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<http://dx.doi.org/10.1016/j.geomorph.2010.08.018>

PUBLISHER

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Cook, Simon J., David J. Graham, Darrel A. Swift, Nicholas G. Midgley, and William G. Adam. 2019.
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Sedimentary signatures of basal ice formation and their preservation in ice-marginal sediments

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Abstract

Reconstruction of subglacial processes from sedimentological evidence is central to our understanding of glaciological conditions beneath former ice masses. At Svínafellsjökull, southeast Iceland, we assess the extent to which two different processes of basal ice formation (regelation and glaciohydraulic supercooling) can be identified from ice-marginal sediments. Our results indicate that the sedimentary characteristics of deposits produced by these two processes can be distinguished from one another and that it may be possible to recognise evidence of these processes in Quaternary sediments and to reconstruct their spatial pervasiveness. Sediments derived from the melting of regelation basal ice have (i) a massive structure; (ii) a sediment matrix (0 to 10Φ) dominated by coarse sand; and (iii) a higher proportion of angular clasts than supercool basal ice and associated sediments. Sediments derived from “supercool” basal ice (i) can be either massive or layered; (ii) tend to have a silt-dominated matrix; and (iii) contain a slightly higher proportion of rounded and well-rounded clasts than

regelation basal ice and sediments. Previous studies indicate that the dominance of silt within supercool basal ice may be unique to this process, and hence, supercooling should leave a readily recognisable signature in the sedimentary record. Our results from Svínafellsjökull lend support to that idea, although we suggest that further work is required to assess whether silt dominance is a process signature diagnostic of supercooling, and in particular, the extent to which subglacial sediment supply determines the sedimentary character of basal ice facies and associated sediments.

Keywords: basal ice; glaciohydraulic supercooling; ice-marginal sediments; melt-out till; Quaternary; regelation; subglacial sediment

1. Introduction

Our ability to reconstruct conditions and processes beneath former ice masses from sedimentological evidence is key to our understanding of the controls on palaeo-ice mass behaviour. In modern glacial environments, the basal ice layer exposed at the glacier margin provides a window into the relatively inaccessible subglacial environment, providing a wealth of evidence concerning the nature of the ice-bed interface, including thermal conditions, hydrology, and the mechanisms of ice flow (Hubbard and Sharp, 1989; Knight, 1997). Sediments deposited during melt-out of the basal layer of former ice masses offer similar opportunities for the reconstruction of subglacial processes, provided that appropriate models are available to link the properties of different types of basal ice to their associated sedimentary products. At Svínafellsjökull, southeast Iceland, we assess the extent to which the distinctive characteristics of “stratified” (i.e., visibly layered and debris-laden) basal ice produced by two different subglacial processes (regelation and glaciohydraulic supercooling) are preserved in ice-marginal sediments and, hence, whether the influence of such processes might be identifiable within the sedimentary record. Svínafellsjökull represents an ideal study site because the origins and spatial distribution of basal ice facies are well known (Cook et al., 2007, 2010), enabling subglacial processes to be related directly to ice-marginal sediments.

2. Research context

Whilst many studies have sought to determine which gross sedimentary characteristics are reliably preserved in ice-marginal sediments (e.g., clast shape and roundness, clast fabric, and grain size distribution; Lawson, 1981;

61 Ham and Mickelson, 1994; Knight et al., 2000; Adam and Knight, 2003), very few studies have assessed the
62 extent to which different processes of basal ice formation can be inferred from analysis of ice-marginal sediments
63 (e.g., Larson et al., 2006). Consequently, we have examined the sedimentary products of the melt-out of basal
64 ice produced by two processes that reflect two very different basal regimes: regelation and glaciohydraulic
65 supercooling.

66
67 Regelation is the pressure melting and refreezing of ice around bedrock obstacles, during which loose sediment
68 may be entrained (Weertman, 1957; Kamb and LaChapelle, 1964; Hubbard and Sharp, 1993), and hence the
69 presence of regelation ice is important evidence for basal sliding. Regelation ice tends to (i) be visibly layered
70 from multiple episodes of melting and refreezing around bedrock obstacles; (ii) have low debris concentrations of
71 ~ 5% by volume; (iii) contain polymodal grain size distributions; and (iv) contain dominantly basally worked clasts
72 with occasional sharp-edged fracture planes (e.g., Kamb and LaChapelle, 1964; Boulton, 1978; Hubbard and
73 Sharp, 1993, 1995; Alley et al., 1997). The sedimentary products of regelation basal ice have only rarely been
74 described from modern glacial environments, although the process has been inferred from post-glacial sediments
75 (e.g., Kemmis, 1981; Hughes et al., 1985; Domack et al., 1998). Regelation operates across small bedrock
76 obstacles (up to 50 cm in amplitude), being remelted at the next bump; and hence basal ice layers formed by
77 regelation should be only millimetres to decimetres thick and therefore of limited significance in glacial sediment
78 budgets (Hubbard and Sharp, 1993; Alley et al., 1997). Nevertheless, tectonic thickening of basal layers (e.g.,
79 Sharp et al., 1994) can result in metres-thick sequences of regelation ice that may contribute significantly to
80 moraine-building and till deposition (e.g., Spedding and Evans, 2002).

