



**HAL**  
open science

## A new approach to estimating hazard posed by debris flows in the Westfjords of Iceland

Conway Susan, Armelle Decaulne, Balme Matthew R., Murray John B.,  
Towner M.C.

### ► To cite this version:

Conway Susan, Armelle Decaulne, Balme Matthew R., Murray John B., Towner M.C.. A new approach to estimating hazard posed by debris flows in the Westfjords of Iceland. *Geomorphology*, 2010, pp.556-572. 10.1016/j.geomorph.2009.08.015 . hal-00826916

**HAL Id: hal-00826916**

**<https://hal.science/hal-00826916>**

Submitted on 30 Nov 2020

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **A new Approach to Estimating Hazard posed by Debris Flows in the**  
2 **Westfjords of Iceland**

3 Conway, S. J.<sup>a</sup> (corresponding author), Decaulne, A.<sup>b</sup>, Balme, M. R.<sup>a</sup>, Murray, J. B.<sup>a</sup> and  
4 Towner, M. C.<sup>c</sup>

5 <sup>a</sup> Department of Earth and Environmental Sciences, Open University, Milton Keynes  
6 MK7 6AA, UK. s.j.conway@open.ac.uk tel:+44 (0)1908 659777 fax:+44 (0)1908 655151

7 <sup>b</sup>University Blaise Pascal, CNRS UMR6042 Geolab, Clermont-Ferrand, France.

8 <sup>c</sup>Impacts and Astromaterials Research Centre, Department of Earth Science and  
9 Engineering, Imperial College London, SW7 2AZ, UK.

10 **Abstract**

11 The aim of this study is to improve the assessment of hazard posed by debris flows to  
12 the people and settlements of northwest Iceland by studying very recent examples from above  
13 the town of Ísafjörður and other nearby localities. Debris flows are a recognised hazard in the  
14 region: above Ísafjörður, they occur with particularly high frequency and have appreciable  
15 volumes (up to 14 000 m<sup>3</sup>). We have used airborne laser altimeter (LiDAR) and differential  
16 Global Positioning System (GPS) data to produce isopach maps of flows that occurred in  
17 1999, 2007, and 2008. Our data show that these flows begin depositing at higher slope  
18 gradients and are also more mobile than hillslope debris flows reported by other authors.  
19 Above a 19° slope, erosion is initiated independent of the distance along the flowpath. Using  
20 the isopach maps and associated field observations, we have found a relationship between  
21 ground slope and patterns in deposition volume. We have used this finding as a basis for an  
22 empirical model that enables an estimate of the total travel distance and final thickness of  
23 future debris flows to be calculated. This has enabled us to identify areas of the town which  
24 are at risk; some of these are not obvious without this analysis. This model is notable for its  
25 simplicity, which allows future debris flow characteristics to be predicted without the need to

26 determine the precise fluid dynamic parameters of the flow such as viscosity and velocity,  
27 which are required to implement more complex models.

28

29 *Keywords:* debris flow; Icelandic Westfjords; geohazards; LiDAR

## 30 **1. Introduction**

### 31 *1.1. Background*

32 Debris flows move at great speed (e.g., 0.8-28 ms<sup>-1</sup> from debris flows measured in the  
33 field; Rickenmann, 1999) and are able to carry metre-size boulders (e.g., Clague et al., 1985;  
34 Kanji et al., 2008). They have great destructive ability and can pose a significant hazard to  
35 people and infrastructure. We have begun a new study in the Westfjords region, situated in  
36 the north-western tip of Iceland (Fig. 1), where the infrastructure and local population are at  
37 considerable risk from a variety of slope-process hazards, including avalanches, landslides,  
38 slush-flows, rock falls, and debris flows. Many recent incidents related to snow avalanches  
39 have been serious: for example, 20 people died in a single avalanche in Flateyri in 1995  
40 (Arnalds et al., 2004). These events have stimulated study of these processes in this region,  
41 and as a result government agencies have defined hazard zones (Arnalds et al., 2002). Debris  
42 flows have not caused major loss of life in this area in recorded history (Decaulne et al.,  
43 2005), but with the expansion of the traditional settlements from spits in the middle of the  
44 fjords toward the hillslope, it becomes increasingly likely that a debris flow event will occur  
45 that results in considerable destruction or death. Residents report the frequent blocking of  
46 roads by debris flows, and in 1999 several flows overcame the lower slope ditch (marked in  
47 Fig. 2), which was built to protect the town and damaged houses in Ísafjörður (Decaulne et  
48 al., 2005). The main purpose of this study is to reassess the hazard posed to these new  
49 settlements using improved data on recent debris flows.

