Journal of Glaciology* 52, 440-450.
- 1351 Wang, W., Yao, T., Yang, X., 2011. Variations of glacial lakes and glaciers in the Bosula mountain range, southeast
1352 Tibet, from the 1970s to 2009. *Annals of Glaciology* 52, 9-17.
- 1353 Watanabe, T., Rothacher, D., 1996. The 1994 Lugge Tsho glacial lake outburst flood, Bhutan Himalaya. *Mountain
1354 Research and Development* 16, 77-81.
- 1355 Weirich, F.H., 1986. The record of density-induced underflows in a glacial lake. *Sedimentology* 33, 261–277.
- 1356 Weirich, F.H., 1985. Sediment budget for a high energy glacial lake. *Geografiska Annaler* 67A, 83–99.
- 1357 Willems, B.A., Powell, R.D., Cowan, E.A., Jaeger, J.M., 2011. Glacial outburst flood sediments within Disenchantment
1358 Bay, Alaska: Implications of recognizing marine jökulhlaup deposits in the stratigraphic record. *Marine Geology* 284, 1-
1359 12.

1360 Winsemann, J., Brandes, C., Polom, U., 2011. Response of a proglacial delta to rapid high-amplitude lake-level change:
 1361 an integration of outcrop data and high-resolution shear wave seismics. *Basin Research* 23, 22-52.

1362 Woodworth-Lynas, C.M.T., Guigné, J.Y., 1990. Iceberg scours in the geological record: examples from glacial
 1363 LakeAgassiz. In: Dowdeswell, J.A., Scource, J.D. (Eds.), *Glacimarine environments: processes and sediments*.
 1364 Geological Society of London Special Publication 53, pp. 217-223.

1365 Yao, T., ZhiGuo, L., Wei, Y., XueJun, G., LiPing, Z., ShiChang, K., YanHong, W., WuSheng, Y., 2010. Glacial
 1366 distribution and mass balance in the Yarlung Zangbo River and its influence on lakes. *Chinese Science Bulletin* 55, 2072-
 1367 2078.

1368
 1369
 1370
 1371
 1372
 1373
 1374
 1375
 1376
 1377
 1378
 1379
 1380

1381 **List of Tables**

1382
 1383
 1384
 1385
 1386
 1387
 1388
 1389
 1390
 1391
 1392
 1393
 1394
 1395
 1396
 1397
 1398
 1399

Table 1. Selected examples of studies on modern proglacial lakes

Table 2. Selected studies on palaeo proglacial lakes

Table 3. Examples of studies documenting and analysing increased number and size of proglacial lakes (usually ice-marginal lakes) around the world.

Table 4. Summary of the control of water depth of ice-contact lakes on ice margin character and behaviour

Table 5. Summary of differences in physicochemical properties between ice-contact and other (distal) proglacial lakes. These properties determine the geochronological archive preserved within each type of lake.

Table 6. Summary of the controls, physical characteristics, spatial and temporal dynamics and geological importance of proglacial lakes.

Table 7. Ice-contact proglacial lake landforms and sediments adapted from Ashley (1995).

1401
 1402
 1403
 1404
 1405
 1406

1407

1408 **List of Figures**

1409

1410 **Figure 1:** Proglacial lake evolution in response to ice advance and retreat, where dashed line
1411 indicates a previous ice margin, or slope margin in part D. Note that part A and B are in longitudinal
1412 view, and parts C and D are in plan view. No spatial or temporal scale is implied.

1413

1414 **Figure 2.** Examples of proglacial lake types; A: moraine-dammed lake at Mueller Glacier, Aoraki-
1415 Mt Cook, New Zealand; B: bedrock-dammed lake at Sonnblickkees, central Austria; C: ice-dammed
1416 lake at Russell Glacier, western Greenland; D and E: lake dammed by sandur as glacier surface
1417 downwasting of ice surface proceeds at Tasman Glacier, New Zealand and at Skaftafellsjökull,
1418 southern Iceland, respectively.

1419

1420 **Figure 3.** Illustration of the development of multiple proglacial lakes; in this case in the vicinity of
1421 Tasersuaq Glacier, west Greenland. Note that proglacial lakes in this area are increasing in number
1422 and in size and occur on the margins of the Tasersuaq outlet glacier, on the margins of the ice sheet
1423 itself and around nunataks.

1424

1425 **Figure 4.** Schematic extent of major Quaternary proglacial lakes; i.e. land surface directly affected by
1426 major proglacial lakes. Note that not all lakes existed simultaneously and some lakes drained and re-
1427 formed several times. This figure is a compilation of reconstructions, predominantly those by
1428 Grosswald (1988), Teller (1987), Mangerud et al., (2004), Spielhagen et al., (2004), Baker (2007)
1429 and Astakhov (2008). Note that the geological impact of some of these lakes is considerably more
1430 widespread than that depicted due to glacial lake outburst flood (GLOF) or jökulhlaup erosion and
1431 deposition.