81
82 Glaciohydraulic supercooling occurs when the pressure melting point of water ascending the adverse slope of a
83 subglacial overdeepening rises faster than the water is heated by viscous dissipation (Alley et al., 1998; Lawson
84 et al., 1998). This causes water to freeze to the base of the glacier as frazil and anchor ice, producing very
85 distinctive ice facies that commonly have (i) visible layers as a result of successive episodes of freeze-on of water
86 and sediment to the glacier base; (ii) sediment concentrations averaging ~ 30% by volume; (iii) high proportions of
87 silt as a result of preferential filtering of silt from subglacial water by frazil ice growth; and (iv) a high proportion of
88 fluvially worked clasts as a result of sediment transport by water (Alley et al., 1998; Lawson et al., 1998; Larson et
89 al., 2006). Although Larson et al. (2006) proposed a landform–sediment assemblage that is diagnostic of
90 supercooling (including hummocky moraine, debris flow deposits, and melt-out tills), the power of such an
91 approach has been criticised because the assemblage is too similar to those produced by a range of other

92 glaciological processes (Evans, 2009). Furthermore, diagnostic sedimentary criteria, such as the dominance of silt
93 in basal ice produced by glaciohydraulic supercooling (hereafter referred to as “supercool” basal ice), have been
94 based on research at just one glacier (Matanuska Glacier, Alaska).

95
96 The process implications of regelation versus supercooling mean that the development of robust diagnostic
97 sedimentary criteria would significantly enhance our understanding of former ice mass behaviour. For example,
98 sediments derived from regelation basal ice would indicate glacier motion through basal sliding over bedrock.
99 Sediments derived from supercool basal ice would indicate the presence of water at the glacier base, which would
100 also influence glacier motion (e.g., by allowing ice-bed separation) and would also indicate specific subglacial
101 hydrological configurations beneath the glacier (i.e., supercooling is typically associated with distributed, rather
102 than channelised, routing of subglacial water; Lawson et al., 1998). Sedimentary analyses have already been
103 used to invoke supercooling as a central process in the formation of a wide range of Quaternary landforms and
104 sediments, including melt-out tills (e.g., Kristensen et al., 2008), moraines (e.g., Lawson et al., 1998), and
105 Heinrich layers (e.g., Roberts et al., 2002). However, it is first essential that these criteria, and the limitations of
106 their preservation in the sedimentary record, are tested at other modern glaciers (Cook and Knight, 2009).

107
108

109 **3. Field site and methods**

110 Ice-marginal sediments derived from the melt-out of stratified basal ice were investigated in summer 2007 at
111 Svínafellsjökull (63°59' N., 16°52' W.), a temperate outlet glacier of the Oræfajökull ice cap, southeast Iceland
112 (Fig. 1). Mapping and analyses of stratified basal ice facies in 2004 and 2005 (Cook et al., 2007, 2010) enabled
113 investigation to be focused in areas where sediment supply to the ice-marginal environment was known to be
114 dominated by melting of facies formed by regelation and tectonic thickening (subfacies A and B of Cook et al.,
115 2007, 2010) and facies formed by glaciohydraulic supercooling (subfacies C and E). Three sites were
116 investigated where basal ice and ice-marginal sediments were related to supercooling (sites 1, 2 and 3), and two
117 sites were investigated where basal ice and ice-marginal sediments were related to regelation (sites 4 and 5) (Fig.
118 1; Table 1). Sites were selected where inputs from other sediment sources (e.g., supraglacial) were minimal.

119

120 **Fig. 1.**

121

122 **Table 1.**

123

124 Basal ice and ice-marginal sediments were described and logged following standard techniques (e.g., Lawson,
125 1979; Evans and Benn, 2004). At each site, between one and eleven samples of 50 basalt clasts were extracted
126 from basal ice layers, and between one and eight samples were collected from adjacent ice-marginal sediments
127 (Table 1). These samples were analysed for shape and roundness using standard techniques described by Benn
128 (2004). The Tri-Plot program of Graham and Midgley (2000) was used to derive C40 indices for each sample (i.e.,
129 the proportion of clasts with a $c:a$ axial ratio of ≤ 0.4). Plots of C40 versus relative angularity (i.e., the proportion of
130 very angular and angular clasts) and C40 versus relative roundness (i.e., the proportion of well-rounded and
131 rounded clasts) were then used to assess the extent to which different basal ice origins could be inferred from
132 clast characteristics of melt-out sediments.

133

134 Sediment samples (Table 1) were also taken from basal ice layers and adjacent ice-marginal sediments for
135 particle size determination to enable assessment of whether ice and sediment types can be differentiated on the
136 basis of silt concentration. Size was determined using a laser granulometer (size range 0 to 10 Φ) after removing
137 sediment coarser than 0 Φ by wet sieving. Sediment size description was assisted by use of the GRADISTAT
138 package (Blott and Pye, 2001).

