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**INCISION AND AGGRADATION IN PROGLACIAL RIVERS:  
POST-LITTLE ICE AGE LONG-PROFILE ADJUSTMENTS OF  
SOUTHERN ICELAND OUTWASH PLAINS**

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18  
19 12 **Abstract:**

20  
21 13 The retreat of glaciers in response to climate warming leads to substantial changes in meltwater and sediment  
22 14 yield. Glacial shrinkage also induces the emergence and growth of proglacial margin landforms which strongly  
23 15 affect water and sedimentary transfers from the glacier to the outwash plains. On a decadal-timescale, field  
24 16 observations show that outwash plains of retreating glaciers typically exhibit proximal incision which decreases  
25 17 in magnitude downstream and stops at an inflection point where aggradation begins. Nevertheless, there is a  
26 18 lack of knowledge about the rates and magnitude of this fluvial adjustment and the effects of the proglacial  
27 19 margin configuration on the temperance or the aggravation of this fluvial adjustment to glacier retreat. This  
28 20 paper investigates the proglacial rivers of 14 retreating glaciers in southeast Iceland over a post-Little Ice Age  
29 21 timescale, combining fluvial deposits mapping, lichenometric dating and long-profile measurements of  
30 22 proglacial fluvial terraces. Our results demonstrate that: (1) proximal incision, associated with distal  
31 23 aggradation and downstream migration of the inflection point is the dominant pattern of proglacial river  
32 24 response to post-LIA glacier retreat in Iceland; (2) estimated mean rates of downstream migration of the  
33 25 inflection point range between 5 and 46 m.a<sup>-1</sup>; (3) the downstream migration rate of the inflection point is  
34 26 positively correlated with the proportion of proglacial lakes within the glacier foreland. These findings suggest  
35 27 that proglacial margins dominated by proglacial lakes intensify the rates of proximal incision and inflection  
36 28 point migration.  
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45 29 **Keywords:** proglacial river, glacial retreat, proglacial landforms, fluvial geomorphology, paraglacial processes  
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## 49 31 1. INTRODUCTION

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53 33 Since the end of the Little Ice Age, rising temperatures have elevated the equilibrium lines altitude of many  
54 34 glacial systems and intensified ice melting (Barry, 2006; Vaughan *et al.*, 2013). This implies an adjustment of  
55 35 glacier geometry, which is usually reflected by the retreat of the glacier front. Glacial retreat leads to the  
56 36 emergence and growth of proglacial margin landforms at the interface between the glacier and the fluvial  
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3 37 system (Heckmann *et al.*, 2016; Carrivick & Heckmann, 2017). The water discharge of proglacial rivers is largely  
4 38 supplied by meltwater and they are directly connected to the glacier, such that sediment released by glacial  
5 39 melt is immediately available to be carried as fluvial sediment load. The supply of both water and sediment is  
6  
7 40 highly sensitive to changes in glacier mass balance. The primary hydrological impact of glaciers on downstream  
8 41 river systems is to modulate the timing and seasonality of hydrological fluxes (Röthlisberger & Lang, 1987). A  
9  
10 42 shift to deglacial conditions leads to marked changes in the seasonality of river flow (e.g., a shift of the  
11 43 hydrograph to an earlier peak flow in spring months) and the amount of annual glacier runoff (Bliss *et al.*, 2014;  
12 44 Milner *et al.*, 2017). Current trends in annual glacial runoff differ among world regions and glacier hypsometry  
13 45 but there is a consensus on the typical sequence of meltwater changes during catchment deglaciation (Bliss *et al.*  
14 46 *et al.* 2014): at the beginning of deglaciation, when the glacier is still sufficiently voluminous, the glacial meltwater  
15  
16 47 tends to increase for a period lasting several decades, before decreasing when the ice stock runs out (Braun *et al.*  
17 48 *et al.*, 2000; Jansson *et al.*, 2003; Marren, 2005; Huss *et al.*, 2008). The successive growth and decay of the glacial  
18  
19 49 meltwater supply during deglaciation periods is both supported by palaeohydraulic studies (Maizels, 1986) and  
20 50 simulations of meltwater discharge (Bliss *et al.*, 2014). In Iceland, modelling approaches predict increased  
21 51 meltwater runoff until 2050. According to these simulations, glacier runoff declines afterwards (Flowers *et al.*,  
22 52 2005; Jóhannesson *et al.*, 2006; Bliss *et al.*, 2014). A shift to deglacial conditions also affects the sediment  
23 53 supply to proglacial rivers in three ways: (1) The erosive capacity of a glacier is a function of basal sliding such  
24 54 that there is a dependence of erosion rate on the ice thickness which rely on the ice mass balance driven by  
25 55 climate conditions. Thus, in the long term, the loss of glacier thickness and volume limits their own ability to  
26 56 produce glacial material (Hallet *et al.*, 1996; de Winter *et al.*, 2012); (2) Deglaciation produces a lagged  
27 57 paraglacial sediment pulse caused by the reworking of stored englacial, subglacial and marginal sediments  
28 58 (Church & Ryder, 1972; Church & Slaymaker, 1989; Ballantyne, 2002; Mercier, 2008). Paraglacial sediment  
29 59 supply is highest during the initiation of glacial retreat and declines as sediment sources are exhausted or  
30 60 stabilized; (3) However, glacier retreat also induces the emergence and growth of proglacial margin landforms,  
31 61 like moraine ridges or proglacial lakes, which trap and store sediments and decrease the sediment connectivity  
32 62 in the glacier foreland (Cossart, 2008; Cossart & Fort, 2008; Heckmann & Schwanghart, 2013; Carrivick &  
33 63 Tweed, 2013; Cossart & Fressard, 2017; Cordier *et al.*, 2017, Lane *et al.*, 2017). As a result, the downstream  
34 64 sediment flux of retreating glaciers may be significantly reduced, particularly where lasting proglacial lakes  
35 65 develop (Geilhausen *et al.*, 2013 ; Bogen *et al.*, 2015, Staines *et al.*, 2015). Nevertheless, sediment connectivity  
36 66 may temporarily or durably be restored by rare and extreme floods triggered by rainstorms (Marren &  
37 67 Toomath, 2013 ; Owczarek *et al.*, 2014), glacial outbursts (Westoby *et al.*, 2014; Worni *et al.*, 2014) or iceberg-  
38 68 jam failures (Roussel *et al.*, 2016).

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49 69 Changes in meltwater and sediment fluxes from retreating glaciers lead to substantial geomorphic adjustments  
50 70 of proglacial rivers. Understanding the behaviour of proglacial rivers during periods of rapid change of glacier  
51 71 mass balance is especially important at present, given that climate change projections indicate that most  
52 72 glaciated regions will undergo a rapid decrease in glacier extent over the coming century (Marzeion *et al.*,  
53 73 2012; Radić *et al.*, 2014), coupled with major hydrogeomorphological changes (Bliss *et al.*, 2014; Milner *et al.*,  
54 74 2017). Reduced sediment flux from a retreating glacier usually induces incision of the upper reach of the

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3 75 proglacial river (proximal outwash plain) and the formation of a single deep channel (Fahnestock, 1969 ;  
4 76 Maizels, 1979, 1983 ; Germanoski & Schumm, 1993; Gurnell *et al.*, 1999; Marren, 2005 ; Wilkie & Clague, 2009,  
5 77 Owczarek *et al.*, 2014). In Iceland, this fluvial response has been observed on the proglacial margins of the  
6 78 southern glacial outlets of the Vatnajökull icecap, especially on the proglacial rivers of Skaftafellsjökull and  
7 79 Svínafellsjökull, (Thompson & Jones, 1986 ; Thompson, 1988 ; Marren, 2002; Roussel *et al.*, 2008 ; Marren &  
8 80 Toomath, 2013, 2014). During the incision phase, fluvial bars tend to merge into larger sedimentary units,  
9 81 which are not in equilibrium with the water and sedimentary flux (Germanoski & Schumm, 1993). The incision  
10 82 of the proximal river results in the establishment of glacio-fluvial terraces whose morphosedimentary features  
11 83 reflect the former hydrological conditions before the incision (Marren, 2005). Flume experiments show that the  
12 84 long profile of an incising braiding river is usually characterized by an inflection point, downstream of which  
13 85 aggradation is dominant (Germanoski & Schumm 1993). Indeed, the reworked material of the incising upper  
14 86 reach is transported and deposited downstream induces an increase of the braiding intensity of the lower  
15 87 reach of the river. When the sediment delivery deficit continues, flume experiments have shown that the  
16 88 inflection point, which separates the incision from the aggradation reach, tends to migrate downstream  
17 89 (Germanoski & Harvey, 1993). At the same time, glacial retreat promotes the formation of proglacial lakes that  
18 90 trap the coarser fraction of the sediment flux and may strengthen the proximal river incision and the  
19 91 aggradation of the distal river reach (Embleton & King, 1968; Chew & Ashmore, 2001; Benn *et al.*, 2003;  
20 92 Gardarsson & Eliasson, 2006; Schomacker, 2010; Carrivick & Tweed, 2013; Bogen *et al.*, 2015). Nevertheless,  
21 93 this pattern of fluvial response to glacier retreat can vary over space and time due to topographical constrains  
22 94 induced by marginal landforms: (1) the spatial and temporal evolution of the overall sediment connectivity  
23 95 within the proglacial margin can lead to damming and localised river aggradation (Cossart, 2008 ; Cossart &  
24 96 Fort, 2008); (2) Channel pattern changes can be controlled by moraine ridges between which the river is forced  
25 97 to find a course (Marren & Toomath, 2013, 2014).

26 98 Field observations report that most proglacial rivers associated with retreating glaciers in Iceland exhibit  
27 99 proximal incision which decreases in magnitude downstream and stops at an inflection point where  
28 100 aggradation begins (Marren, 2005 ; Roussel *et al.*, 2008 ; Marren & Toomath, 2013). However, no studies have  
29 101 measured longitudinal profile adjustments of this type on a large sample of proglacial rivers and over a  
30 102 sufficiently long time period to determine whether this behaviour is a representative response to glacial  
31 103 retreat. Furthermore, there is a lack of information about the rates and magnitude of this fluvial adjustment  
32 104 and the effects of the glacial retreat rate and the proglacial margin configuration on the temperance or the  
33 105 aggravation of the fluvial response to glacier retreat.

34 106 Therefore, this paper investigates the proglacial landscapes and the outwash plains of 14 retreating glaciers in  
35 107 southeast Iceland over a post-Little Ice Age timescale. It combines quantitative assessment of the glacier  
36 108 retreat, the landform assemblage of the proglacial margin and the post-LIA outwash plains changes through  
37 109 lichenometric dating and longitudinal profile measurements of active outwash and fluvial terraces. The aims of  
38 110 this paper are threefold: (1) to test the representativeness of the outwash plains response to glacier retreat  
39 111 described above over the time-scale of centuries; (2) to assess the rates of this fluvial response through the

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3 112 reconstruction of the downstream migration of the inflection point; (3) to explore the influence of the  
4 113 landforms assemblage of the proglacial margin on the rate of the outwash plains response.