1432

1433 **Figure 5.** Spatial variations in lake sedimentation characteristics under different dispersal
1434 mechanisms, as driven by water density stratification and bathymetry. A: example for an ice contact
1435 lake; B: example for a proglacial lake. Adapted from Smith and Ashley (1985) and Ashley (1995).

1436

1437 **Figure 6.** Summary schematic diagram of the influence of proglacial lakes on climatic, oceanic,
1438 terrestrial and glaciological processes

1439

1440 **Figure 7.** Summary schematic of the influence of an ice-marginal lake on glacier dynamics. Forces
1441 are in italicised text and with black arrows. Processes are in black text and with grey dashed lines to
1442 denote interactions.

1443

1444

1445

1446

1447

1448

1449

1450

1451

1452

1453

1454

1455

Region	Selected recent references
Greenland	Russell et al., 1990; Hasholt, 1993 ; Hasholt et al., 2000
Iceland	Roberts et al., 2005; Schomacker, 2010
European Alps	Haeberli et al., 2002; Huggel et al., 2002; Huss et al., 2007
Tibetan Plateau	Richardson and Reynolds, 2000; Chen et al., 2007; Yao et al., 2010; Wang et al., 2011
Himalaya	Fujita et al., 2009
Alaska	Fleisher et al., 2003; Loso et al., 2004; Walder et al., 2005; Josberger, et al., 2010
South America	Harrison et al., 2006; Pasquini et al., 2008; Thompson et al., 2011
Caucasus Mountains, Russia	Stokes et al., 2007
New Zealand	Hicks et al., 1990; Kirkbride, 1993; Hochstein et al., 1998
Norway	Liermann et al., 2012
Canada	Lewis et al., 2002; Lamoureux and Gilbert, 2004

1456
1457
1458
1459

Table 1: Selected examples of studies on modern proglacial lakes

Region	Lake	Selected recent references
North America	LakeAgassiz	Teller et al., 2002; Clarke et al., 2003, 2004;
Baltic	Baltic ice lake	Bodén et al., 1997
North America	LakeBonneville	O'Connor, 1993
North America	Glacial LakeMissoula	O'Connor and Baker, 1992
West Siberia	Mansi, Komi	Komatsu and Baker, 2007
Central Asia	Khvalyn	Arkipov et al., 1995
Southern Siberia	Lakes feeding the YeneseiRiver catchment	Krивonogov et al. 2005; Komatsu et al. 2009
South-central Siberia	Chuja-Kuray (Altai flooding)	Carling et al., 2002; Herget, 2005; Reuther at al., 2006
Kirgizstan	Lakelssyk-Kul	Grosswald and Rudoy, 1996
Siberia	Lake Baikal	Baker, 2007

1461

1462 **Table 2:** Selected studies on palaeo proglacial lakes.

1463

1464

1465

1466

1467

1468

1469

1470

1471

1472

1473

1474

1475

1476

1477

1478

1479

1480

1481

1482

1483

Location	Example references
European Alps	Paul et al., 2007
Iceland	Schomacker, 2010
Svalbard	Schomacker and Kjær, 2008
Caucasus Mountains	Stokes et al., 2007
South America and Patagonia	Ames, 1998; Hubbard et al., 2005; Loriaux and Cassasa, 2012
Canada and North America	O'Connor and Costa, 1993; Clague and Evans, 2000
New Zealand	Chinn, 1996
Himalaya	Gardelle et al., 2011
Mt Everest region	Tartari et al., 2008
Bhutan	Komori., 2008
Tibet	Ageta et al., 2000; Chen et al., 2007; Komori, 2008; Wang et al., 2011

1484

1485 **Table 3:** Examples of studies documenting and analysing increased number and size of proglacial
 1486 lakes (usually ice-marginal lakes) around the world.
 1487

1488

1489

1490

1491

1492

1493

1494

1495

1496

1497

1498

1499

1500

1501

1502

1503

1504

1505

1506

1507

1508

1509

Decreased water depth	Impact on glacier	Increased water depth
Reduced Convex	Likelihood of calving Volume of calving Ice surface profile	Enhanced Concave
Increased Increased	Likelihood of a frozen (cold) ice margin Overall: ice margin stability	Reduced Reduced (possible retreat, possible surging)

1510

1511 **Table 4:** Summary of the control of water depth of ice-contact lakes on ice margin character and
 1512 behaviour.

1513

1514

1515

1516

1517

1518

1519

1520

1521

1522

1523

1524

1525

1526

1527

1528

1529

1530

1531

1532

1533

1534

1535

1536

1537

1538

1539

1540

1541

1542

Ice-contact (proximal)	Physicochemical property	Proglacial (distal)
higher	Suspended sediment concentration	lower
higher	Quantity and clast size of ice rafted debris, drop-stones	lower
higher	Sedimentation rate	lower
lower	Light penetration to depth	higher
lower	Water temperature	higher
lower	Animal and plant abundance	higher
lower	Taxonomic diversity	higher

1543
1544
1545
1546
1547
1548
1549
1550
1551
1552
1553
1554
1555
1556
1557
1558
1559
1560
1561
1562
1563
1564
1565
1566
1567
1568
1569
1570
1571
1572
1573
1574
1575
1576
1577
1578
1579
1580
1581

Table 5: Summary of differences in physicochemical properties between ice-contact and other (distal) proglacial lakes. These properties determine the geochronological archive preserved within each type of lake.