50

51 **[Fig. 1 here]**

52

53       The focus of debris flow hazard prediction models is skewed toward so-called confined  
54 debris flows, which travel along confined preexisting channels or torrents and emerge on to  
55 alluvial or debris fans (Rickenmann, 1999; Berti and Simoni, 2007; Gartner et al., 2008;  
56 Prochaska et al., 2008). In contrast, few studies concentrate on the hazard posed by hillslope-  
57 style debris flows (Fannin and Wise, 2001), which are not restricted by preexisting valleys  
58 over the majority of their length. Hillslope debris flows are common in steep terrain  
59 throughout the world; however, these types of flows form significant recognised hazards in  
60 Iceland (Decaulne and Sæmundsson, 2007) and Scandinavia (Rapp and Stromquist, 1976).

61       This study presents new results from quantification of the volume and pattern of debris  
62 flow deposits using topography digital elevation models (DEMs) generated from differential  
63 GPS (global positioning system) measurements, and from LiDAR (light detection and  
64 ranging) data. This aim of this study is to improve hazard assessment in the region by  
65 empirical description of hillslope debris flows.

## 66 *1.2. Regional setting*

67       Our study area in the Westfjords area of Iceland (Fig. 1) is a typical post-glacial  
68 landscape consisting of deep fjords cut into a sequence of basaltic lava flows of Miocene age  
69 (~ 15 Ma). The hillsides in the Westfjords area rise from sea level to 700 m with average  
70 slope angles of 25-35°. The slopes are rocky and poorly vegetated; the dominant species are  
71 grasses and mosses on the soils and lichens on the rocks. The fjords themselves are incised  
72 into 2-30 m thick layers of basalt rock, which dip gently toward the SE (Decaulne et al.,  
73 2005). The slopes are very steep in the upper portion (~ 45°) and often form bedrock cliffs.  
74 The lower slopes comprise talus and relict debris flow deposits. The channels that dissect  
75 these slopes are principally incised by debris flows. These channels can lie as close together  
76 as 15 m, are densely packed along most of the slopes in the study area, and often span the  
77 entire slope from top to bottom (up to 1.5 km in places). The area retains many inherited

78 glacial features as well as active paraglacial features that include solifluction lobes and thick  
79 surface deposits of till on flat surfaces. Active slope processes are common here, most  
80 probably as a result of the post-glacial slope readjustment that has been ongoing over the last  
81 10 ka since glacial retreat (Norðdalh, 1990). The temperatures in the area usually vary  
82 between -5 and 10°C with the 30 year mean annual precipitation being ~2000mm/yr. Much  
83 of the precipitation falls as snow and snow patches can be preserved in shadow into the  
84 summer months. The maritime position of the Westfjords means that snow cover can be very  
85 variable and liable to thaw suddenly even in winter.

86

87 **[Fig. 2 here]**

88

89 The town of Ísafjörður is mostly located on a spit formed by the action of the sea, with  
90 expansion of the town over the last 50 years being accommodated along the basal slopes of  
91 the fjord. The slope above Ísafjörður (Fig. 2C) is interrupted at ~ 450 m altitude by the  
92 Gleiðarhjalli bench, which slopes gently to the SE and is covered by ~ 30 m of glacial  
93 sediments; these comprise gravelly to silty sand and subangular to subrounded clasts that  
94 range in size from centimetre to metre. On top of these deposits lie many centimetres to  
95 metres sized angular clasts derived from frost shattering of the bedrock and glacial clasts  
96 themselves. These sediments reach the angle of repose very quickly, as frost shattering  
97 promotes erosion of the bedrock cliff at their base and creep pushes the sediment body  
98 forward toward the bench edge. This means that the debris flows above Ísafjörður are not  
99 supply limited, but limited by the frequency of triggering events, unlike most other flows in  
100 the area (Glade, 2005).