## 6 114 **2. Materials and Methods**

### 8 115 ***Site conditions and history***

10 116 Three southern Icelandic marginal areas were selected: the Sólheimajökull area in the south of the  
11 117 Mýrdalsjökull icecap, the Örfajökull and southeastern Vatnajökull areas, both located on the southern margin  
12 118 of the Vatnajökull icecap (Figure 1). These three study areas present a sample of 14 glacier tongues which feed  
13 119 12 proglacial rivers (Table 1). Two pairs of formerly coalescent glaciers feed proglacial rivers which merge  
14 120 within the proglacial margin (Hrútarjökull/Fjallsjökull and Skálafellsjökull/Heinabergsjökull). None of the  
15 121 studied glaciers exhibit surge dynamics (Thórarinnsson, 1969; Björnsson *et al.*, 2003; Ingólfsson *et al.*, 2016).  
16 122 Three glaciers (Sólheimajökull, Kotárjökull and Heinabergsjökull) are known to be jökulhlaup outlets (Thompson  
17 123 & Jones, 1986; Sigurðsson, 1998; Björnsson, 1992; Roberts *et al.*, 2003; Russell *et al.*, 2003, 2010). For  
18 124 convenience, the investigated glaciers and outwash plains are called afterward by their ID number (Table 1)  
19 125 instead of their Icelandic name. Additional information on site conditions and history is available in the  
20 126 appendix.

### 26 127 ***Methods***

27 128 In order to address the aims of this study, we followed three stage methodological workflow (Figure 2)  
28 129 including field surveying and GIS mapping of proglacial landforms, lichenometric dating of outwash terraces,  
29 130 and topographic surveys of the active proglacial rivers and outwash terraces.

#### 32 131 ***Proglacial landform mapping***

33 132 The proglacial margin plays an essential role in sediment connectivity and may impose sediment flux  
34 133 discontinuities into the glaciofluvial continuum. Therefore, characterizing the landform assemblage of the  
35 134 proglacial margins is essential to fully assess the fluvial response of outwash plains to post-LIA glacial retreat.  
36 135 The mapping work is based on the recognition of 11 typical classes of proglacial landforms in the field (Figure 2-  
37 136 A): Glacier front, fresh proximal till deposits (including dirty cones, hummocky debris, dead-ice with  
38 137 supraglacial debris), moraine ridge, active and abandoned intra-morainic plain, intra-morainic lake, proglacial  
39 138 lake, alluvial fan, rocky outcrop, active outwash and fluvioglacial terraces. Artificial dams and embankments  
40 139 built in the proglacial margins were also mapped as they may act on the sediment connectivity and marginal  
41 140 landforms evolution (e.g. inhibiting basal erosion of morainic ridges). LIA moraines mark the maximum glacier  
42 141 snout position during the LIA and their locations are well known for most of the glaciers we investigated. They  
43 142 have already been examined and mapped by several authors (Thórarinnsson, 1956; Evans *et al.*, 1999, 2017;  
44 143 Bradwell, 2004; Chenet *et al.*, 2010, Hannesdóttir *et al.*, 2015). In the field, the locations of LIA moraines and  
45 144 outwash terraces were collected using a handheld GPS (Trimble Geoexplorer XH). Post-processing of the GPS  
46 145 signal enabled a planimetric precision of 1.5 m on average. The fieldwork phase ensured the robustness of the  
47 146 subsequent mapping work based on the photo-interpretation of recent photographs with GIS software.  
48 147 Coupling this field database to 2009 and 2012 georeferenced orthophotos (2 m resolution on average)



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3 148 provided by DigitalGlobe® within ArcGIS software (10.4), the landform assemblages in the proglacial margin,  
4 149 the outwash terraces, and the active outwash were mapped. The proglacial margin areas provide a quantitative  
5 150 assessment of the deglaciated surface since the LIA. An average linear retreat of the glacier fronts was  
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7 151 computed by dividing the proglacial margin area by the glacier front length for each glacier. A manual  
8  
9 152 measurement of the linear retreat of glacier fronts was also performed, along the centerline of the glacier  
10 153 tongues, between the maximum LIA moraines and the glacier front in 2009.

#### 11 154 *Lichenometric dating*

12 155 Lichenometric dating of outwash terraces (Figure 2-B) was performed using the generalized extreme value  
13 156 approach (GEV) described in Jomelli *et al.* (2007) for the statistical treatment of the measurements of the  
14 157 longest axis of the thalli of *Rhizocarpon Geographicum*. This procedure has already been successfully applied in  
15 158 Iceland to date the LIA moraines of the south Vatnajökull (Chenet *et al.*, 2010). This method provides a more  
16 159 statistically robust estimate of the age of the deposits because it takes into account the bias induced by the  
17 160 strategy of data collection (i.e. the selection of the largest thalli whose distribution is similar to the model GEV).  
18 161 In addition, this method provides confidence intervals to assess the quality of the estimated age.  
19 162 In the field, measurement of lichen long axes was carried out according to the procedure recommended by  
20 163 Jomelli *et al.* (2007): (i) a random selection of 50 boulders distributed over the whole surface of the deposit; (ii)  
21 164 on each boulder, the long axis of the largest thallus of *Rhizocarpon Geographicum* was measured with an  
22 165 accuracy of 0.5 mm. Coalescing lichens and thalli with irregular shape are systematically rejected. Consistent  
23 166 with all lichenometric methods, two datasets of thalli long axis were collected in the field: on already dated  
24 167 surfaces and on the deposits requiring dating. Eight well-known dated surfaces in an area of ca. 45 km<sup>2</sup> in  
25 168 south foreland of Vatnajökull were used to ensure that climatic conditions do not vary excessively (Chenet *et*  
26 169 *al.*, 2010). Dated surfaces included jökulhlaup deposits, lava flows, rockfalls, dams, and moraines; all made of  
27 170 basalt to ensure lithological homogeneity. Surfaces were dated using historical descriptions, aerial photographs  
28 171 (available since 1945), and personal communications from the Skaftafell Park staff. Additional consideration of  
29 172 the statistical treatments applied to the lichenometric database are available in several papers (Cooley *et al.*,  
30 173 2006; Naveau *et al.*, 2007; Rabatel *et al.*, 2008).

#### 31 174 *Topographic survey*

32 175 Longitudinal topographic profiles of active outwash and outwash terraces were surveyed in the field.  
33 176 Immediately downstream of LIA moraines of each investigated glacier, valley transverse profiles were also  
34 177 undertaken in order to capture the nesting of outwash terraces (Figure 2-C). Following the main direction of  
35 178 flow, longitudinal profiles of the active outwash and terraces were surveyed from the LIA moraines to the  
36 179 downstream edge of the fluvial deposit (confluence with a tributary or the shoreline). Transverse topographic  
37 180 profiles located just downstream of LIA moraines enable the computation of the relative altitude of each  
38 181 outwash terraces in respect to the active outwash. They are essential to align longitudinal profiles between  
39 182 them and to capture the downstream migration of the inflection points separating the upstream incising reach  
40 183 from the downstream aggrading reach of the proglacial rivers. These profiles were achieved using a laser  
41 184 telemeter (Impulse 200LR from Laser Technology) with a centimeter accuracy and a tripod target. The average

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3 185 distance between two measurements was 20 meters. Two measurements by stations (foresight and backsight)  
4 186 were carried out in order to systematically check that the difference between measurements were below the  
5 187 telemeter accuracy (0.03m) and to limit error propagation. As the objective was to assess the topography of  
6  
7 188 the outwash plains, measurements were carried out between topographic stations located on the heads of  
8  
9 189 fluvial bars. Therefore, fine topography at the channel scale was not captured. Each topographic station was  
10 190 located using a handheld GPS (Trimble Geoexplorer XH).

### 11 191 *Reconstruction of the downstream migration of the inflection point (IP)*

12  
13 192 Inflection points (*sensu* Germanoski & Harvey, 1993) separate upstream incising reaches from downstream  
14 193 aggrading reaches of a river. The reconstruction of changes in the location of the inflection point (IP)  
15 194 characterizes the evolution of the extent of proximal outwash affected by incision. IP changes were  
16 195 reconstructed based on the identification of intersection points of the longitudinal profiles of two successive  
17 196 (dated) terrace generations. These intersections are the former IP location separating the incision and the  
18 197 aggradation reach of the outwash plain at the date of the youngest of the intersecting terrace profiles (Figure  
19 198 2-D). For each reconstructed IP, its location (distance from LIA moraines and elevation) was validated in the  
20 199 field and recorded with the handheld GPS (Trimble Geoexplorer XH). The initial IP location (distance = 0 m) at  
21 200 the LIA glacial maximum coincides with the contact between the LIA moraines and the oldest and highest  
22 201 outwash terrace (T1), if lichenometric dating of the latter is younger than LIA moraine ridges. In other words, at  
23 202 the LIA glacial maximum, aggradation of the outwash is likely predominant and there is no upstream incision  
24 203 because there is no outwash upstream to the LIA moraines. The reconstruction of the former location of the  
25 204 inflection point when T1 was incised and the IP location observed in 2007 enabled the computation of average  
26 205 rates of longitudinal migration (increasing distance of the IP from the LIA moraines) and altitudinal lowering  
27 206 (decrease in the IP elevation) of the IP through time. A synthetic metric of average rate of downstream  
28 207 migration of the inflection point was also computed as the Euclidean norm of the vector (square root of the  
29 208 sum of the square of coordinate values) defined by the two values of longitudinal migration and altitudinal  
30 209 lowering of the inflection points. Note that this average rate of IP downstream migration does not necessarily  
31 210 reflect a gradual progression of the inflection point as IP migration may occur suddenly during extreme events.  
32 211 Finally, a stepwise multiple linear regression was performed in order to test the effect of proglacial landform  
33 212 assemblage on the downstream migration rates of the inflection point.  
34 213

## 35 214 **3. RESULTS**

### 36 215 *Proglacial landform assemblages*

37 216 The proportion of each landform unit within the post-LIA proglacial margin has been quantified (Table 2 and  
38 217 Figure 3). Glacigenic deposits, combining moraine ridges and fresh proximal till deposits, are the most  
39 218 abundant proglacial landforms (respectively 44.8 % and 5.2% on average of the investigated proglacial  
40 219 margins). The marginal landscape is obviously dominated by glacial deposits associated with seasonal  
41 220 fluctuations of glacier fronts and the continuous re-advances of the 1970s and 1980s. Proglacial margins of the  
42 221 steepest, Öräfajökull glaciers (glaciers 2 to 10), show a higher proportion of moraine deposits. Steep proximal