	Controls	Character	Behaviour	Geological importance
Water depth	Ratio of inflow versus outflow, plus for ice-contact lakes; ice thickness, surrounding topography and dam stability	Highly variable spatially and temporally between lakes and within lakes	Can be static, linear, or cyclical in evolution	<p>Deep water (relative to ice thickness) promotes calving, a concave glacier surface profile and thus ice margin retreat.</p> <p>Increasing water depth can cause ice margin flotation, flexure or fracture, and jökulhlaups.</p> <p>Deep water also probably promotes a distributed subglacial drainage system.</p> <p>Controls stratigraphy (evolution) of deltaic sediments and in particular deeper water (away from the ice margin) promotes laminations and couplet (varve) formation</p>
Bathymetry	Glacially-subdued, scoured and smoothed terrain overlain by a drape of silts and clays	Flat floor and near-impermeable surface		<p>One of the most obvious and ubiquitous indicators of past lake positions and extents.</p> <p>Encourages postglacial peatland development</p>
Water density stratification	Temperature and suspended sediment concentration; i.e. type and balance and regime of water sources	Magnitude of density largely determined by suspended sediment. Density profile dominated by dynamics of water temperature	<p>Seasonal over-turning of temperature profile.</p> <p>Basal sediment plumes common (density-currents)</p>	<p>Identification of density gradient type can help to distinguish between an ice-contact lake (density gradient dominated by suspended sediment) and a non ice-contact lake (density gradient dominated by temperature). Density gradient control circulation and hence sedimentation style and patterns. Controls chemical and biological activity.</p>
Sedimentation	<p>Ice berg production / calving.</p> <p>Suspended sediment concentration of input streams.</p> <p>Distance from ice-margin.</p> <p>Stability of ice-margin and of glacial drainage network</p>	<p>Till, deltaic deposits, varves and other rhythmites, ice - rafted debris (IRD; dropstones), beach or shoreline deposits.</p> <p>Proximal ice-contact moraines, deltas, fans and ramps to ice-distal foresets to paraglacial (slump and hillslope) sedimentation.</p>	<p>Diurnal and seasonal cycles of sedimentation</p> <p>Spatial transition with distance from ice-margin.</p>	<p>Representation of control of glacier behaviour, ambient climate and hillslope hydrology, (Leemann and Niessen. 2004).</p> <p>Dropstones are diagnostic of ice berg and hence of a calving ice margin.</p> <p>Varves in particular are used to establish glacial and glacialacustrine chronologies.</p> <p>Denotes occurrence and style of deglaciation.</p> <p>Glacialacustrine sediments form extensive outcrops (Teller, 1987) and typically form valley-fills that are a major source of fluviially reworked sediment during the Holocene (Ballantyne, 2003 and references cited therein)</p>
Landforms	Local topography, fluvial / glacio-fluvial processes, mass movements (e.g. Rubensdotter and Rosqvist, 2009)	<p>Deltas, 'Delta moraines', 'De Geer moraines', 'washboard' or 'sub-lacustrine moraines',</p> <p>Wave-cut beaches; 'shorelines' or 'glacialacustrine terraces'</p> <p>Grounding line fans</p> <p>Ice berg scours and plough marks</p>		<p>(e.g. Larsen, et al., 2006; Gollledge et al., 2008)</p> <p>For very large (Pleistocene) lakes deformed beach elevations used to reconstruct isostatic rebound (and hence ice thickness)</p> <p>Used to infer ice-margin position and thickness. Direction of ice advance and if cross-cutting number of ice advances</p>

1582
1583
1584
1585
1586

Table 6: Summary of the controls, physical characteristics, spatial and temporal dynamics and geological importance of proglacial lakes.

Sedimentological description	Inferred processes	Indicative landform
Well-sorted coarse sediments. Parallel bedded, steeply dipping foresets (20 – 33°), normal and inverse graded beds of sand and gravel. Clasts parallel to bedding planes.	Mass movements (creep, slump, debris flows, grain flows, surge currents)	Coarse-grained (Gilbert-type) delta
Well-sorted medium to fine sediments. Sets of climbing ripple sequences, draped lamination occurring as low angle (< 20o) foresets of sand and silt. Deformational structures and dewatering structures common.	Rapid deposition from density underflows	Fine-grained delta
Proximal to distal open work gravel, chaotic bedding, convolute lamination, dewatering structures, climbing ripple sequences and drape lamination.	Deposition from a high velocity expanding jet	Sub-aqueous fan
Poorly-sorted, inter-bedded mass flow deposits, lacustrine mud and dropstones	Mass-movements (rockfall, debris slides) calving, squeezed debris at base	Ice cliff margin
Poorly-sorted stacked diamicts interbedded with sand beds and mud drapes	Mass movements (debris flow, creep, slumps) surge currents	Submerged ice ramp
Fine-grained, rhythmic, parallel-bedded sediments with occasional dropstones and biogenic structures.	Deposition from underflows, interflows and overflows and occasional ice bergs.	Lake bottom

1587

1588 **Table 7:** Ice-contact proglacial lake landforms and sediments adapted from Ashley (1995).