139

140

141 **4. Results**

142 *4.1. Basal ice composition*

143 Basal ice formed by supercooling, previously identified and mapped by Cook et al. (2007, 2010), was present at
144 sites 1, 2, and 3 (Fig. 1). At all three sites, the ice was dominated by subfacies C (using the classification scheme
145 of Cook et al., 2007, 2010), which can be classified as banded solid (BSO) basal cryofacies according to the
146 scheme proposed by Hubbard et al. (2009).

147

148 At site 1, 0.9 m of subfacies C basal ice was observed in summer 2003 that thickened as it dipped upglacier
149 beneath the lake surface (Fig. 2A). This ice contained angular aggregates of predominantly silt-sized material
150 (Fig. 2B) within a clean ice matrix and had a mean debris concentration of 28% by volume. Subhorizontal layers
151 persisted throughout that were clearly picked out by differences in debris concentration and distribution, although
152 individual layers were laterally discontinuous. Rapid recession of the ice margin into the lake (Fig. 2A) meant that
153 basal ice was no longer accessible by 2004.

154

155 Up to 1.9 m of subfacies C ice was observed at site 2 in 2004 and 2005 (Fig. 2C) along with a thick sediment
156 layer that appeared to be melting-out in situ. Excavation below ground level revealed buried subfacies C ice with
157 a total thickness approaching ~ 4 m. Again, recession of the ice margin into the lake meant that by 2007 the
158 stratified basal ice layer was inaccessible. At site 3, up to 0.7 m of subfacies C basal ice was observed in 2005
159 when the ice was just overtopping a moraine; and again this basal ice was no longer accessible by 2007.

160

161 **Fig. 2.**

162

163 Facies demonstrated to have formed by regelation and tectonic thickening (Cook et al., 2010) were present at
164 sites 4 and 5. Exposures of subfacies A up to 2 m thick were observed at these sites in 2004, 2005, and 2007,
165 with a minor component of subfacies B at site 5 (Fig. 2D). Subfacies A comprises alternating, debris-rich and
166 debris-poor laminae, with low debris concentrations (< 6% by volume). Subfacies B is composed of dispersed
167 particles and debris aggregates within a clean ice matrix with debris concentrations below 4% by volume. This
168 layered basal ice with low debris content can be classified as banded dispersed (BD) basal cryofacies according
169 to the scheme of Hubbard et al. (2009).

170

171 *4.2. Composition of ice-marginal sediments*

172 At site 1 where melt-out of subfacies C ice had been observed in 2003, the area comprised several low profile
173 (i.e., < 0.5 m height) moraine mounds, with long axes that were formed parallel to the former ice margin. Two of
174 the mounds were logged (Fig. 3, log 1 and log 2) from trenches cut across the long axis. The first mound was
175 composed primarily of alternating layers of stratified or laminated muddy diamict; layers of laminated fine to
176 medium sand, with occasional lenses of fine to medium sand or granule gravel, were also observed. The
177 composition of the second mound was similar but overlain by up to 0.15 m of massive diamicton and included
178 occasional layers or lenses of granule gravel not more than 0.04 m in thickness and not more than 0.2 m in lateral
179 extent. We note here that diamicton appeared structureless to the naked eye (and hence is coded as massive)
180 although it is not possible to say with certainty that it did not contain micro-scale structures because we did not
181 undertake micromorphological analyses. The same can be said for all subsequent descriptions of apparently
182 massive diamictons.

183

184 **Fig. 3.**

185

186 Sediments at site 2 had been observed to be melting-out in situ in 2004 and 2005 and could be observed in
187 section. Fig. 3 demonstrates that these sediments were composed of muddy diamicton with a structure that
188 ranged from weakly stratified to laminated. The top of the sequence was capped by a 0.07-m layer of massive
189 medium sand that had been eroded from a nearby moraine. At site 3, a small excavation was made into the crest
190 of the moraine on the ice-proximal side of the apex, which demonstrated sediments composed almost entirely of
191 muddy diamicton with an occasional weakly stratified structure (Fig. 3).

192

193 Sites 4 and 5 were both situated at the crest of small (~1.5 m high) moraines that had been in contact with the
194 glacier in 2004 and 2005, although the size of the moraines probably reflects their origin as seasonal-readvance
195 moraines rather than entirely by the debris flux provided by the ice. Sediments at site 4 were composed primarily
196 of apparently massive diamicton, although weak stratification was noted near the base of the excavated section
197 (Fig. 3); a 0.04-m gravel layer separated the upper and lower diamictons. Site 5 was composed almost entirely of
198 apparently massive, clast-rich sandy diamicton with very weak visible stratification between 0.6 and 0.7 m depth
199 (Fig. 3).

200

201 4.3. Sediment particle size distribution

202 Having given some overall description of ice-marginal sediments and particle size in Fig. 3, we focus here on the
203 sediment particle size distributions of the matrix between 0 and 10 Φ (Fig. 4).

204

205 Fig. 4.

206

207 Basal ice and ice-marginal sediments associated with supercooling (sites 1, 2 and 3) tend to have finer grained
208 sediment particle size distributions than basal ice and sediments associated with regelation (Table 1; Fig. 4). At
209 sites 2 and 3, mean basal ice particle size distributions were 3.9 Φ (very fine sand) and 5.4 Φ (coarse silt),
210 respectively. So despite the overall fine-grained nature of the basal ice, some variability exists between sites. No
211 basal ice particle size samples could be obtained at site 1 as a result of the recession of the ice margin into the
212 lake.