222 topography is associated with a large amounts of moraine deposits that may be related to large production  
223 rates of glacial sediments and/or limited fluvial reworking. Abandoned and active intra-morainic plains form  
224 respectively around 16.8 % and 8.9 % on average of the proglacial landforms. The abundance of these two  
225 types of landforms testify the involvement of fluvial processes in the morphogenesis of the proglacial margin.  
226 Rocky outcrops (11.4% on average) are only present in the proglacial margins of piedmont glaciers (Glaciers 1,  
227 11, 12 and 13) whose tendency to overdeepening would generally exhume more resistant areas of the glacial  
228 bed, and in the foreland of glacier 6 where steep proximal relief tends to rapidly clean the glacial bed and  
229 remove till layers via gravity and runoff processes. Proglacial and intra-morainic lakes (respectively 10.4% and  
230 1.5% on average) are totally absent from the proglacial margins of the steepest glaciers of the Öraefajökull  
231 sector (glaciers 6 and 7), most likely due to the extreme steepness of the ablation zone and the glacier  
232 forefield. Alternatively, proglacial lakes are common on the margin of piedmont glaciers of the southeastern  
233 sector of Vatnajökull where their large frontal lobes probably favored overdeepening of the marginal areas  
234 during the LIA glacier advance. Alluvial fans (0.6 % on average) are only present in steep marginal settings  
235 (glaciers 7 and 9). This association seems logical since development of alluvial fans is strongly dependent on the  
236 presence of steep marginal slopes. Embankments (0.3 % on average) are only present on the margins of two  
237 piedmont glaciers (glaciers 3 and 13). Artificial embankments are associated either with tourist trails running  
238 through the proglacial margin (in the case of glacier 13), or with consolidation structures of the main Icelandic  
239 road (road number 1) built through the LIA moraines (glacier 3).

#### 240 ***Outwash terrace mapping and dating***

241 Outwash terrace mapping and lichenometric dating (Figure 3) emphasizes four types of fluvial processes  
242 affecting the proglacial river responses to post-LIA glacier retreat: (1) post-LIA transient aggradation; (2)  
243 incision and contraction of the proximal outwash; (3) shifts in the location of the fluvial activity due to stream  
244 capture occurring within the proglacial margin and (4) outwash incision prior to LIA glacial maximum. Based on  
245 the analysis of glacier foreland mapping and lichenometric dating of outwash terraces, an overview of  
246 successive aggrading and incising stages of proximal outwash response to post-LIA glacial retreat has been  
247 produced (Figure 4). The outwash terraces of the proglacial rivers 6 and 7 could not be dated due to the  
248 absence of lichens: the oldest terrace (T1) of the outwash plain 6 is the historic jökulhlaup deposit of 1727 and  
249 is exclusively composed of fine materials devoid of lichens. The terrace (T1) of the outwash plain 7 is lightly  
250 vegetated and its abandonment by proglacial flows might be recent and artificial, relating to the upstream  
251 embankment structure (Figure 3). The youth of this fluvial deposit may explain the absence of lichens on the  
252 proximal surfaces.

#### 253 ***Post-LIA transient aggradation of proximal outwash***

254 First generation outwash terraces (T1 on Figure 3) are adjacent to the moraines ridges marking the maximal  
255 glacier extent during the LIA. They are interpreted as fill terraces built up by the aggrading proglacial river  
256 during the LIA glacier advances. Dating reveals that proximal aggradation, or at least the maintenance of the  
257 outwash plain in a steady state, has persisted after the glaciers reached their maximum LIA extent and their  
258 fronts likely initiated their retreat or stagnation phase. This post-LIA aggradation stage (or steady state phase)

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3 259 affected the proximal outwash of the proglacial rivers 1, 2, 5, 8, 9, 11, 13 and 14. The duration of this  
4 260 aggradation or steady state stage (computed as the difference between the T1 lichenometric dating and the  
5 261 age of LIA moraines) is highly variable and ranges between 5 ( $\pm 14$ ) and 147 ( $\pm 15$ ) years for the outwash 11 and  
6 262 5 respectively (Figure 4 and Table 3). The outwash 7 is the only one which seems to persist in the aggradation  
7 263 stage (Figure 4). Nevertheless, as its proximal reach is affected by an artificial embankment, its fluvial response  
8 264 is not fully controlled by natural drivers. Based on the other investigated outwash surfaces, aggradation may be  
9 265 considered as a transient stage of post-LIA outwash response.

#### 13 266 *Contraction and incision of the proximal outwash*

14 267 The post-LIA contraction of the proximal outwash width is detectable in the successive abandonment of  
15 268 outwash terraces (T2 to T5 on Figure 3) by proglacial rivers. These fluvial deposits are interpreted as nested cut  
16 269 terraces and reveal the incising dynamic affecting proximal outwash. This glaciofluvial evolution follows the  
17 270 transient aggradation stage and is still currently the dominant behaviour in most of the rivers. The outwash  
18 271 plain 7 is the only one which appears to still be aggrading or remaining in a steady state, likely due to the  
19 272 artificial constraints described above (Figure 4). On the other outwash plains, the proximal fluvial activity was  
20 273 gradually concentrated downstream of a single breach in the LIA moraines. Currently, the active outwash plain  
21 274 is framed by multiple paired or unpaired terraces whose preservation is dependent on the lateral mobility  
22 275 and/or the rate of proximal river incision (Charlton, 2008).

#### 28 276 *Stream capture and shift in the outwash plain location*

29 277 The mapping of glacier forelands (Figure 3) and the sequence of outwash terrace abandonment (Figure 4) also  
30 278 shows a typical marginal fluvial process: stream capture within the proglacial margin leading to a shift of the  
31 279 outwash plain location. This process affected the outwash plain 3 in 1939 ( $\pm 3$ ), 5 in 1891 ( $\pm 3$ ), 11 in 1914 ( $\pm 8$ )  
32 280 and 1959 ( $\pm 5$ ), and 13 in 1918 ( $\pm 7$ ). Stream capture seems to preferentially occur within proglacial margins  
33 281 where two ice lobes were coalescent at the LIA glacial maximum (Figure 3). This is the case for the glaciers 3, 11  
34 282 and 13 (Figure 3) whose glacial fronts were respectively coalescing with those of 4, 12 and the western arm of  
35 283 13 at the LIA glacial maximum. Stream capture and location shift of the proximal outwash plain can occur  
36 284 slowly, and follows a sequence of proximal outwash narrowing: In the foreland of glaciers 11 and 12 (Figure 3),  
37 285 three outwash terraces (T1, T2 and T3) were formed due to the contraction of the proximal braiding belt of the  
38 286 outwash plain shared by the two coalescing glaciers. In 1914, about 50 years after the LIA glacial maximum, a  
39 287 first stream capture occurred within the glacier 11 proglacial margin causing the abandonment of the outwash  
40 288 plain T3 and the development of the outwash plain T4. After 45 years of activity (during which T4 may have  
41 289 eroded the outwash terrace T3), a new stream capture occurred in the proglacial margin of glacier 11. T4 is  
42 290 abandoned in 1959 in favour of glacier 11 intra-morainic plains and the outwash plain which is still currently  
43 291 active. Ultimately, proximal incision and stream capture processes do not exclude each other. Moreover,  
44 292 according to our results, stream captures occur exclusively in the incising stages of the proximal outwash.

#### 53 293 *Proximal outwash incision prior to the LIA maximum*

54 294 The lichenometric dating of the first terrace generation (T1) of the proglacial rivers 3 and 4 predates the LIA  
55 295 glacial maximum (M1). According to these lichenometric ages, the abandonment of outwash T1 downstream of

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3 296 the glacier 3 may have occurred 16 years ( $\pm 25$  yr.) before the LIA maximum. But, as the absolute uncertainty  
4 297 exceed the difference between the ages of M1 and T1, proximal outwash incision and LIA maximum could also  
5 298 have occurred synchronously between 1864 and 1873. Dating results are much more surprising for the river 4,  
6 299 since the abandonment of the oldest terrace occurred almost two centuries ( $179 \pm 21$  years) before the LIA  
7 300 maximum (Figure 3 and Figure 4). Thus, proximal incision, or at least lateral contraction, of the outwash of the  
8 301 rivers 3 and 4 began before the glacier reached its maximum LIA extent. Early incision also affected the  
9 302 outwash 6 whose T1 terrace (Figure 3) was built by the 1727 jökulhlaup. The incision of this deposit may be  
10 303 independent of the fluctuations of the front of the glacier 6 and is instead related to a progressive return of the  
11 304 proglacial river to pre-jökulhlaup conditions (Thompson & Jones, 1986).  
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### 18 306 ***Outwash long profile adjustment***

19 307 Outwash longitudinal profiles reveals a dominant pattern of fluvial adjustment characterized by a proximal  
20 308 incision often accompanied by distal aggradation (Figure 5). The inflection point (IP) connecting the incising  
21 309 upper reach and the aggrading lower reach tends to migrate downstream through time.

### 22 310 *Proximal incision, slope decrease and distal aggradation*

23 311 Post-LIA proximal incision can be quantitatively assessed for the rivers 1, 2, 8, 9 and 14, which were not  
24 312 affected by stream captures or early incision prior to the LIA glacial maximum. These proglacial rivers present  
25 313 several nested outwash terraces, the oldest of which, (T1) is always backed by the LIA moraine ridges (Figure  
26 314 5). More recent outwash terraces can be disconnected from these moraines. This is the case for the rivers 8, 9  
27 315 and 14. This observation reflects either a downstream migration of the proximal outwash contraction or the  
28 316 destruction of the upstream part of recent terraces due lateral erosion and avulsion of the active river channel.  
29 317 Following the transient aggradation stage (or steady state stage), the initiation of proximal incision implies the  
30 318 abandonment of the oldest outwash terrace (T1) by river flows. As proximal degradation continues, proglacial  
31 319 rivers abandon younger terraces. This is particularly the case for the rivers 2 and 14 where six and four  
32 320 generations of terraces are distinguishable, respectively. The rate of proximal outwash incision, computed over  
33 321 the period from the abandonment of the oldest terrace until 2007, averages  $0.073 \pm 0.03$  m.a<sup>-1</sup> and ranges from  
34 322  $0.045 \pm 0.006$  m.a<sup>-1</sup> to  $0.131 \pm 0.012$  m.a<sup>-1</sup> for the rivers 2 and 14 respectively (Table 3).