101 Debris flows in this area are triggered by rapid snowmelt or prolonged rainfall (Decaulne  
102 et al., 2005; Decaulne and Sæmundsson, 2007). These processes saturate the sediment stack,

103 which further destabilises the already unstable sediments. A debris flow is then triggered as a  
104 result of undercutting of these sediments by water emerging from beneath the sediment stack  
105 at the interface with the basalt bedrock. Rockfalls originating at the exposed edge of the  
106 debris stack have been observed immediately prior to a debris flow and are a probable cause  
107 of failure (Decaulne et al., 2005). The glacial till fails by rotational sliding and then forms a  
108 debris flow.

109 The mean interval between large flows is only five years (Decaulne et al., 2005). On  
110 other slopes in Iceland, debris flows are much less frequent and generally smaller because  
111 they are supply limited (Glade, 2005) — the debris on the slopes must reach a certain  
112 thickness and steepness before it can slide (Ballantyne and Benn, 1994; Wilkerson and  
113 Schmid, 2008). The debris flows above the town of Ísafjörður provide a unique opportunity  
114 to study debris flows because (i) the frequency of large events is unusually high and (ii) the  
115 majority of the deposits are preserved on the slopes. This means that we have the opportunity  
116 to study very fresh debris flows in which the influence of post-depositional reworking is  
117 minimised, thus allowing more accurate quantification of erosion and deposition volumes and  
118 patterns.

119 In addition to the SE-facing slope above Ísafjörður, two additional sites (Figs. 2A and  
120 2B) were selected because they had also experienced fresh debris flows just prior to the field  
121 visits in 2007 and 2008. Firstly, we studied an area to the south of Hnífsdalur, a village  
122 located to the north of Ísafjörður. Debris flows are much less frequent here than in Ísafjörður,  
123 but we investigated a small fresh flow sourced from the soil mantle on the slope above the  
124 valley road, which occurred here in late spring or early summer 2007. This flow originated, in  
125 all likelihood, as a failure triggered by concentration of overland flow that then eroded  
126 downslope before deposition. Secondly, on the north side of Súgandafjörður, debris flows  
127 regularly block the road and two fresh flows had cut off the road between Botn and Grensfjall

128 between the 2007 and 2008 field visits. The flows originate by the “fire hose” (e.g., Johnson  
129 and Rodine, 1984; Coe et al., 2007; Carrara et al., 2008) mechanism in alcoves cut into the  
130 bedrock cliffs bounding the fjord. This triggering mechanism is characterised by the  
131 concentration of overland flow by chutes or depressions in the bedrock that evolves into a  
132 debris flow as it picks up material from the slope where it emerges. This material has to build  
133 up by weathering and erosion of the bedrock before a debris flow can be formed (as for  
134 Glade, 2005), hence the time between large events is much longer than at Ísafjörður. The  
135 source material is the product of frost shattering of material that has collected in these alcoves  
136 under the action of gravity. Interestingly, the flows did not originate from the top of the fjord  
137 (700 m asl) but from material accumulated at ~ 500 m or lower.

138

## 139 **2. Materials and methods**

### 140 *2.1. Previous work and methodology for this study*

141 Debris flow volumes are usually estimated from either the failure scar (e.g. Gabet and  
142 Bookter, 2008) or the deposits themselves (e.g. Decaulne et al., 2005). Traditionally this is  
143 done by measuring cross sections and long sections of the features, although the precise  
144 method and associated errors are rarely reported (e.g., Rapp and Nyberg, 1981; Gardner,  
145 1989; Okuda, 1989; Decaulne et al., 2005). Exceptions to this include Santi et al. (2008), who  
146 report errors as small as  $\pm 23\%$  on volume estimation using the cross section technique with  
147 a slope profiler. They take into account the variation in technique between individuals and the  
148 use of differing locations for the cross sections, but do not include an error associated with  
149 estimating the pre-flow topography. A report that examined methods for estimating the  
150 erosion volumes removed by rills (Casali et al., 2006) recommended that sampling by  
151 microtopographic profile meter, which produces 50 points over 1 m to get an error of  $< 10\%$   
152 in volume calculation.