1589

1590

1591

1592

1593

1594

1595

1596

1597

1598

1599

1600

1601

1602

1603

1604

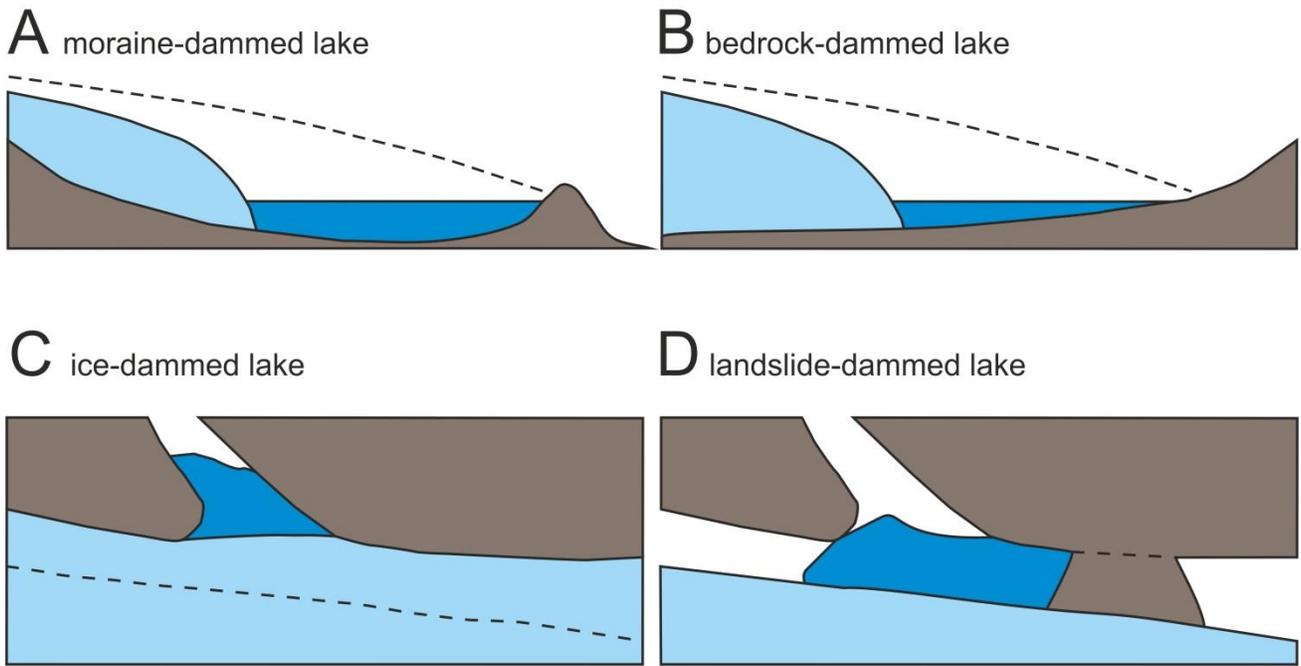
1605

1606

1607

1608

1609



1610

1611

1612 **Figure 1:** Proglacial lake evolution in response to ice advance and retreat, where dashed line
1613 indicates a previous ice margin, or slope margin in part D. Note that part A and B are in longitudinal
1614 (side) view, and parts C and D are in plan view. No spatial or temporal scale is implied.