35 323 The slope of the proximal rivers has decreased almost systematically since the LIA maximum. This is  
36 324 qualitatively detectable on Figure 5 by a visual comparison of the long profiles of the first generation of post-  
37 325 LIA outwash terraces (T1) with those active in 2007 (A). The mean slope of the proximal rivers (the first 500  
38 326 meters from the maximum LIA moraines) were calculated using a simple linear regression: results indicate that  
39 327 proximal slope decreased by  $0.011$  m.m<sup>-1</sup> (SD =  $0.009$  m.m<sup>-1</sup>) on average between the first-generation of post-  
40 328 LIA outwash terraces and the active rivers in 2007. However, there is a high variability in the post-LIA lowering  
41 329 of the proximal slope. For example, the proximal slope values of the active and the outwash terraces of the  
42 330 proglacial river 7 are identical, in agreement with the absence of proximal incision (Table 3). Conversely, the  
43 331 proximal slope of the river 9 decreased by  $0.0311$  m.m<sup>-1</sup>, dropping from  $0.0339$  m.m<sup>-1</sup> in 1891 (79 years after  
44 332 the LIA maximum) to  $0.0028$  m.m<sup>-1</sup> in 2007 (195 years after the LIA maximum PAG). For the river 9, the  
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3 333 comparison of the old (terrace T1) and current (2007) proximal slopes is only based on the first 200 meters  
4 334 from the LIA maximum moraines due to the narrowness of the conserved fragment of T1 terrace.  
5 335 Consequently, the slope measurements on this outwash plain reflect more closely the proximal concavities and  
6 336 are difficult to compare with the other rivers.  
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8 337 Decrease of the proglacial rivers slopes is mainly due to the proximal incision of the outwash plains. However,  
9 338 proximal incision is often associated with a distal aggradation of the outwash plain, which contributes to the  
10 339 overall decrease of the proglacial river slope. Indeed, nine of the twelve studied outwash plains present this  
11 340 type of post-LIA adjustment of their longitudinal profile: these include the outwash plains of glaciers 2, 3, 4, 5,  
12 341 8, 9, 11, 13 and 14 (Figure 5).

#### 16 342 *Downstream migration of the inflection point (IP)*

17 343 Post-LIA changes in the location of the inflection point (IP) were reconstructed for the proglacial rivers 2, 3, 4,  
18 344 5, 8, 9, 11, 13 and 14 (Figure 5). The longitudinal profiles of terraces and active outwash of the proglacial rivers  
19 345 1, 6 and 7 do not exhibit inflection points. Results demonstrate the post-LIA downstream migration of the  
20 346 inflection points, indicating a longitudinal increase of the extent of proximal outwash area affected by incision  
21 347 (Figure 4). This evolution may indicate a perennial sediment deficit in the marginal area leading to a  
22 348 downstream progression of the proximal incision. According to these results, the sediment recharge of the  
23 349 proglacial rivers is primarily carried out by the reworking of bed material (proximal incision) rather than lateral  
24 350 erosion of the former proximal outwash terraces (proximal contraction).

25 351 Average rates of longitudinal migration, elevation lowering and downstream migration of the inflection points  
26 352 were also computed for the proglacial rivers 2, 3, 4, 5, 8, 9, 11, 13 and 14 (Table 3). Rates of IP longitudinal  
27 353 migration average  $20.4 \text{ m.a}^{-1}$  ( $SD=13.6 \text{ m.a}^{-1}$ ) and range from  $5.2 \text{ m.a}^{-1}$  for the river 5 to  $46.4 \text{ m.a}^{-1}$  for the river 14.  
28 354 Altitudinal lowering rates of the inflection points average  $0.3 \text{ m.a}^{-1}$  ( $SD=0.15 \text{ m.a}^{-1}$ ) and range from  $0.09 \text{ m.a}^{-1}$   
29 355 for the river 9 to  $0.5 \text{ m.a}^{-1}$  for the river 14. The synthetic rates of IP downstream migration are similar to  
30 356 longitudinal migration rates (average =  $20.4 \text{ m.a}^{-1}$ ,  $SD=13.6 \text{ m.a}^{-1}$  and values range from  $5.2 \text{ m.a}^{-1}$  for the Virkisá  
31 357 to  $46.4 \text{ m.a}^{-1}$  for the Hoffellsá).

32 358 A category of proglacial rivers in which the downstream migration of the inflection point is rather slow can be  
33 359 identified. These are rivers 4, 5, 8, and 9, whose post-LIA average rates of IP longitudinal migration and  
34 360 elevation lowering are respectively lower than  $15 \text{ m.a}^{-1}$  and  $0.2 \text{ m.a}^{-1}$ . A second category of proglacial rivers  
35 361 (rivers 2, 11 and 14), exhibit the highest rates of IP longitudinal migration and elevation lowering, exceeding  $28$   
36 362  $\text{m.a}^{-1}$  and  $0.40 \text{ m.a}^{-1}$  respectively. Between these two categories, the rivers 13 and 3 display intermediate rates  
37 363 of IP longitudinal migration ( $16.85$  and  $26.5 \text{ m.a}^{-1}$  respectively) and IP elevation lowering ( $0.25$  and  $0.32 \text{ m.a}^{-1}$   
38 364 respectively). These results suggest that the proximal sediment deficit of the rivers 4, 5, 8 and 9 is less severe  
39 365 than for the rivers 2, 11, and 14, whose inflection points, and the spatial extent of proximal incision, rapidly  
40 366 migrated downstream.

41 367 Linear regression analysis (Figure 6-A) indicates that average rates of longitudinal migration and altitudinal  
42 368 lowering are significantly and positively correlated ( $R^2=0.791$ ,  $P=0.001$ ). It suggests that the overall process of  
43 369 post-LIA downstream migration of proximal incision involves the same proportion of longitudinal migration and  
44 370 elevation lowering of the IP whatever the intensity of the downstream migration.

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3 371 The stepwise multiple linear regression procedure test the dependency of the IP downstream migration rate on  
4 372 the landform assemblage of the proglacial margin and the post-LIA glacial retreat. The linear stepwise  
5 373 procedure only selected the proportion of proglacial lakes within the marginal landscape as a significant model  
6 374 parameter ( $t=3.527$ ,  $p=0.01$ ). The downstream migration rate of the inflection point is positively and  
7 375 significantly correlated with the percentage of proglacial lakes within the proglacial margin ( $R^2=0.640$ ,  $P=0.010$ ).  
8 376 According to this result (Figure 6-B), the development of large proglacial lakes in the glacier foreland increases  
9 377 the rate of that the IP migrates downstream.

#### 13 378 *Atypical outwash adjustments*

14 379 The outwash plains of the glaciers 1, 6 and 7 exhibit different post-LIA adjustments of their longitudinal profile  
15 380 (Figure 5). The outwash plain of glacier 1 has experienced an incision of its proximal part since the LIA  
16 381 maximum. However, no evidence of distal aggradation was found in the field. In addition, the post-LIA decrease  
17 382 of the proximal slope remains extremely low ( $0.013 \text{ m.m}^{-1}$  for T1 terrace versus  $0.012 \text{ m.m}^{-1}$  for the river in  
18 383 2007). The deep incising efficiency of recurrent volcanic jökulhlaups which affect the Glacier 1 glacier foreland  
19 384 may produce this uniform degradation of the entire outwash plain and inhibits post-LIA distal aggradation. The  
20 385 glacier 6 is also affected by volcanic jökulhlaups. Moreover, its outwash terrace T1 (Figure 5) constitutes the  
21 386 deposit of the historical jökulhlaup of 1727. The incision of this deposit may be independent of the fluctuations  
22 387 of the glacier front and is rather related to a progressive return of the river 6 to the pre-jökulhlaup conditions  
23 388 (Thompson & Jones, 1986). Alternatively, the case of the outwash plain 7 is more surprising: no incision of the  
24 389 abandoned and vegetated outwash plain was observed on the field. As mentioned above, the vegetated  
25 390 outwash plain of glacier 7 seems extremely recent (absence of lichens). Its abandonment by proglacial flows  
26 391 seems artificial and related to the embankment structure located on the right bank of the upstream reach of  
27 392 the river 7 (Figure 3). As a consequence, the abandoned outwash plain of the river 7 and the decrease in the  
28 393 lateral extent of the fluvio-glacial dynamic cannot be considered as a purely natural response of the proglacial  
29 394 river to glacial retreat. Alternatively, large alluvial fans located within the proglacial margin of this steep glacier  
30 395 may provide an abundant sediment supply that mitigates the marginal sediment deficit and inhibits proximal  
31 396 incision.

#### 41 397 *Local controls on the long profile of active outwash in 2007*

42 398 Long profiles of the active outwash of the glacier 4, 8, 10 and 13 (in 2007) reveal the local controls exerted by  
43 399 embankment structures or rocky outcrops on the efficiency of sediment transport. Indeed, these long profiles  
44 400 display significant decrease of local river slope values in the upstream vicinity of bridgeworks (related to the  
45 401 Icelandic Ring Road) or rocky outcrops. These zones force sediment deposition, related to dam effects and  
46 402 lateral constraints exerted by embankment and outcrops, and can hinder the downstream migration of  
47 403 sedimentary waves and mitigate the standard pattern of post-LIA adjustment of the outwash long profile by  
48 404 moderating proximal incision. Alternatively, the large alluvial fan located on the left bank of the river 14 seems  
49 405 to exert a control over the river long profile. A local increase in the slope value can be observed in the vicinity  
50 406 of the fan toe, probably due to lateral sediment contribution coming from the alluvial fan (Knighton, 1998).  
51 407 Conversely, the alluvial fan located on the left bank of the distal part of the outwash plain 2 does not seem to



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3 408 exert any control over the slope values of the active river in 2007. Nevertheless, it appears that presence of  
4 409 large active alluvial fans can also modify the post-LIA adjustment of the outwash long profile by exerting  
5 410 control over local slope values.  
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#### 8 412 **4. DISCUSSION**

##### 10 413 ***The dominant sequence of post-LIA outwash adjustment: a two-stage descriptive model***

11 414 According to our results, the dominant response of Type I (*sensu* Maizels, 1993) Icelandic proglacial rivers to  
12 415 post-LIA glacier retreat follow two successive stages: (1) a first stage of transient aggradation, or steady state,  
13 416 of the proximal outwash, (2) a second stage characterising by proximal incision, distal aggradation and the  
14 417 downstream migration of the inflection point (IP) which separates the upstream incising reach and the  
15 418 downstream aggrading reach of proglacial rivers.

##### 19 419 *Stage I: Outwash transient aggradation (or in balance), a paraglacial signature?*

20 420 During the first stage, even if the post-LIA glacial retreat is initiated, the outwash plain is still aggrading or, at  
21 421 least, kept in a steady state (Figure 7-A). Two explanations of this transient aggrading stage are possible: (1)  
22 422 The glacial front may have registered a slight retreat during stage I and experienced a steady period with minor  
23 423 seasonal fluctuations that maintain high glacial sediment supply to proglacial rivers in which aggradation  
24 424 continues (or remains in its LIA maximum state); (2) Alternatively, if the ice front registered a pronounced and  
25 425 continuous post-LIA retreat, the transient aggradation stage can only be related to efficient recharge of the  
26 426 marginal sediment stock by paraglacial processes and / or greater rates of subglacial sediment evacuation. In  
27 427 particular, in the early stages of deglaciation, thermokarstic processes, related to the dismantling of dead-ice  
28 428 moraines, may be able to compensate for the decrease of glacial sediment supply induced by glacial retreat  
29 429 for a time (Mercier *et al.*, 2009, Irvine-Fynn *et al.*, 2011). When the efficiency of subglacial sediment evacuation  
30 430 decrease, thermokarstic processes cease and the moraine ridges are stabilized, the paraglacial recharge of the  
31 431 proglacial fluvial system is no longer sufficient to maintain high sediment supply and stage I ends.