213

214 Ice-marginal sediments associated with supercooling had similar particle size distributions to the parent basal ice
215 (Table 1; Fig. 4). Although no direct comparisons between basal ice and ice-marginal sediments at site 1 can be

216 made, the ice-marginal sediments had a very similar particle size distribution to basal ice and sediments at site 2
217 (Table 1; Fig. 4).

218

219 Basal ice and ice-marginal sediments associated with regelation at sites 4 and 5 had coarser particle size
220 distributions (i.e., mean between 2.6 and 3.3 Φ ; Table 1; Fig. 4). Although the mean particle size of regelation-
221 related basal ice and ice-marginal sediments at site 4 is similar to that of supercooling-related basal ice and
222 sediments at sites 1 and 2, the modal particle size of the two populations is visibly different, with a coarse skew
223 for regelation-related basal ice and sediments (Fig. 4).

224

225 4.4. *Clast characteristics*

226 Figs. 5A and 5B presents covariant plots of clast shape (C40) versus relative angularity (proportion of very
227 angular and angular clasts) for sites 1, 2, and 3 (supercool) and sites 4 and 5 (regelation), respectively; and Figs.
228 5C and 5D presents C40 versus relative roundness (proportion of well-rounded and rounded clasts) for sites 1, 2,
229 and 3 and sites 4 and 5, respectively.

230

231 **Fig. 5.**

232

233 We can clearly see from Fig. 5 and Table 1 that at all sites, both in areas that are dominated by supercool and by
234 regelation basal ice, the clast shape and angularity/roundness characteristics of basal ice and associated ice-
235 marginal sediments are similar. There is a slightly higher proportion of angular clasts within basal ice (mean =
236 15.3%) and ice-marginal sediments (mean = 15.3%) at sites 4 and 5 than at sites 1, 2, and 3 (basal ice mean =
237 12.5%; ice-marginal sediments mean = 11.8%) (Fig. 5A and 5B; Table 1). Equally, there is a slightly higher
238 proportion of rounded clasts within basal ice (mean = 17.4%) and ice-marginal sediments (mean = 8.1%) at sites
239 1, 2, and 3 than at sites 4 and 5 (basal ice mean = 5.8%; ice-marginal sediments mean = 7%). A Mann-Whitney
240 U-test reveals that there is a significant difference between supercool (sites 1, 2, and 3) and regelation basal ice
241 (sites 4 and 5) in terms of the proportion of rounded clasts (at 99% significance), although not for the proportion of
242 angular clasts (at either 95% or 99% significance). However, the difference in roundness between basal ice
243 populations is not observed in the ice-marginal sediments where a Mann-Whitney U-test revealed no statistical
244 difference between ice-marginal sediments of supercooling or regelation origin, either for roundness or angularity.

245

246 Clast shape (C40) appears not to be able to differentiate between sediments of different origins because there is
247 a similar range of C40 values in each of the plots on Fig. 5 (see also Table 1). There is some suggestion that
248 there may be a difference in shape between supercooling- and regelation-derived ice-marginal sediments
249 because a Mann-Whitney U-test reveals a difference at 95% significance. However, this difference is not
250 observed between basal ice populations of different origins.

251

252

253 **5. Discussion**

254 We discuss first the extent to which the sedimentary characteristics of basal ice of different origins have been
255 preserved within ice-marginal sediments at Svínafellsjökull, followed by a discussion of the significance of our
256 results for the reconstruction of conditions and processes beneath former ice masses.

257

258 *5.1. Supercool sediments*

259 On the basis of previous research at the Matanuska Glacier, Alaska, basal ice produced by glaciohydraulic
260 supercooling is considered to be characterised by a layered appearance, high debris content, the dominance of
261 silt-sized sediment, and a high proportion of fluvially worked clasts (Alley et al., 1998; Lawson et al., 1998; Larson
262 et al., 2006). Some of these characteristics are consistent with basal ice of the same origin at Svínafellsjökull
263 (Cook et al., 2007, 2010). Supercool (subfacies C) basal ice at sites 1, 2, and 3 is characterised by a layered
264 appearance (Figs. 2A-C) with a high debris content (~ 28% by volume on average) and a high proportion of
265 coarse silt and very fine sand (Fig. 4; Table 1). There is a statistical difference in clast roundness between
266 supercool and regelation basal ice, with generally more rounded clasts in supercool basal ice.

267

268 At the Matanuska Glacier, and for some sites once covered by ice in North America and Scandinavia, it has been
269 suggested that the distinctive sedimentary characteristics of supercool basal ice have been preserved in
270 sediments derived from basal ice melt-out (Larson et al., 2006; Kristensen et al., 2008). However, these
271 supercooling signatures have lacked verification from other modern sites. Our results from Svínafellsjökull
272 indicate (i) that ice-marginal sediments do occasionally preserve sedimentary layering inherited from supercool
273 basal ice; (ii) that the conspicuous dominance of silt and very fine sand in supercool basal ice is preserved in ice-
274 marginal sediments; and (iii) that the large proportion of fluvially rounded clasts found within supercool basal ice is
275 not always reflected in ice-marginal sediments and, hence, may not be a reliable indicator of supercooling
276 (although this last finding is based on a relatively small number of samples).