1615

1616

1617

1618

1619

1620

1621

1622

1623

1624

1625

1626

1627

1628

1629

1630

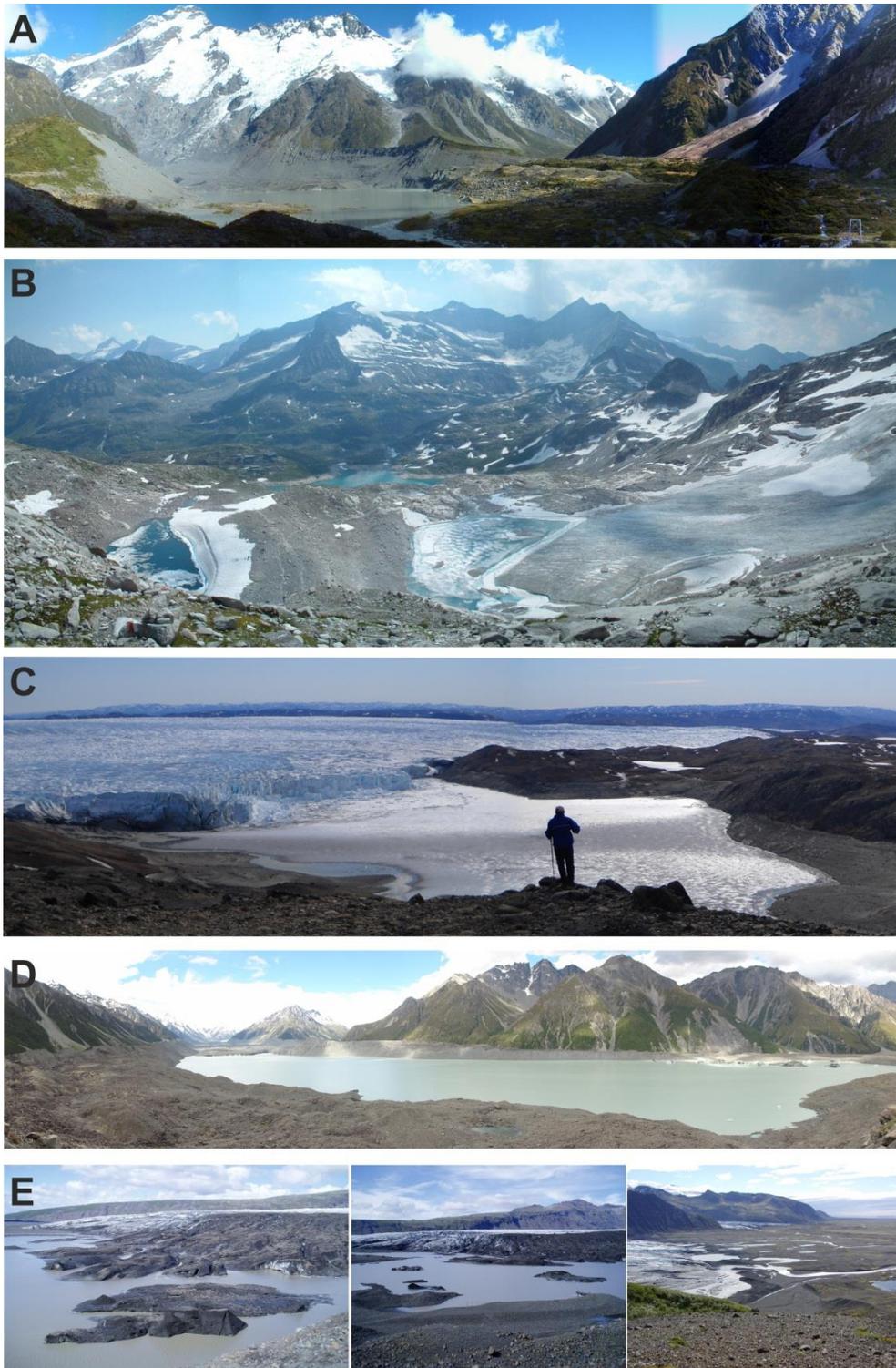
1631

1632

1633

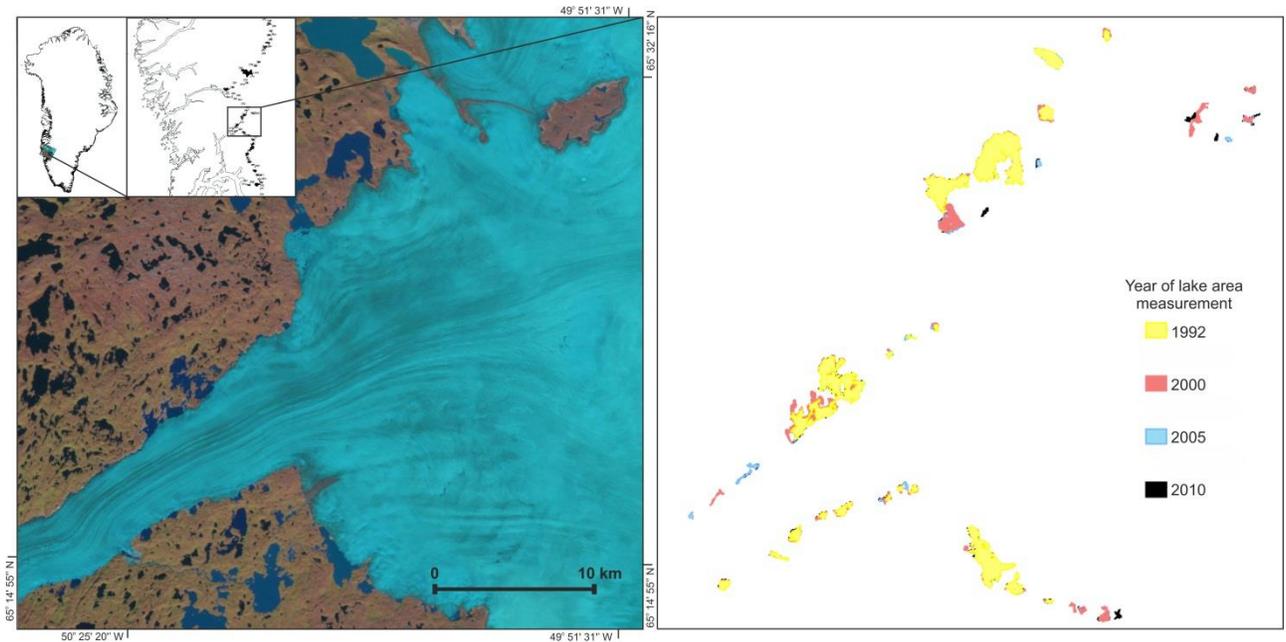
1634

1635



1636
 1637
 1638
 1639
 1640
 1641
 1642

Figure 2: Examples of proglacial lake types; A: moraine-dammed lake at Mueller Glacier, Aoraki-Mt Cook, New Zealand; B: bedrock-dammed lake at Sonnblickkees, central Austria; C: ice-dammed lake at Russell Glacier, western Greenland; D and E: lake dammed by sandur as glacier surface downwasting of ice surface proceeds at Tasman Glacier, New Zealand and at Skaftafellsjökull, southern Iceland, respectively.



1643

1644

1645 **Figure 3:** Illustration of the development of multiple proglacial lakes; in this case in the vicinity of
 1646 Tasersuaq Glacier, west Greenland. Note that proglacial lakes in this area are increasing in number