32 432 According to lichenometric dating of the first generation outwash terraces (T1), the duration of the transient  
33 433 aggrading stage is highly variable: it averages 61.8 years (SD= 40.48 years) and ranges between 5 ( $\pm 14$ ) and 147  
34 434 ( $\pm 15$ ) years. However, the range of duration of post-LIA transient aggradation stage of the South Icelandic  
35 435 fluvioglacial plains is in agreement with previous studies on the duration of paraglacial processes as effective  
36 436 sediment providers for the proglacial fluvial system. On the proglacial margin of the Small River Glacier in  
37 437 Canada, marginal deposits and mostly abandoned intra-morainic plains have been shown to cease to function  
38 438 as sediment sources after several decades (Orwin and Smart, 2004). Our results tends to support this  
39 439 hypothesis of a stabilization of morainic ridges and intra-morainic deposits within half a century or even a  
40 440 century. This period of time is too short to encompass all of what is commonly referred as the so-called  
41 441 paraglacial period (Ballantyne, 2002, Mercier, 2010, Cossart, 2005). More likely, the duration of stage I is only  
42 442 the time period during which the effectiveness of paraglacial processes is sufficient to, at least, keep the  
43 443 outwash plain in balance. As the marginal landscape differs widely from one glacier to another, the duration of  
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3 444 the transient aggrading period also varies accordingly. This variability may be related to the amount of the  
4 445 morainic sediment stock in the proglacial margin and its sensitivity to potential reworking processes.  
5 446 In particular, the presence of dead ice in the moraine deposits may play a major role in the initiation of debris  
6 447 flows eroding moraine ridges inducing the recharge of the proglacial fluvial system with paraglacial sediments  
7 448 (Church & Ryder, 1972, Church & Slaymaker 1989, Mercier, 2009).

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10 449 *Stage II: proximal incision, distal aggradation and downstream progression of incision wave*  
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12 450 The incision stage of the proximal outwash plain is initiated when the sediment stock of the proglacial margin is  
13 451 deficient and / or disconnected and the efficiency of paraglacial remobilization of the morainic and intra-  
14 452 morainic deposits is no longer sufficient to maintain the outwash plain in balance (Figure 7-A). The erodibility of  
15 453 the marginal sediment stock and the continuation of glacial retreat results in the lowering of the local base  
16 454 level which promotes stream captures within the proglacial margin. The occurrence of stream captures implies  
17 455 the abandonment by proglacial flows of former intra-morainic plains, often to the benefit of a single moraine  
18 456 breach which constitutes the favoured outlet of water and sediment flows to the outwash plain.  
19 457 This post-LIA response of the marginal channel network was also observed in Spitsbergen on the Lovén glacier  
20 458 margins (Griselin 1982, Mercier, 2001, Mercier & Laffly, 2005). The response of south-Icelandic outwash plains  
21 459 to post-LIA glacial retreat is the consequence of this marginal sediment deficit and the concentration of water  
22 460 and sediment flux at a single moraine breach: The sediment recharge of the outwash plain is primarily carried  
23 461 out by the incision of the proximal fluvio-glacial plain, resulting in the abandonment of the previous aggrading  
24 462 outwash plain and the contraction of the proximal fluvial activity width. The production of glaciofluvial  
25 463 sediments in the upstream incising reach caused further aggradation in the downstream reach. As the marginal  
26 464 sediment deficit continues, the degradation of the proximal outwash progresses downstream as an incision  
27 465 wave (Germanosky & Harvey, 1993). Rather than a uniform degradation of the outwash plain, the successive  
28 466 formation of different terrace generations reflect the crossing of geomorphological thresholds and the  
29 467 nonlinearity of the fluvio-glacial response to fluctuations of water and sediment fluxes. These crossing of  
30 468 geomorphological thresholds may be linked to abrupt variations in the efficiency of the marginal sediment  
31 469 connectivity caused especially by moraine dams and their failures (Cossart, 2008, Cossart & Fressard, 2017).  
32 470 Proglacial lakes within the marginal landscape also play a key role as they interrupt the delivery of water and  
33 471 sediment to the outwash plain (Schomacker, 2010; Carrivick & Tweed, 2013; Geilhausen, 2013; Bogen *et al.*,  
34 472 2015, Staines *et al.*, 2015). According to our results, the abundance of proglacial lakes within the proglacial  
35 473 margin speed up the downstream progression of the incision wave affecting proximal outwash. They clearly  
36 474 reduce the marginal sediment connectivity in trapping the coarsest part of the glacial sediment production.  
37 475 Thus, in a similar way to artificial dams, proglacial lakes deliver at their outlets “hungry water” prone to channel  
38 476 incision (Kondolf, 1997) and bed armoring (Vericat *et al.*, 2006). High-magnitude/low-frequency events  
39 477 emerging from proglacial lakes as outburst floods (Westoby *et al.*, 2014; Worni *et al.*, 2014), rainstorm floods  
40 478 (Marren & Toomath, 2013) and iceberg jam floods (Roussel *et al.*, 2016) may be able to temporarily reconnect  
41 479 the sediment connectivity between the proglacial lake and the outwash plain.

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49 480 ***Singularities in the dominant outwash adjustment model***  
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3 481 The dominant sequence of post-LIA response of the South Icelandic type I outwash developed above has to be  
4 482 qualified on the basis of field observations. The reported singularities are not major divergences from the  
5 483 overall logic of the dominant outwash plain adjustment. They rather reflect the effects of individual marginal  
6 484 landscape assemblages on the response of outwash plains to post-LIA glacial retreat.

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9 485 *Coalescent glacier fronts at the LIA maximum and stream capture*

10 486 The post-LIA response of the outwash plains 3, 5, 11 and 13 demonstrate that processes of marginal stream  
11 487 capture and large-scale shifts of the outwash location appear to be associated with a particular glacial  
12 488 configuration: Two coalescent lobes at the LIA maximum (Figure 7-B). As the contact between two glacier lobes  
13 489 is a preferential outlet for water and sediment fluxes (Thompson & Jones, 1986), the active proximal outwash  
14 490 plain is typically located downstream of the junction of the glacier fronts at the LIA glacial maximum. When the  
15 491 ice fronts of coalescent glaciers were disconnected following the post-LIA glacial retreat, the outwash plain  
16 492 shared by coalescent lobes was abandoned in favour of the intra-morainic plains of each of the two forefields  
17 493 which then developed two distinctive outwash plains. Downstream progression of incision waves and stream  
18 494 capture processes do not exclude each other. They may succeed each other in the history of outwash plain  
19 495 response to post-LIA glacial retreat.

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25 496 *Outwash incision prior to the LIA maximum*

26 497 Evidence of proximal outwash plain incision prior to the LIA maximum (proglacial rivers 3 and 4) suggests two  
27 498 alternative interpretations: (1) a lateral contraction and/or a stream capture and a shift in the location of the  
28 499 fluvial activity may occur during periods of glacial advance or glacial stagnation. In periods of glacial advance,  
30 500 this kind of adjustment may be related to the damming effect of proglacial moraine ridges which spatially  
31 501 constrain and channelize water and sediments flows; (2) A lateral contraction and/or a stream capture and a  
32 502 shift in the location of the fluvial activity may be caused by a transient retreat of the ice front during the LIA.  
33 503 The later advance of the ice front, up to the maximum glacial extension of the LIA, does not produce a  
34 504 sufficient aggradation or widening of the outwash plain to destroy or bury the glaciofluvial deposit built prior to  
35 505 the temporary LIA glacial retreat. These scenarios may explain the conservation of outwash terraces older than  
36 506 the LIA maximum.

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41 507 ***Deviation to the dominant outwash adjustment model: Jökulhlaups outwash (Type III)***

42 508 The glacial tongues of the glaciers 1 and 6 are known to be outlets of jökulhlaups triggered by subglacial  
43 509 eruptions (Sigurðsson, 1998). Our results show an alternative post-LIA response of the longitudinal profile of  
44 510 the outwash plains 1 and 6. The river 1 experienced an incision of its upper reach since the LIA maximum.  
45 511 However, no evidence of distal aggradation was found in the field. In addition, the post-LIA decrease in the  
46 512 proximal outwash slope remains extremely low ( $0.013 \text{ m.m}^{-1}$  for T1 and  $0.012 \text{ m.m}^{-1}$  for the active outwash). It  
47 513 suggests that the strong incisional power of the volcanic jökulhlaups that affect the foreland of glacier 1 is  
48 514 responsible for this uniform degradation of the outwash plain and the absence of distal aggradation. The  
49 515 outwash plain 6 is also affected by volcanic jökulhlaups (the outwash terrace T1 is the major deposit of the  
50 516 1727 historical jökulhlaup). Following Thompson & Jones (1986), we believe that the successive incisions of this  
51 517 inherited deposit are independent of the fluctuations of the glacier 6 and rather testify to the gradual return of

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3 518 the outwash plain to pre-jökulhlaup conditions. In more general terms, and as Nicholas & Sambrook-Smith  
4 519 (1998) suggest, in terms of morphogenesis and reworking of the fluvio-glacial sediment stock, the outwash  
5 520 plains impacted by jökulhlaups (Type III) are insensitive to the range of meltwater discharge associated with the  
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7 521 "normal" glacial ablation. The size of the material deposited during these catastrophic floods is beyond the  
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9 522 scope of seasonal proglacial flows. Consequently, the re-shaping of fluvio-glacial forms of type III outwash is  
10 523 totally independent of glacial fluctuations. Their fluvial morphogenesis seems to depend exclusively on the  
11 524 frequency and magnitude of volcanic jökulhlaups.