153 Empirical estimates of volumes have been derived from morphological data (e.g.,  
154 Larsson, 1982; Innes, 1983; Fannin and Wise, 2001), but these rely on a large sample size  
155 and their applicability varies by region. Empirical relationships from large data sets relating  
156 volumes, total travel distance, and other dimensions have been found for confined debris  
157 flows (Rickenmann, 1999) and hillslope debris flows (Lorente et al., 2003), but neither of  
158 these empirical approaches give information on the structure and pattern of deposition and  
159 erosion. Iverson, et al. (1998) produced a widely applied model called LAHARZ, which  
160 calculates the inundation of a debris flow given a DEM. This routine produces a set of  
161 potential debris flow inundation zones with an associated hazard rating based on their  
162 statistical analysis. It is based on empirical equations relating cross sectional area and  
163 inundation area to total volume. However, this analysis is not reliable if the flows are  
164 unconfined over most of their length, as the equations are derived from the study of 27  
165 confined lahars originating from nine volcanoes. It does not attempt to estimate eroded  
166 volumes or deposition volumes along the flow. Fannin and Wise (2001) produced an  
167 empirical–statistical model that calculates erosion and deposition per reach of the flow, with  
168 the equations dependent on whether the flow is confined, transitional, or unconfined. It is  
169 based on the study of 449 debris flow events in Queen Charlotte Islands, British Columbia,  
170 Canada. This model comes closer than other empirical models to describing the realistic  
171 behaviour of debris flows without full flow dynamic modelling.

172 Repeat stereo photogrammetry has been used to estimate overall slope denudation (Coe  
173 et al., 1997; Breien et al., 2008). Coe et al. (1997) used a 2 x 2 m grid and achieved a volume  
174 error of  $\pm 5\%$ . Breien et al. (2008) used a 3.3 x 3.3 m grid and achieved an error of  $\pm 10\%$ .  
175 Neither study revealed the fine-scale structure of the debris flows (e.g., the levees were  
176 poorly resolved). In landslide studies LiDAR is often used in conjunction with other datasets,  
177 e.g., Chen et al. (2006) used DEMs derived from photogrammetry to compare with LiDAR



178 topography. However, the lower accuracy of the photogrammetry and the difficulty in  
179 georeferencing all the datasets meant that the authors were only able to detect 10-100 m  
180 vertical changes. Good results have been obtained by comparing repeated LiDAR surveys  
181 (Scheidl et al., 2008) with estimated errors in the volume calculation ranging from just 9% up  
182 to 55%. No repeat LiDAR surveys have been performed in the Westfjords area, so we have  
183 used a combination of LiDAR data and differential GPS data to quantify the changes in  
184 morphology along the debris flows.

## 185 *2.2. Data collection*

186 Eight debris flows were surveyed using a Leica System 500 differential GPS (Fig. 2) in  
187 2007-2008. Five debris flows were examined on the slopes above Ísafjörður (Fig. 2C): one on  
188 the slope above Hnífsdalur in the adjacent valley (Fig. 2B), and two on the east slopes of  
189 Súgandafjörður (Fig. 2A). The relative timing of the activity of the debris flows in this study  
190 is shown in Table 1. A base GPS unit was positioned at the foot of the slope within 3 km of  
191 the rover GPS units. Point elevation data were collected by two roving units, with the  
192 operator collecting three or more epochs of data per point. To ensure high quality, data were  
193 not collected when the Global Dilution of Precision (GDOP) value (which is calculated real-  
194 time from relative satellite positions) was  $> 7$ . A Leica System 800 Total Station (TPS) was  
195 used to collect additional data in 2008. The location and orientation of the TPS was obtained  
196 by collecting shared points with the GPS. The TPS collects point elevation data using a laser  
197 ranger equipped with accurate internal determinations of horizontal and vertical angles. The  
198 TPS could collect points at a maximum distance of 450 m.

199 Four main types of sampling were performed:

- 200 (i) channel long profile: recording the lowest point between the levees;
- 201 (ii) levee long profile: recording the maximum elevation of the levees on each side of the  
202 channel;

203 (iii) cross profiles: taken at ~ 50 m intervals (10 m for 5DF, 20 m for 7,8,10DF) along the  
204 debris flow; and  
205 (iv) debris flow edge: only measured if the flow was well defined.

206 For each of these methods the topography was sampled at 0.5-2.0 m intervals, with more  
207 frequent sampling used where the topography changed more rapidly. This frequency of cross  
208 sections follows the scaled-up methodology advised by Casali et al. (2006).

209 The GPS data were supplemented with LiDAR data acquired using an Optech  
210 ALTM3033 instrument and aerial photography taken with a Leica-Wild RC10. These data  
211 were collected on 5 August 2007 by the U.K. Natural Environment Research Council's  
212 Airborne Research and Survey Facility (NERC ARSF; Fig. 1). Seventeen flight lines were  
213 flown allowing the collection of 63 million LiDAR points and 63 aerial photographs. The  
214 aerial photographs were orthorectified, mosaiced, and georeferenced using BAE System's  
215 SocetSet software.