 1647 and in size and occur on the margins of the Tasersuaq outlet glacier, on the margins of the ice sheet
 1648 itself and around nunataks.
 1649

1649

1650

1651

1652

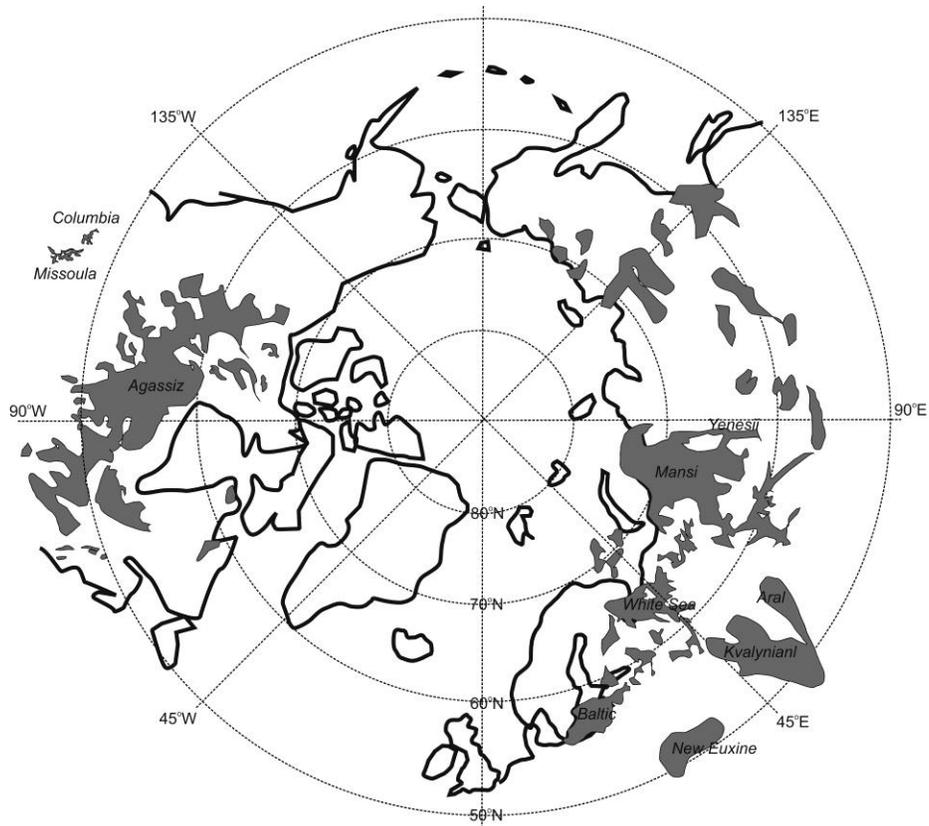
1653

1654

1655

1656

1657



1658
1659

1660 **Figure 4:** Schematic extent of major Quaternary proglacial lakes; i.e. land surface directly affected
 1661 by major proglacial lakes. Note that not all lakes existed simultaneously and some lakes drained and
 1662 re-formed several times. This figure is a compilation of reconstructions, predominantly those by
 1663 Grosswald (1988), Teller (1987), Mangerud et al., (2004), Spielhagen et al., (2004), Baker (2007)
 1664 and Astakov (2008). Note that the geological impact of some of these lakes is considerably more
 1665 widespread than that depicted due to glacial lake outburst flood (GLOF) or ‘jökulhlaup’ erosion and
 1666 deposition.