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## 14 526 **5. CONCLUSION**

15 527 Mapping, lichenometric dating and long-profiles surveys of Icelandic proglacial margins, glacio-fluvial terraces  
16 528 and active proglacial rivers permit to address the threefold aims of this study: (1) Proximal incision, associated  
17 529 with distal aggradation and downstream migration of the inflection point, is the dominant pattern of proglacial  
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19 530 river response to post-LIA glacier retreat in Iceland. The post-LIA contraction and incision of Icelandic proximal  
20 531 outwash plains usually occurs after a first transient aggradation or steady state stage of proximal outwash  
21 532 (duration ranges between  $5 \pm 14$  and  $147 \pm 15$  years) which may be related to efficient recharge of the marginal  
22 533 sediment stock by paraglacial processes and / or greater rates of subglacial sediment evacuation. Proximal  
23 534 incision, distal aggradation and downstream migration of the inflection point can precede or be preceded by  
24 535 stream capture phenomena which particularly affects marginal landscapes where two glacier fronts were  
25 536 coalescent at the LIA maximum. Outwash plain incision prior to the LIA maximum have been observed and may  
26 537 be related to damming effect of proglacial moraine ridges or transient glacial retreat during the LIA. Two  
27 538 proglacial rivers affected by historical jökulhlaups exhibit an alternative adjustment rather controlled by  
28 539 extremes events than by glacier retreat. (2) The mean rates of downstream migration of the inflection point  
29 540 average  $20.4 \text{ m.a}^{-1}$  ( $SD=13.6 \text{ m.a}^{-1}$ ) and range from  $5.2 \text{ m.a}^{-1}$  for the river 5 to  $46.4$  for the river 14. IP migration  
30 541 results suggest that the proximal sediment deficit of the rivers 4, 5, 8 and 9 is less severe than for the rivers 2,  
31 542 11 and 14, whose inflection points, and the spatial extent of proximal incision, rapidly migrated downstream.  
32 543 (3) The downstream migration rate of the inflection point is positively correlated with the proportion of  
33 544 proglacial lakes within the glacier foreland. These findings suggest that proglacial margins dominated by  
34 545 proglacial lakes intensify the rates of the fluvial adjustment to glacial retreat.

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832 **Figures and Tables**

833 Figure 1: Location of investigated glaciers and associated proglacial rivers



- 834 Figure 2: Methodological workflow: A - Field prospection and GIS mapping of proglacial and glaciofluvial  
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- 843 Figure 7: A - The dominant sequence of post-LIA fluvial adjustment: a two-stages descriptive model. B - LIA  
 844 coalescent glaciers specific case, with stream capture and shift in the outwash location.
- 845 Table 1: Main characteristics of glaciers and associated proglacial rivers investigated in this study.

ID	Name	LIA max dating (cal. yr. AD)*	Confidence interval*	Glacier					River		
				Glacier Area (Km <sup>2</sup> )	Glacier length (km)	Glacier Slope (°)	Elevation max (m a.s.l.)	ELA (m a.s.l.)**	name	Outwash Type***	
1	Sólheimajökull	1851	(1839 - 1863)	46.7	15.4	5.1	1480	na	Jökulsá	Type III	
2	Morsárjökull	1888	(1873 - 1903)	26.3	13.1	6.2	1421	1000-1130	Morsá	Type I	
3	Skaftafelljökull	1878	(1864 - 1892)	87.0	19.0	6.6	1889	1000-1160	Skaftafellsá	Type I	
4	Svínafellsjökull	1765	(1749 - 1776)	31.7	12.7	12.4	2104	1000-1120	Svínafellsá	Type I	
5	Virkisjökull	1740	(1731 - 1755)	20.6	11.3	10.7	2076	na	Virkisá	Type I	
6	Kotárjökull	1819	(1809 - 1828)	6.1	6.6	12.8	1840	1000-1130	Kotá	Type III	
7	Hólárjökull	1844	(1838 - 1857)	5.2	6.9	12.9	1838	na	Holá	Type I	
8	Kvíárjökull	1810	(1798 - 1824)	18.6	11.7	10.3	2010	1010-1130	Kvíá	Type I	
9	Hrútárjökull	1812	(1805 - 1820)	11.9	8.5	14.6	2027	880-910			
10	Fjallsjökull	1812	(1798 - 1833)	48.8	13.4	9.1	2040	870-960	Fjallsá	Type I	
11	Skálafellsjökull	1865	(1856 - 1876)	136.2	32.4	3.3	1520	910-1020			
12	Heinabergsjökull	1851	(1835 - 1865)	93.8	23.5	4.8	1520	990-1100	Kolgrimá	Type I	
13	Fláajökull	1821	(1811 - 1834)	213.1	29.1	3.3	1520	1060-1120	Hólmsá	Type I	
14	Hoffellsjökull	1888	(1874 - 1898)	246.0	32.0	3.3	1512	1050-1120	Hoffellsá	Type I	

\* after Chenet *et al.*, 2010 and Roussel *et al.*, 2008 ; \*\* after Chenet *et al.*, 2010 and Hannesdóttir *et al.*, 2014 ; \*\*\* after Maizels, 1993, 1997 ; "na" for not available

ID	Glacier	Deglaciated surface since the LIA (km <sup>2</sup> )	Computed average linear retreat (m)	Measured linear retreat (m)	Alluvial fan		Rocky outcrop		Fresh proximal till deposits		Intra-morainic lake		Proglacial lake		Moraine		Active intra-morainic plain		Abandoned intra-morainic plain		Embankment		TOTAL
					m <sup>2</sup>	%	m <sup>2</sup>	%	m <sup>2</sup>	%	m <sup>2</sup>	%	m <sup>2</sup>	%	m <sup>2</sup>	%	m <sup>2</sup>	%	m <sup>2</sup>	%	m <sup>2</sup>	%	
1	Sólheimajökull	2.1	888	1211	0	0.0	256366	12.4	299121	14.4	13921	0.7	0	0.0	467737	22.6	569831	27.5	466563	22.5	0	0.00	2073538
2	Morsárjökull	2.6	2047	1643	0	0.0	0	0.0	202767	8.5	4981	0.2	334873	14.0	870060	36.4	114907	4.8	862098	36.1	0	0.00	2389686
3	Skaftafelljökull	7.1	2420	2044	0	0.0	0	0.0	237577	3.4	154871	2.2	233199	3.3	3528684	49.8	819307	11.6	2110658	29.8	2521	0.04	7086818
4	Svínafellsjökull	1.6	566	877	0	0.0	0	0.0	228231	14.1	18155	1.1	75034	4.6	1211262	74.7	77301	4.8	10581	0.7	0	0.00	1620564
5	Virkisjökull	1.2	827	1157	0	0.0	0	0.0	140826	11.9	3088	0.3	0	0.0	336390	28.4	98437	8.3	603721	51.1	0	0.00	1182463
6	Kotárjökull	0.5	404	587	0	0.0	99918	20.6	0	0.0	0	0.0	0	0.0	321017	66.1	25122	5.2	39893	8.2	0	0.00	485950
7	Hólárjökull	0.5	774	1258	70171	13.7	0	0.0	19702	3.8	0	0.0	0	0.0	176764	34.4	80554	15.7	166569	32.4	0	0.00	513760
8	Kvíárjökull	5.3	1199	1631	0	0.0	0	0.0	1009960	19.0	25342	0.5	172200	3.2	3135337	59.1	342038	6.4	624307	11.8	0	0.00	5309185
9	Hrútárjökull	2.3	1665	1950	319076	14.1	0	0.0	172327	7.6	10191	0.5	0	0.0	1059046	46.9	544421	24.1	152509	6.8	0	0.00	2257570
10	Fjallsjökull	7.3	1071	1601	0	0.0	0	0.0	203291	2.8	161030	2.2	2113291	29.0	3873712	53.1	434737	6.0	507985	7.0	0	0.00	7294046
11	Skálafellsjökull	9.5	3544	2121	0	0.0	5726805	60.3	220745	2.3	101078	1.1	112348	1.2	1709461	18.0	923917	9.7	708383	7.5	0	0.00	9502737
12	Heinabergsjökull	8.7	1810	3171	0	0.0	67878	1.3	186334	3.6	70993	1.4	1689050	32.6	2687400	51.9	30710	0.6	441328	8.5	0	0.00	5173693
13	Fláajökull	15.1	2562	2429	0	0.0	785263	5.2	236760	1.6	374913	2.5	1246571	8.2	7609144	50.3	1359487	9.0	3500009	23.1	13708	0.09	15125855
14	Hoffellsjökull	0.7	160	335	0	0.0	0	0.0	0	0.0	0	0.0	500736	72.8	186911	27.2	0	0.0	0	0.0	0	0.00	687647
				<b>TOTAL</b>	389247	0.6	6936230	11.4	3157642	5.2	938563	1.5	6477302	10.7	27172926	44.8	5420769	8.9	10194605	16.8	16229	0.03	60703512

847 Table 2: Post-LIA glacier retreat and landform assemblages of proglacial margins

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850 Table 3: Outwash responses to post-LIA glacial retreat

ID	Glacier name	River name	Outwash Type*	Duration of aggradation on stage (yr)	Post-LIA proximal incision (m.a <sup>-1</sup> )	Post-LIA decrease of proximal slope (m.m <sup>-1</sup> )	Average IP longitudinal migration (m.a <sup>-1</sup> )	Average IP altitudinal lowering (m.a <sup>-1</sup> )	Average IP downstream migration (m.a <sup>-1</sup> )
1	Sólheimajökull	Jökulsá	Type III	41 (±16)	0.047 (±0.002)	0,00057	<i>na</i>	<i>na</i>	<i>na</i>
2	Morsárjökull	Morsá	Type I	51 (±18)	0.045 (±0.006)	0,00584	28,7	0,44	28,68
3	Skaftafelljökull	Skaftafellsá	Type I	<i>na</i>	<i>na</i>	0,0206	26,5	0,32	26,47
4	Svínafellsjökull	Svínafellsá	Type I	<i>na</i>	<i>na</i>	0,0044	8,9	0,13	8,91
5	Virkisjökull	Virkisá	Type I	147 (±15)	<i>na</i>	0,0157	5,2	0,19	5,21
6	Kotárjökull	Kotá	Type III	<i>na</i>	<i>na</i>	0,0177	<i>na</i>	<i>na</i>	<i>na</i>
7	Hólárjökull	Holá	Type I	<i>na</i>	0	0	<i>na</i>	<i>na</i>	<i>na</i>
8	Kvíárjökull	Kvíá	Type I	60 (±21)	0.076 (±0.004)	0,0122	6,6	0,20	6,57
9	Hrútárjökull	Fjallsá	Type I	79 (±25)	0.068 (±0.003)	<i>na</i>	14,0	0,09	13,97
10	Fjallsjökull								
11	Skálafellsjökull	Kolgrímá	Type I	5 (±14)	<i>na</i>	<i>na</i>	30,3	0,47	30,34
12	Heinabergsjökull								
13	Fláajökull	Hólmsá	Type I	<i>na</i>	<i>na</i>	0,0108	16,9	0,25	16,86
14	Hoffellsjökull	Hoffellsá	Type I	50 (±20)	0.131 (±0.012)	0,0056	46,4	0,5	46,38

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\* After Maizels, 1993, 1997, "na" for not applicable