277

278 At Svínafellsjökull, the layered appearance of the basal ice appears to have been preserved within ice-marginal
279 sediments in some situations (Figs. 2 and 3). At site 1, the layering within ice-marginal sediments probably does
280 not record the structure of the basal ice. We observed reworking of melt-out sediments by flow along a shallow
281 gradient toward what is now a large proglacial lake. Hence, sediment flow likely contributed to the layered
282 appearance of the sediments here (cf. Lawson, 1982). Site 2 provides the best example of a true melt-out till at
283 Svínafellsjökull because conditions at this location favoured development of such a till (flat area at the base of a
284 moraine slope that washed insulating sediment on top of melting basal ice). Under these circumstances basal ice
285 was allowed to melt-out in situ; and so layering was preserved in ice-marginal sediments. At site 3, there is only
286 very faint layering evident within an otherwise apparently massive till, indicating that layering was destroyed as
287 basal ice melted onto a steep moraine slope. So, in general, the preservation of the distinctive layered
288 appearance of supercool basal ice depends largely on the conditions under which it melts, and hence this
289 signature can vary significantly around the glacier margin. Lawson (1979) found that melt-out tills only accounted
290 for around 5% of the deposits at the Matanuska Glacier, and our observations are broadly consistent with that.

291

292 The dominance of silt and very fine sand within supercool basal ice was recorded within ice-marginal sediments
293 at sites 2 and 3, although such an assessment was not possible at site 1 (Fig. 4; Table 1). Although the particle
294 size distributions of basal ice and ice-marginal sediments at sites 1 and 2 are all similar, the particle size
295 distributions of basal ice and ice-marginal sediments at site 3 are different, being more fine-grained. Nonetheless,
296 the dominance of silt and very fine sand in basal ice and melt-out sediments is clear and is distinctively more fine-
297 grained than regelation basal ice and sediments at sites 4 and 5. This result is consistent with previous reports of
298 silt-dominated basal ice and sediments associated with supercooling (e.g., Larson et al., 2006).

299

300 Although there is a statistical difference between supercool basal ice and regelation basal ice in terms of clast
301 roundness, the same trend was not observed in ice-marginal sediments. Inspection of Fig. 5C and Table 1
302 reveals that there was significant variability in basal ice clast roundness between sites 1, 2, and 3; and hence, the
303 preservation of a clast morphology signature of supercooling in ice-marginal sediments appears unlikely. The
304 reasons for the lack of a consistent clast morphology signature are unclear, but we suggest that the subglacial
305 supply of rounded clasts could be variable. Lawson et al. (1998) described concentrations of sorted gravels with
306 rounded clasts within basal ice, perhaps related to channel fill beneath the glacier. Swift et al. (2006) also
307 regarded the basal sediment within overdeepenings to be a mixture of subglacially and fluvially transported

308 material, and hence it should be expected that sediment within basal ice will exhibit heterogeneous
309 characteristics. It seems likely, therefore, that although basal ice contained concentrations of rounded clasts
310 where sampled, ice-marginal sediments may have formed from basal ice that contained more mixed clast
311 characteristics. Clast shape (C40), in this study, also appears not to be able to discriminate reliably between
312 populations derived from basal ice of different origins (Fig. 5; Table 1).

313

314 5.2. *Regelation sediments*

315 Regelation basal ice has been described in numerous studies and is generally considered to be layered, to
316 contain low concentrations of debris, to contain a range of grain sizes, and to be dominated by basally worked
317 clasts that may show signs of fracture and angularity (e.g., Kamb and LaChapelle, 1964; Boulton, 1978; Hubbard
318 and Sharp, 1993, 1995; Sharp et al., 1994; Alley et al., 1997). Basal ice at sites 4 and 5 is broadly consistent with
319 these previous descriptions, being characterised by a layered appearance, low debris contents (~ 5% by volume
320 on average), dominated by coarse sand (Figs. 2D and 4; Table 1), and containing a higher proportion of angular
321 clasts than rounded clasts. Few studies have considered the sedimentary products of regelation ice from modern
322 environments, although this process has been invoked to explain the origin or development of some post-glacial
323 sediments (e.g., Kemmis, 1981; Hughes et al., 1985; Domack et al., 1998).

324

325 Overall, our results indicate (i) that sedimentary layering from regelation ice is not preserved in ice-marginal
326 sediments; (ii) the sandy texture of the basal ice is preserved in ice-marginal sediments and is distinct from
327 sediments derived from supercooling; and (iii) that the higher proportion of angular clasts within regelation basal
328 ice is preserved in ice-marginal sediments, although it has not been possible to differentiate ice-marginal
329 sediments of different origins on the basis of clast morphology.

330

331 The high ice to debris ratio of regelation basal ice means that the preservation of layering within ice-marginal
332 sediments is very unlikely (Paul and Eyles, 1990; Evans et al., 2006). Therefore, the very faint layering within ice-
333 marginal sediments at sites 4 and 5 (Fig. 3; Table 1) probably represents layering from sediment flow or from
334 reworking by a seasonal glacier readvance rather than from direct melt-out of basal ice in situ.