216 Further processing of the LiDAR data was required to correct for between-track  
217 horizontal shifts of up to 2 m, which in steep areas results in an equivalent magnitude of  
218 vertical error. This problem has been highlighted by Favalli et al. (2009) and they state that  
219 sub-metre scale measurements cannot be taken without correction for these between-track  
220 errors. To achieve this correction we used a least squares matching technique developed by  
221 Akca (2007a, b), which matches the surface shape and LiDAR intensity between each track  
222 to align the tracks relative to one another. This adjusted data set was then georeferenced by  
223 aligning it to the GPS data collected in the 2007 campaign. This processing resulted in the  
224 cross-track and georeferencing errors in the LiDAR data being reduced to ~0.1 m vertically  
225 and < 0.25 m horizontally as detailed in Table 2.

### 226 2.3. *Generation of elevation models*

227 To measure volumes of debris flows, we calculated the slope shapes before and after  
228 debris flows. In all calculations we used the last return LiDAR data where the height of the

229 ground at the LiDAR shot point is calculated using the return time of the last laser light to  
230 reach the receiver from that particular shot. We used these data to create a regional 5-m DEM  
231 using the LiDAR Explorer 2.0 extension for ArcGIS. This program uses the mean value of  
232 the LiDAR shots within each pixel to produce a smooth DEM and if necessary uses linear  
233 interpolation between the LiDAR shots to fill small data gaps.

234 The combined 2007 GPS and last return LiDAR survey data for the debris flows were  
235 converted into local 0.25-m DEMs for each debris flow. This was performed using the  
236 universal Kriging interpolation method provided within the geostatistical analyst tool of ESRI's  
237 ArcMap software, which has been verified as a valid method for this type of data (Scheidl et  
238 al., 2008). We used Kriging rather than Natural Neighbour, as recommended by Scheidl et al.  
239 (2008), because the Kriging method allows inclusion of the expected asymmetry of the surface  
240 as well as the asymmetry of the sampling, and provides an estimation of the errors associated  
241 with the prediction. Because of the relatively low number of points compared to those  
242 processed by Scheidl et al. (2008), this processing was computationally inexpensive to  
243 perform — high cost being the main argument presented against this method by Scheidl et al.  
244 (2008).

245 For those debris flows that occurred before the LiDAR survey (1DF, 2DF, 3DF, and  
246 5DF), the pre-flow morphology was estimated using the 2007 data alone. This was achieved  
247 by taking all the GPS and LiDAR points within a 5-m buffer around the boundary of the flow  
248 (i.e., excluding all the points that lie on the new debris flow) and performing a Kriging  
249 interpolation based only on these points — in essence “smoothing out” the debris flow to  
250 estimate the preexisting topography. Where the debris flow is wide, especially in the alcoves,  
251 the interpolation was performed across large distances (of the order of 50 m). The post-flow  
252 surface was estimated using all of the 2007 data across the flow. For those debris flows which  
253 occurred after the LiDAR survey (7DF, 8DF, and 10DF), the pre-flow morphology was

254 interpolated from the 2007 LiDAR and GPS data and the post-flow morphology derived from  
255 the 2008 GPS and TPS data.

#### 256 *2.4. Volume estimation and patterns*

257 To assess trends in deposited volume over the length of the debris flow, the GPS points  
258 representing the margins of the debris flow were converted into a polygon shapefile using  
259 ArcGIS software. This polygon was then split into along-flow segments (Fig. 3). These  
260 segments were equally spaced and lay perpendicular to the channel centre line (i.e., they were  
261 not necessarily of equal area). Section length was at 5-m intervals for all debris flows —  
262 apart from the small debris flow, 5DF, which had a 2-m interval. For each debris flow, an  
263 isopach map was produced by subtracting the post-flow surface from the pre-flow surface.  
264 Then for each segment, the total volume of erosion and of deposition was calculated by  
265 summing the negative and positive pixels, respectively, of the isopach map falling within the  
266 segment. To account for the varying areas of each segment, the volumes were divided by the  
267 area of the segment, giving a representative thickness (of erosion and deposition) for each  
268 segment. The concept of representative thickness is a proxy for volume.