1667

1668

1669

1670

1671

1672

1673

1674

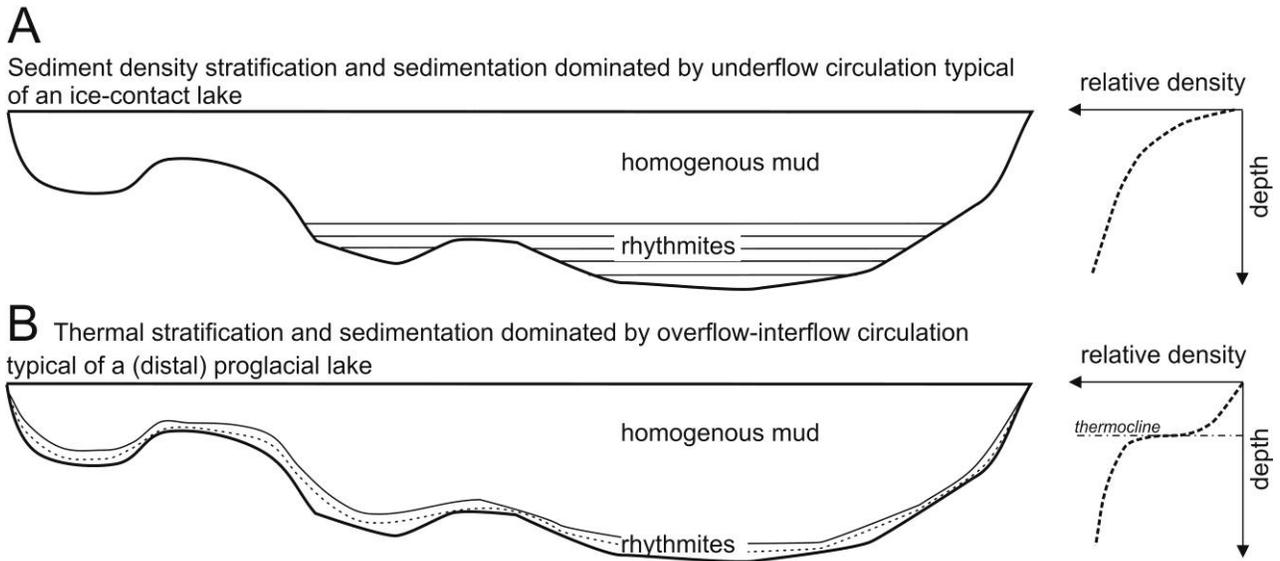
1675

1676

1677

1678

1679



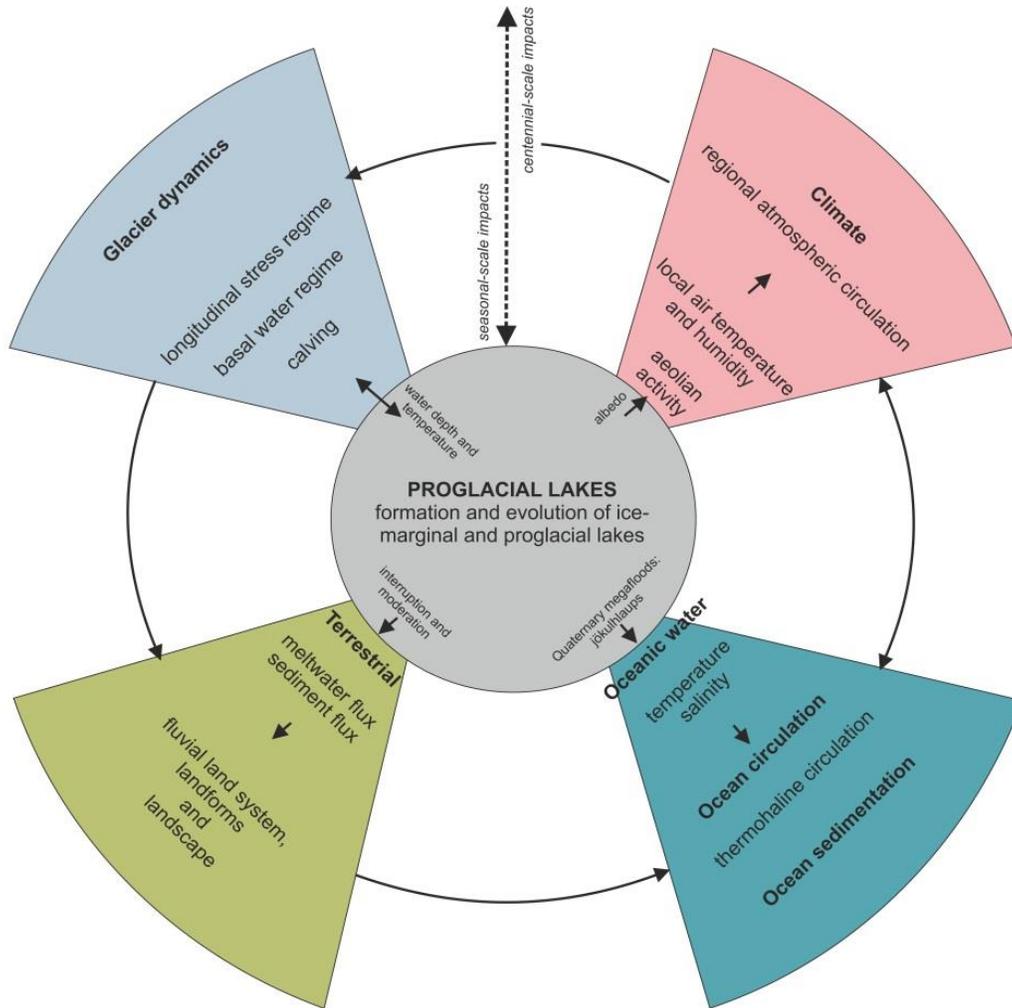
1680

1681

1682 **Figure 5:** Spatial variations in lake sedimentation characteristics under different dispersal
1683 mechanisms, as driven by water density stratification and bathymetry. A: example for an ice contact
1684 lake; B: example for a proglacial lake. Adapted from Smith and Ashley (1985) and Ashley (1995).

1685

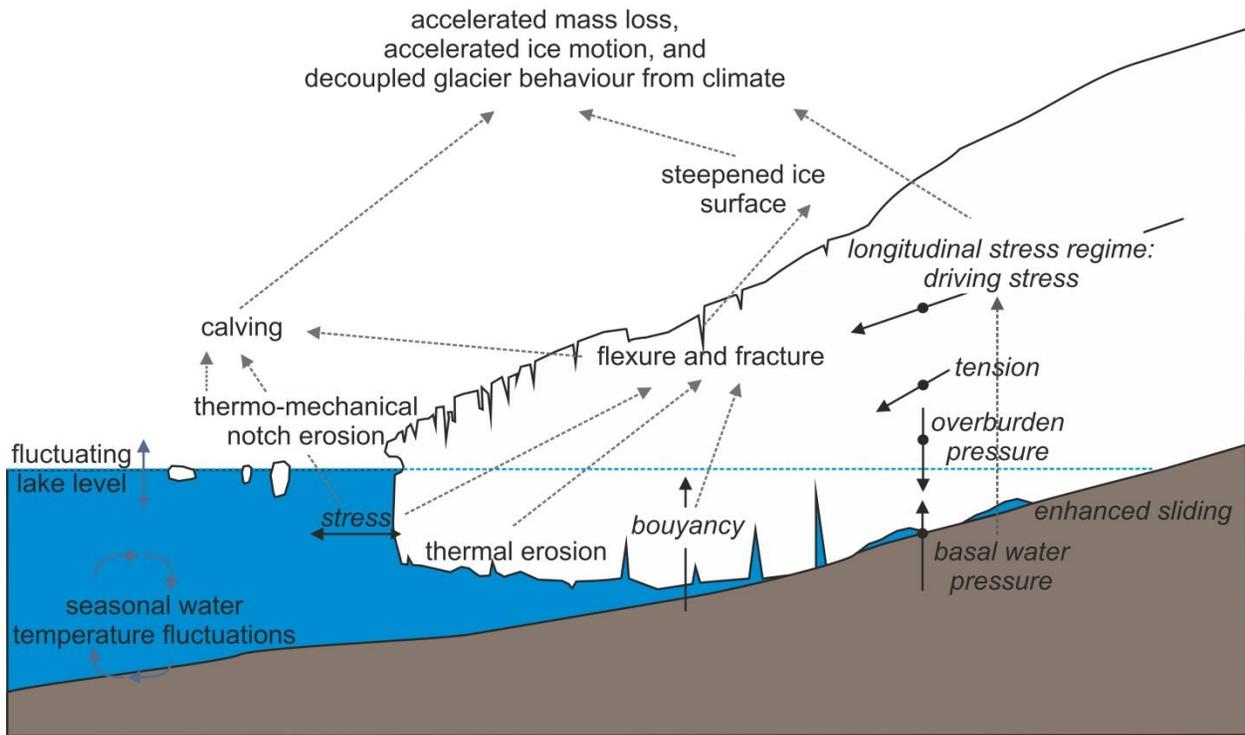
1686



1687
 1688
 1689
 1690
 1691
 1692
 1693
 1694
 1695
 1696
 1697
 1698
 1699
 1700
 1701
 1702
 1703
 1704
 1705
 1706

Figure 6: Summary schematic diagram of the influence of proglacial lakes on climatic, oceanic, terrestrial and glaciological processes.

1707



1708

1709

1710

1711

1712

1713

Figure 7: Summary schematic of the influence of an ice-marginal lake on glacier dynamics. Forces are in italicised text and with black arrows. Processes are in black text and with grey dashed lines to denote interactions.