335

336 The sediment particle size distribution of basal ice at sites 4 and 5, dominated by coarse sand, is preserved within
337 ice-marginal sediments and is similar between sites (Fig. 4, Table 1). This coarse sediment signature is notably
338 different from the fine-grained supercool basal ice and sediments. The extent to which a coarse sand texture can

339 be considered as diagnostic of regelation, and hence of importance in evaluating the extent of basal sliding
340 beneath palaeo-ice masses, is uncertain. Regelation basal ice and sediments from nearby Breiðamerkurjökull,
341 Iceland, described by Boulton et al. (1974) are similarly dominated by sand. However, Domack et al. (1998)
342 suggested that clots of frozen clay within Prydz Bay marine sediments, Antarctica, resulted from regelation
343 entrainment of a mud-rich slurry. Sediment supply and bedrock lithology may play significant roles in determining
344 the particle size distribution of regelation basal ice and melt-out sediments.

345

346 In general, samples of basal ice at sites 4 and 5 contained higher proportions of angular clasts than they did
347 rounded clasts (Fig. 5, Table 1), and this pattern was also true for ice-marginal sediments. These properties
348 reflect the active subglacial transport of sediment in the basal traction zone (e.g., Boulton, 1978).

349

350 *5.3. Recognising basal processes in formerly glaciated environments: problems and progress*

351 Our results from Svínafellsjökull indicate the potential to identify the former operation of supercooling and
352 regelation from Quaternary sediments, enabling important insight into the conditions beneath former ice masses.
353 For example, correct identification of regelation from Quaternary glacial sediments is important in assessing the
354 potential for glacier motion through basal sliding, and identification of glaciohydraulic supercooling allows
355 inferences to be made about the nature of subglacial hydrology. Furthermore, because of the strong spatial
356 differences in the occurrence of different basal ice facies and subglacial processes (Cook et al., 2007), it may be
357 possible to reconstruct the spatial distribution of basal ice compositions and subglacial processes from post-
358 glacial sediments (Knight et al., 2000; Adam and Knight, 2003). The most robust method of differentiation
359 between sediments of different origins would appear to be on the basis of particle size distribution, although our
360 work does show some variability in particle size distribution of supercool ice facies and sediments around the
361 glacier margin. Where conditions allow it, sedimentary stratification may also be preserved, but this is the
362 exception rather than the norm. Clast shape and roundness/angularity analysis was found to be less reliable in
363 differentiating between sediments of different origins because of significant overlap between populations of
364 regelation-related and supercooling-related sediments.

365

366 Particle size distributions of sediments derived from basal ice melt-out survive robustly in the absence of
367 significant agents of sediment reworking, such as glaciofluvial activity (Knight et al., 2000). Hence the distinctive
368 silt-dominated particle size distribution of ice-marginal sediments derived from supercooling may be recognised
369 relatively easily in post-glacial sediments (Larson et al., 2006; Kristensen et al., 2008). The sedimentary

370 characteristics of regelation sediments, whilst being distinct from sediments derived from supercooling, may not
371 be so easily distinguished from sediments derived from other processes of basal ice formation whereby there is
372 no selective entrainment of a specific sediment particle size. Cook et al. (2010) demonstrated that supercool
373 basal ice facies contributed around five times more debris to the ice-marginal environment at Svínafellsjökull than
374 did regelation basal ice. Hence the preservation potential of a supercooling signature is likely to be greater than
375 for a regelation signature. Nonetheless, some studies have reported the influence of regelation through analysis
376 of post-glacial sediments (e.g., Kemmis, 1981; Hughes et al., 1985; Domack et al., 1998), and such sedimentary
377 signatures and geomorphic impact may be enhanced where debris-laden regelation layers are thickened through
378 glaciotectionic deformation (e.g., Sharp et al., 1994) as at Svínafellsjökull.

379
380 There are significant challenges to be met in order to be able to differentiate between the influences of different
381 subglacial processes, including processes of basal ice formation, within the sedimentary record of past
382 glaciations. Different criteria used to elucidate the origins of sediments (including clast fabric analysis,
383 sedimentary layering, preservation of englacial structures, etc.) have all been criticised and the data can
384 sometimes be equivocal (Paul and Eyles, 1990; Boulton, 1996; Hart, 1998; Bennett et al., 1999; Evans et al.,
385 2006). For example, while Larson et al. (2006) suggested a landform–sediment assemblage indicative of the
386 influence of supercooling (including melt-out tills, sediment flow deposits, hummocky moraine), other workers
387 have criticised these criteria suggesting that they are not unique to this process (Evans, 2009).