269

270 **[Fig. 3 here]**

271

272 The segmented polygons were then used to generate statistics based on underlying  
273 topography. To analyse how the flow responded to variations in the regional slope  
274 morphology, we used a 5-m DEM produced from the LiDAR data. To analyse responses to  
275 the morphology produced by the flow itself, we used the higher resolution 0.25-m DEMs  
276 produced for each debris flow from LiDAR and GPS data. For each DEM, the mean slope  
277 angle and elevation were calculated using the standard tools provided in Spatial Analyst of  
278 ArcGIS. The slope angle is derived using the steepest downhill slope as calculated by fitting a  
279 plane through the eight nearest neighbours.

280 To analyse patterns of erosion and deposition in all the flows together we normalised  
281 their individual segment erosion and deposition representative thicknesses. Normalisation is  
282 performed for erosion and deposition separately and is calculated by dividing representative  
283 thickness for each segment by the total representative thickness for each flow (of erosion or  
284 deposition as appropriate) so that data for all the flows can be compiled together (otherwise  
285 the signal from the largest, freshest debris flow would dominate). This normalisation then  
286 adjusts for differences in both scale and age.

287

### 288 **3. Results**

#### 289 *3.1. Field observations – sources of materials and changes over time*

290 All the debris flows in this study form levees, and some exhibit a terminal lobe. The  
291 levees flank the channel and, when large and fresh, have steep interior and exterior slopes.  
292 The levees all contain a fine matrix that supports the clastic material; however, the source  
293 material and age of the deposits varies between flows.

294 Decaulne (2001) observed that debris flows 2DF, 3DF, and 4DF were sourced from a  
295 rotational slide of the glacial material on top of Gleiðarhjalli bench. This material is  
296 characterised by the high content of subrounded to subangular clasts ranging from  
297 centimetres to metres in size supported by 10-30% orange-brown fines (see grain-size  
298 analysis in Decaulne et al., 2005). We found that the materials that compose the levees in  
299 debris flow 1DF matched the glacial deposits. Hence, the composition of the levees reflects  
300 the composition of the source area. We used visual inspection and correlation to determine  
301 the source deposits of the remaining flows in this study (Table 3). The precise drainage areas  
302 for the Ísafjörður debris flows (1DF, 2DF, 3DF, 4DF, and 7DF) are hard to determine as  
303 much of the water flow occurs beneath the surface of the bouldery Gleiðarhjalli bench. Most  
304 of the contributing area is from the Gleiðarhjalli bench, with some contribution coming from  
305 the small plateau on the slope above. The other debris flows (5DF, 8DF, and 10DF) have

306 rockwall chutes upstream, which have small (or negligible in the case of debris flow 5DF)  
307 plateaus above them.

308 We have observed that debris flows usually take the path of a previous flow for at least  
309 the upper third of the total length. Levees that have been washed free of fines can be  
310 infiltrated by them again in a subsequent flow and in addition the levees can be built up in  
311 height. When flows are frequent, this means that caution is required when estimating the  
312 volume without knowledge of preexisting topography. Other authors have noted that levees  
313 are often reworked in subsequent flows, leaving almost no evidence of the previous flow,  
314 which leads to underestimation of historical frequency (e.g., Luckman, 1992).

315 Decaulne (2001) reported anthropomorphic removal of material from debris flows 2DF  
316 and 3DF because they affected the town. At debris flow 7DF, we observed that a significant  
317 quantity of material had been mechanically excavated from the ditch to the bank between the  
318 2007 and 2008 field visits. These deposits were therefore not included in our study, and this  
319 anthropomorphic modification should be considered when drawing conclusions from volume  
320 data. We observed that large quantities of material had been moved from the road to the  
321 downslope verge in debris flows 8DF and 10DF, however, these deposits were included in  
322 our survey. As the deposits were moved by 5 m or less, which is on the same order as our  
323 sampling distance, we decided this was not sufficient to disrupt the conclusions based on the  
324 analysis of volumes in this study.

### 325 *3.2. Debris flow volumes*

326 Table 4 presents estimates of volumes of the surveyed debris flows. According to the  
327 classification of Innes (1983), these flows are medium-scale flows (except debris flows 5DF  
328 and 7DF which are small-scale flows). On the 1-10 magnitude scale presented by Jakob  
329 (2005) all the flows are rated as size class 2-3, with debris flow 5DF as size class 1-2.