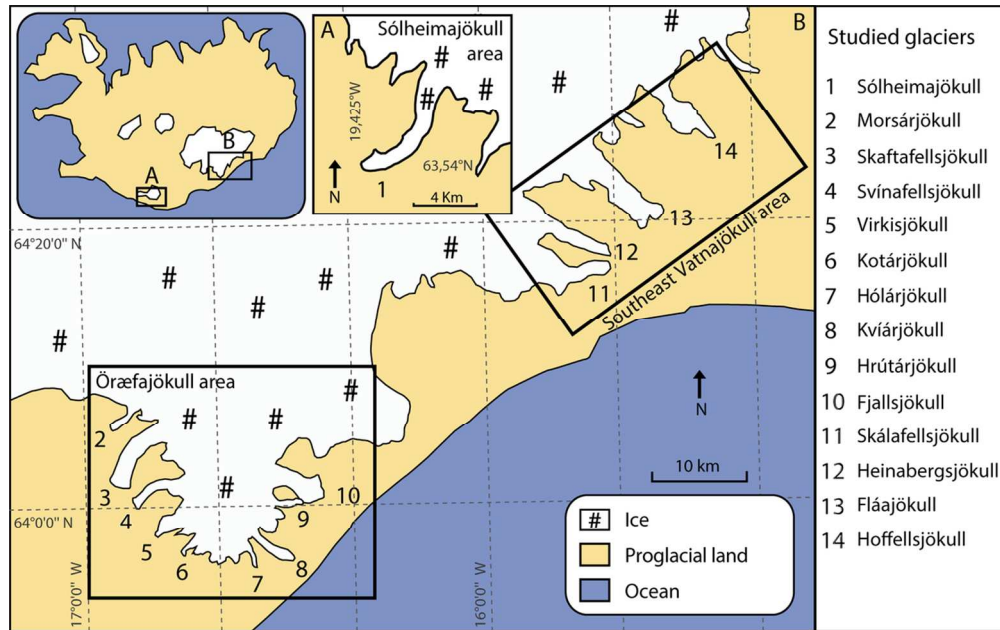


Figure 1: Location of investigated glaciers and associated proglacial rivers

110x69mm (300 x 300 DPI)

Review

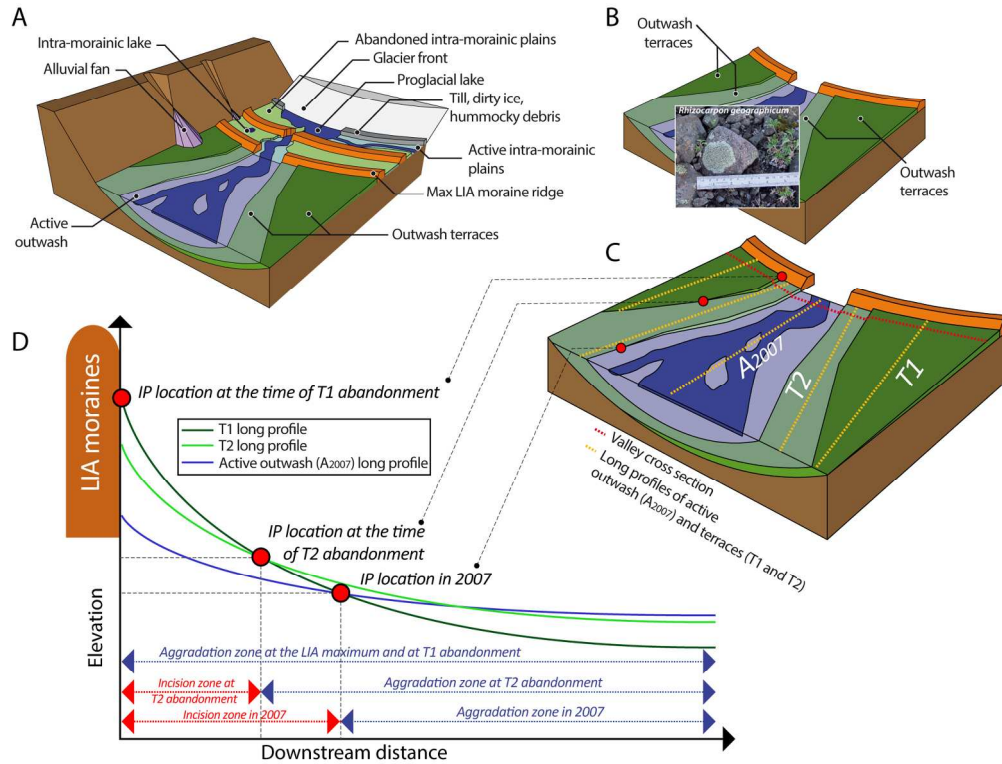


Figure 2: Methodological workflow: A - Field prospection and GIS mapping of proglacial and glaciofluvial landforms ; B - Lichenometric dating of outwash terraces ; C - Topographic survey: Cross section and long profile of active outwash and terraces ; D - Method for the determination of the Inflection Point migration

170x129mm (300 x 300 DPI)

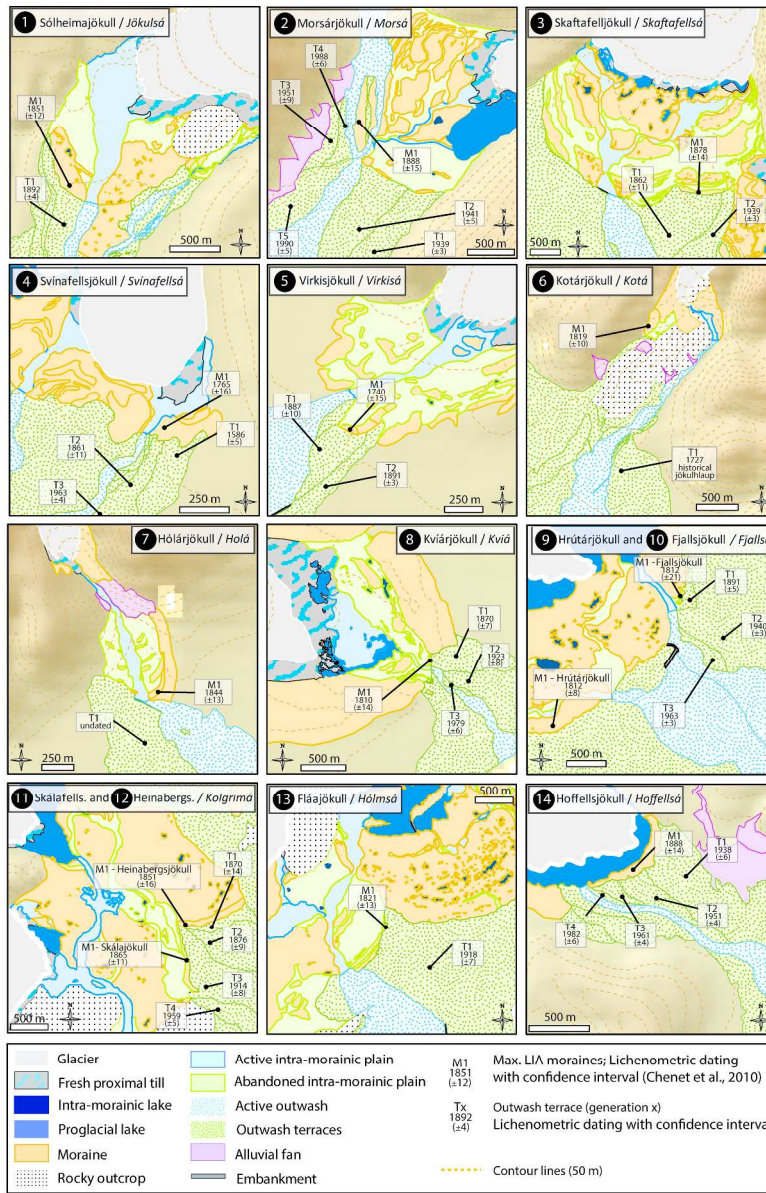


Figure 3: Outwash terraces mapping and dating

275x414mm (300 x 300 DPI)

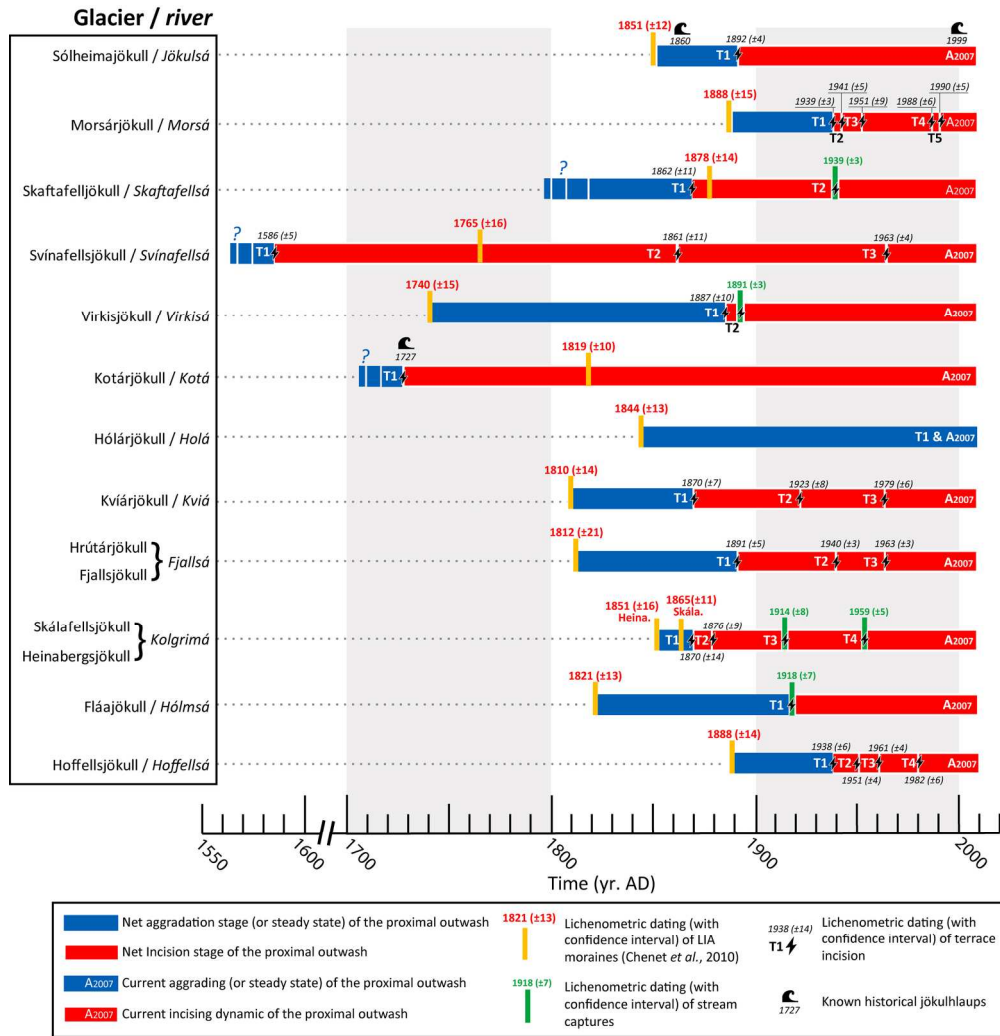


Figure 4: Overview of aggrading and incising stages in the post-LIA outwash adjustment