388
389 Some hope may then come from analysis of the sediments themselves. Larson et al. (2006) suggested that the
390 dominance of silt within basal ice produced by supercooling may be unique to this process. Some subsequent
391 studies (e.g., Kristensen et al., 2008) have also related silt-dominated sediments to a supercooling origin. Until
392 now, the idea that basal ice and ice-marginal sediments produced by supercooling should necessarily be silt-
393 dominated has been based solely on observations at the Matanuska Glacier (Alley et al., 1998; Lawson et al.,
394 1998; Larson et al., 2006). Our study at Svínafellsjökull lends some support to this suggestion. However, the
395 extent to which particle size distributions record a subglacial process signature has been questioned previously.
396 For example, Haldorsen (1982) suggested that melt-out till and lodgement till necessarily had different particle
397 size distributions as a consequence of their different origins. Hart (1998) criticised this assertion suggesting
398 instead that grain size differences merely reflect variations in the nature of the subglacial environment rather than
399 any process signature. It is reasonable to speculate then as to whether silt dominance within supercool basal ice

is a function of the supercooling process itself (i.e., preferential filtering of silt by frazil ice during supercooled freeze-on) or of some other factor such as sediment supply, or both (Cook and Knight, 2009).

We advance a hypothesis for how silt-dominated basal ice and sediments might result irrespective of the nature of supercooled freeze-on. The fact that supercooling relies upon the presence of an overdeepening means that, during times when the glacier recedes into the overdeepening, a lake will form in front of the glacier allowing fine-grained sediments to accumulate. When the glacier subsequently advances into the lake and supercooled freeze-on resumes, the system is already primed so that basal ice will entrain the local supply of silt. Thus silt-dominance may be an overdeepening-specific sediment signature rather than, or in addition to, a supercooling-specific signature. The variability in the clast morphology data across parts of Svínafellsjökull that overly an overdeepening (i.e., where supercool basal ice is dominant; Fig. 1) also suggests that sediment supply is spatially variable and thus, in part, controls the sedimentary character of the basal ice and resultant sediments. Bedrock lithology may also vary beneath different parts of the glacier providing variable sediment supply.

There are other possible causes of the dominance of silt within supercool basal ice or the relative silt deficiency within regelation basal ice. Eyles and Menzies (1983) proposed that bed roughness plays an important role such that smoothed beds promote efficient comminution and enhanced abrasion of rock particles to give fine-grained particle size distributions, whereas rough beds promote grain crushing and a lower proportion of fine-grained products. Eyles and Menzies (1983) also suggested that fine-grained sediments are more likely to become lodged against bedrock obstacles during the regelation process, and hence become removed from debris transport. Boulton (1975) showed that regelation flow occurred around individual particles resulting in only limited entrainment of silt and clay particles. Likewise, particles larger than pebble size would tend not to be entrained because ice is able to deform around them. The issue of whether silt dominance can be regarded as a supercooling signature merits further research, and we invite the testing of our hypothesis for the accumulation of silts within overdeepenings.

Whatever the cause of silt dominance within supercool basal ice, the recognition of silt-dominated tills in the glacial sedimentary record could be significant to interpretations of their genesis. For example, basal ice produced within overdeepenings can reach several metres in thickness, either by supercooling or through enhanced thickening of preexisting basal ice against a reverse bedslope (e.g., Lawson et al., 1998; Swift et al., 2006). Hence the interpretation of till sequences as the product of the melt-out of such basal ice offers an important

alternative explanation to their interpretation as the products of processes such as subglacial sediment deformation (see Boulton, 1996; Hart, 1998; Piotrowski et al., 2001; Evans et al., 2006). A number of workers have already begun to attribute the formation of some melt-out tills and also Heinrich layers to the supercooling process and to the presence of overdeepenings (Lawson et al., 1998; Roberts et al., 2002; Larsen et al., 2004; Larson et al., 2006; Kristensen et al., 2008). It is essential then that potentially diagnostic subglacial process signatures preserved in the sedimentary record are tested further so that we can be confident in our interpretation of sediment origins in a range of different situations.

438

439

440 **6. Conclusions**

Our results from Svínafellsjökull indicate that the distinctive sedimentary characteristics of basal ice produced by two different processes (glaciohydraulic supercooling and regelation) are preserved within ice-marginal sediments during basal ice melt-out. Furthermore, the spatial distribution of basal ice types of different origins may be reconstructed from post-glacial sediments (e.g., Knight et al., 2000; Adam and Knight, 2003). There are key differences between these sediments that may make it possible to differentiate between the influences of these two processes in the sedimentary record of past glaciations. Sediments derived from the melting of basal ice produced by supercooling tend to be silt-dominated with a slightly higher proportion of rounded and well-rounded clasts compared to regelation basal ice and sediments. Where supercool basal ice melts-out in situ, the sedimentary stratification observed in the basal ice is also preserved within ice-marginal sediments, although this is rare. Sediments derived from the melting of basal ice produced by regelation tend to be dominated by coarse sand with a slightly higher proportion of angular and very angular clasts than supercool basal ice and sediments. There is very little evidence of the preservation of basal ice sedimentary stratification within ice-marginal sediments because of the high ratio of ice to sediment within regelation ice.