330 To assess the performance of our method to estimate the pre-flow topography (see  
331 section 2.3 for details) for debris flows 1DF, 2DF, 3DF, and 5DF, we also applied this

332 method to debris flows 7DF, 8DF, and 10DF, where the pre-flow topography is known from  
333 the 2007 LiDAR survey. Table 4 shows the results of this analysis. Our method tends to  
334 underestimate the overall volume of the flow by ~ 30-40 % and overestimate the erosion of  
335 the flow by ~ 2-3 times. However, the overall volume of the erosion and deposition are not  
336 important for the following analysis and hazard assessment, but the preservation of the  
337 patterns of erosion and deposition. We find that the overall patterns of deposition and erosion  
338 are preserved when using our method of estimating pre-flow topography for all the debris  
339 flows (Fig. 4).

340

341 **[Fig. 4 here]**

342

343 The percentage errors appear large for all the flows (details of calculation in Appendix  
344 A) for the following reasons:

345 (i) for those flows without pre-flow data, the interpolation (described in section 2.3) in  
346 the lower surface was performed over long distances, resulting in large estimate errors,  
347 especially in the source areas; and

348 (ii) because the error is expressed as a percentage, it is larger for the smaller debris  
349 flows (5DF, 7DF, 8DF, and 10DF) as the absolute error forms a larger percentage of their  
350 smaller volume. To put this in context, the average error on the deposition volume relates to a  
351  $\pm 20$ -cm thickness and the erosion volume corresponds to a  $\pm 42$ -cm thickness.

352 Despite the significant percentage errors that result from using the Krigé interpolation  
353 over large areas without points (see section 2.3 for details), it presents a superior approach  
354 than just taking a linear surface under the flow. Firstly, because the method uses the  
355 surrounding topography to estimate the pre-existing topography. Secondly, although the  
356 linear and Krigé interpolation methods perform equivalently (see Table 5), the Krigé method

357 allows an estimate of potential error, whereas the linear method does not. In addition, we  
358 compared our volume results to those obtained by extrapolation of the cross-sectional areas  
359 calculated from cross profiles along the flow. We calculated the volume of debris flows 1DF  
360 and 2DF using this method: once using all measured cross sections and again using just three  
361 cross sections that are located at the same approximate position as those made by Decaulne et  
362 al. (2005). Both methods produced equivalent estimates for volumes (Table 5), although we  
363 must emphasise that when fewer cross sections are used greater care is required in ensuring  
364 that they are representative of the flow as a whole (e.g., recommendations of Casali et al.,  
365 2006). However, although extrapolation of cross-sectional area is adequate for estimating  
366 volumes, it cannot be used for detailed study of the patterns of erosion and deposition.

### 367 *3.3. Patterns in erosion and deposition*

368 To demonstrate the overall patterns of erosion and deposition developed by debris flows,  
369 we have chosen two case studies, debris flows 1DF and 5DF, to illustrate the behaviour. The  
370 results from the calculation of total volumes of these debris flows are presented in Table 4,  
371 and the spatial distribution of volume over the flow in Fig. 5. The scale of the two flows is  
372 very different, but they both show slope-dependent behaviour. The relationship between  
373 slope and the depositional regime is evident in Fig. 5, with slope directly affecting the pattern  
374 and quantity of deposition as further detailed below.

375

376 **[Fig. 5 here]**

377

378 In debris flow 5DF (Fig. 5A), a transition between the erosion and depositional regimes  
379 occurs at a sharp change of slope from 28° to 18°. The beginning of this slope change is  
380 marked II on Fig. 5A. Above this, the point at which levees begin to form is marked by a  
381 slight decrease in slope, shown between I and II on Fig. 5A. A slight decrease in deposition  
382 is matched by a slight increase in slope marked III, and a major peak in deposition occurs



383 about 50 m from the end of the flow, matched by a drop in slope at IV. For 5DF, the  
384 complete cessation of erosion occurs somewhere between 25° and 17°, with deposition  
385 starting at 32° (Fig. 5A). Field observations of *insitu* grass between the levees confirm that  
386 erosion has stopped at this point. This flow remains mobile on slopes as low as 7°, but below  
387 the lobe at IV field observations show the deposits have very little relief.