182x188mm (300 x 300 DPI)



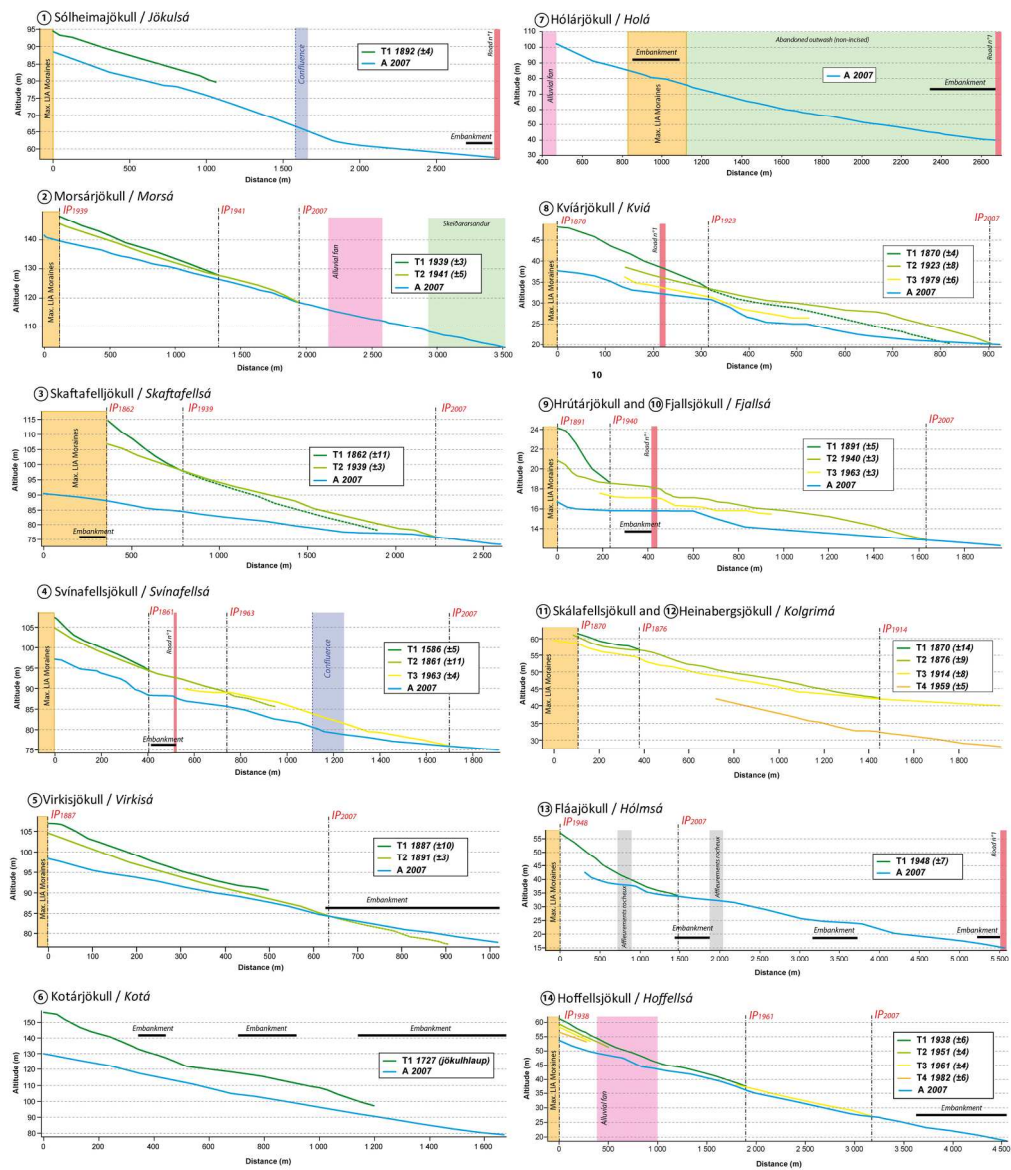


Figure 5: Long profiles of dated outwash terraces (T1 to T4) and active outwash in 2007 (A)

202x233mm (300 x 300 DPI)

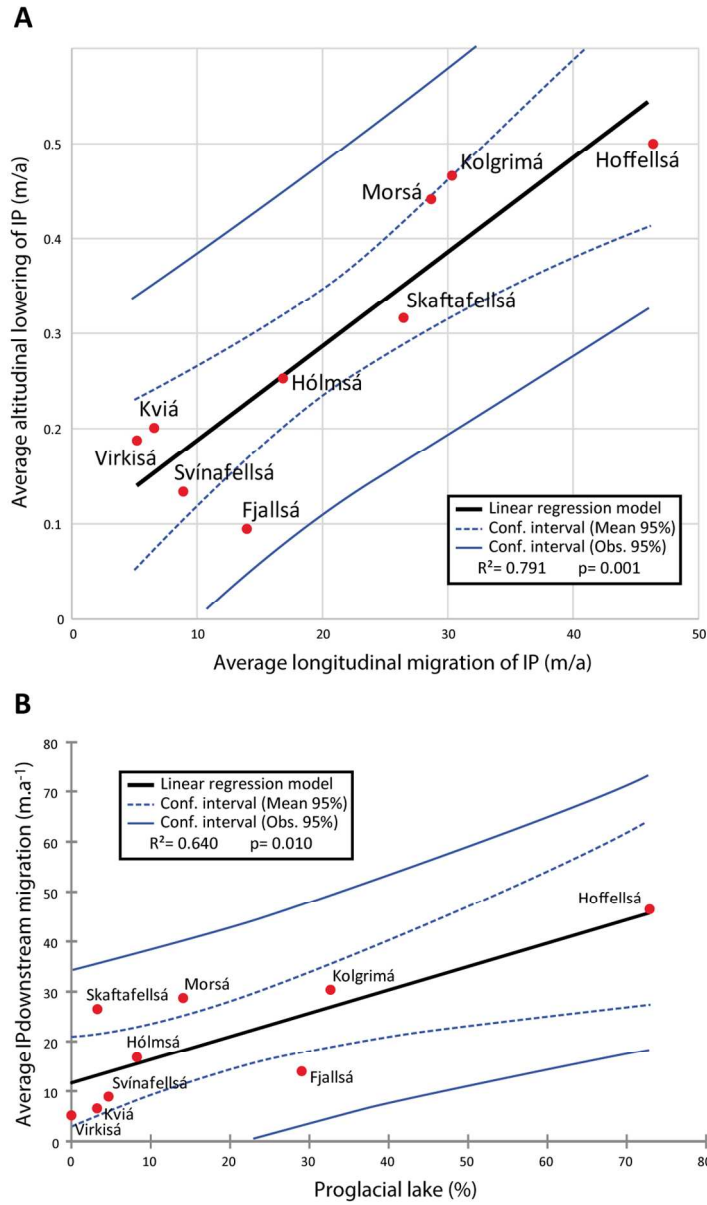


Figure 6: A - Linear regression between average rates of altitudinal lowering and longitudinal migration of the inflection points. B - Linear regression between average rates of IP downstream migration and the proportion of proglacial lakes in the marginal area.

90x154mm (300 x 300 DPI)



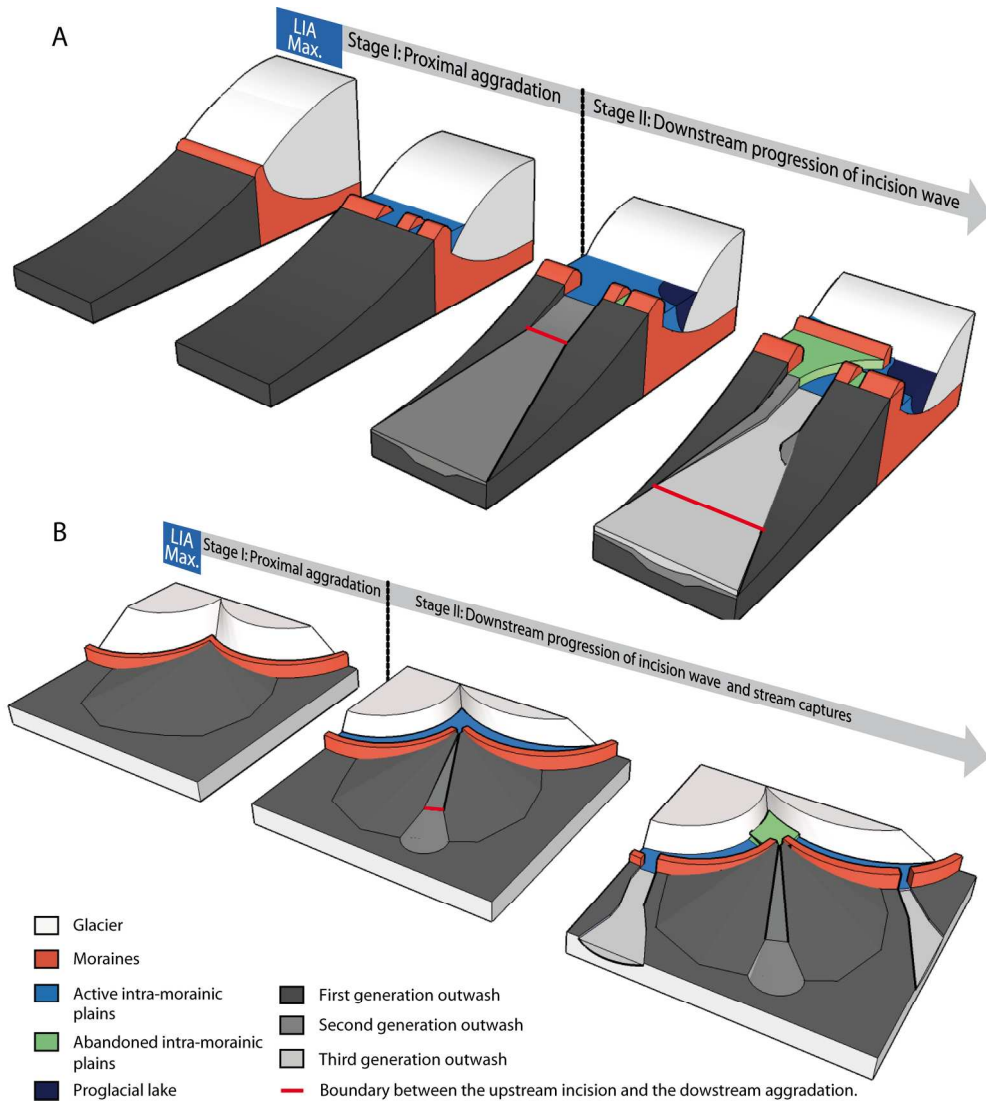


Figure 7: A - The dominant sequence of post-LIA fluvial adjustment: a two-stages descriptive model. B - LIA coalescent glaciers specific case, with stream capture and shift in the outwash location.

192x209mm (300 x 300 DPI)