454

We find that sediment particle size analysis provides the most robust method of differentiating between basal processes from ice-marginal sediments. Because of its higher sediment content, the preservation potential of a supercool basal ice signature in post-glacial sediments is greater than for regelation basal ice, although where regelation ice is tectonically thickened its impact on proglacial sedimentology and geomorphology might be more easily recognised in post-glacial sediments. Until now the assumption that supercooling necessarily produces silt-dominated basal ice and sediments has been based on results at only one glacier (e.g., Lawson et al., 1998). Results from Svínafellsjökull lend support to this idea. However, further research is required in order to assess

462 whether the dominance of silt-sized material within basal ice produced by supercooling, and hence within melt-out
463 sediments, is a function of the supercooling processes itself (i.e., silt filtered from subglacial water during
464 percolation through frazil ice) or of sediment supply. Likewise, sediment supply may play a role in determining the
465 sedimentary character of regelation basal ice and associated ice-marginal sediments. In the case of explaining
466 silt-dominated basal ice and sediments through supercooling, we hypothesise that subglacial overdeepenings
467 may trap significant quantities of silt during times of reduced glacier extent when the overdeepening becomes a
468 proglacial lake. This would provide a ready supply of silt for basal ice accretion when the overdeepening is
469 subsequently inundated once more during times of greater glacier extent. Either way, silt-dominated till may be
470 strongly indicative either of the influence of overdeepenings and/or of supercooling in glacial sediment
471 entrainment and may be developed as a diagnostic tool to aid the interpretation of till genesis.

472
473

474 **Acknowledgements**

475 SJC gratefully acknowledges funding from the Royal Geographical Society. This research benefited from aerial
476 photographs acquired by the NERC Airborne Research and Survey Facility in 2007. We thank Richard Waller for
477 the photograph used in Fig. 2a. This manuscript benefitted from helpful reviews from an anonymous reviewer and
478 the editor Richard Marston.

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620

621 **List of Figures**

622 **FIG. 1.** The location (inset) and ice-marginal environment of Svínafellsjökull, including the distribution of stratified
623 basal ice facies, prominent ice-marginal geomorphological features, and sample locations for analysis of ice-
624 marginal sediments derived from stratified basal ice.

625

626 **Fig. 2.** Basal ice composition at Svínafellsjökull. (A) Supercool basal ice (subfacies C) at site 1 (photograph by
627 Richard Waller); (B) close-up of supercool basal ice at site 2 including angular aggregates of silt-dominated
628 sediment; (C) section of supercool basal ice at site 2; (D) section of regelation basal ice at site 5 composed
629 primarily of subfacies A, with a 20-cm-thick lens of subfacies B immediately below the ice axe head.

630

631 **Fig. 3.** Sedimentary logs for ice-marginal sediments at each site.

632

633 **Fig. 4.** Particle size distributions of the sediment matrices (0 to 10 Φ) of basal ice and ice-marginal sediments.
634 Error bars indicate $\pm$ one standard deviation.

635

636 **Fig. 5.** Covariant plots of clast shape versus relative angularity (RA) (A and B) and relative roundness (RR) (C
637 and D). Plots (A) and (C) compare basal ice and ice-marginal sediments from areas of the glacier where basal ice
638 formation is dominated by glaciohydraulic supercooling (i.e., sites 1, 2, and 3); and plots (B) and (D) compare
639 basal ice and ice-marginal sediments from areas where basal ice formation is dominated by regelation (i.e., sites
640 4 and 5).

641

642

643 **List of Tables**

644 **Table 1.** Summary of site characteristics and sedimentary characteristics of stratified basal ice and ice-marginal
645 sediments.

646

Stratified basal ice formation dominated by regelation

Key

Glacier margin where stratified facies was absent or not exposed

Glacier margin with exposures of stratified facies basal ice

Prominent moraine

Lake

Sampling sites for ice-marginal sediments

N

0.5 km

Stratified basal ice formation dominated by glaciohydraulic supercooling

SVÍNAFELLSJÖKULL

Figure 3

Site 1

Ice-marginal sediments

Site 2

Basal ice

Ice-marginal sediments

Site 3

Basal ice

Ice-marginal sediments

Site 4

Basal ice

Ice-marginal sediments

Site 5

Basal ice

Ice-marginal sediments

Table 1

Summary of site characteristics and sedimentary characteristics of stratified basal ice and ice-marginal sediments.

Site	Dominant basal ice facies	Ice-marginal sediments							
		Basal ice	Mean particle size (Φ)	Mean relative angularity (%)	Mean relative roundness (%)	Mean particle size (Φ)	Mean C40	Mean relative angularity (%)	Mean relative roundness (%)
1	Supercool (subfacies C)	-	-	-	-	3.9 (very fine sand) n=11	8.0 n=1	18.0	6.0
2	Supercool (subfacies C)	3.9 (very fine sand) n=11	16.9 n=3	8.5	25.2	3.9 (very fine sand) n=6	8.8 n=5	13.2	8.4
3	Supercool (subfacies C)	5.4 (coarse silt) n=3	17.2 n=5	14.8	12.8	4.5 (very coarse silt) n=2	18.0 n=2	5.0	8.5
4	Regelation (subfacies A)	3.1 (very fine sand) n=5	14.0 n=1	16.0	6.0	3.3 (very fine sand) n=10	12.0 n=1	18.0	4.0
5	Regelation (subfacies A)	2.6 (fine sand) n=18	16.8 n=11	15.2	5.7	2.7 (fine sand) n=6	18.0 n=8	15.0	7.4