388 The main erosional section of 1DF (where deposition is negligible) terminates at a slope  
389 angle of about 32° (marked I in Fig. 5B). Below this point, erosion continues to take place in  
390 the centre of the channel, but temporarily ceases at the point where a secondary lobe breaks  
391 off from the main flow and restarts below this, marked II. The main depositional phase is also  
392 briefly interrupted over a short, steeper section (marked III) below which a brief pulse of  
393 deposition occurs before the deposition tails off on to the lower slope section. The flow  
394 remains mobile on slopes as low as 10°. This is a relatively small flow for Ísafjörður, as it did  
395 not reach the fjord nor the man-made drainage channel on the lower part of the slope.

396 Despite debris flows 3DF, 2DF, and 4DF being older flows (hence more eroded), the  
397 patterns in deposition and erosion are preserved. We can therefore analyse patterns of erosion  
398 and deposition in all the flows together using the methods described in section 2.4. Figure 6  
399 shows a box-plot showing normalised representative deposition (Fig. 6A) and erosion (Fig.  
400 6B) thickness against slope as a compilation of data for all the debris flows. Using Fig. 6, we  
401 can then compare the onset of deposition and cessation of erosion in these flows with those  
402 found by other authors for hillslope flows. Note that the extension of the boxes above the  
403 zero-line in Fig. 6A (marked X) at slope angles > 43° is an artefact because of the protrusion  
404 of bedrock surfaces in the alcoves of debris flows 2DF and 3DF above the interpolated  
405 surfaces.

406

407 **[Fig. 6 here]**

408

409       Our results are interesting in that we find measurable deposition at slope angles of 37°.  
410 This is higher than reported by previous studies. Lorente et al. (2003) reported 17.8° as the  
411 onset slope for deposition; and Fannin and Wise (2001) reported unconfined (hillslope) flows  
412 as depositing at angles < 18.5° on average in the Queen Charlotte Islands, British Columbia,  
413 Canada, but their data show deposition occurring up to 38° in some cases (it is not clear,  
414 however, if these flows are exclusively hillslope debris flows). However, Larsson (1982)  
415 reported deposition at as much as 35° for debris flows in Longyear Valley, Spitsbergen,  
416 Norway. Matthews et al. (1999) reported deposition on slopes of up to 25° in Leirdalen,  
417 Jotunheimen, Norway; and Rapp and Nyberg (1981) reported deposition on 30° slopes in  
418 Nissunvagge, Sweden. For confined flows, deposition does not begin until much lower slope  
419 angles are reached on the fan (e.g., Staley et al., 2006; Prochaska et al., 2008). Hence, for the  
420 flows studied in this paper, deposition consistently begins at a much higher average slope  
421 angle than reported by the majority of other authors.

422       Fannin and Wise (2001) reported their lowest limit of erosion on average as being 18.5°  
423 for unconfined flows, but this lower limit has not been widely reported elsewhere in the  
424 literature. From Figs. 6B and 5, apparently a lower slope erosion threshold exists of ~ 19° for  
425 debris flows in our study, marked by the vertical line in Fig. 6B. This is reinforced by field  
426 observations of erosion occurring near the distal end of the debris flow coincident with an  
427 increase in local slope as shown in Fig. 7. It is also consistent with the observation of *in situ*  
428 grass between the levees of debris flow 5DF at a sudden decrease in slope below 19°. This  
429 phenomenon has been noted by other authors in other locations (Rapp, 1960; Matthews et al.,  
430 1999; Luckman, 1992), but not quantified.

431

432 **[Fig. 7 here]**

433

## 434 **4. Data analysis**

### 435 *4.1. Comparison with previous empirical relationships for debris flow total travel distance*

436 Rickenmann (1999) used data from 232 confined debris flows from around the world to  
437 derive the following relationships:

$$438 \quad L = 30(MH_e)^{0.25} \quad (1)$$

$$439 \quad L = 1.9M^{0.16}H_e^{0.83} \quad (2)$$

440 where  $L$  is the total travel distance,  $H_e$  is the elevation difference between the source and the  
441 lowest point of deposition, and  $M$  is the magnitude or total volume. Equation (1) is a  
442 theoretical relationship between distance travelled and energy potential ( $MH_e$ ), and the  
443 constant has been selected to approximate average total travel distance in the data of  
444 Rickenmann (1999). Equation (2) is the regression equation of  $L$ ,  $M$ , and  $H_e$  that best fits  
445 Rickenmann's (1999) data. Similarly, Lorente et al. (2003) compiled data from 961  
446 unconfined debris flows in the Flysch sector of central Spanish Pyrenees to derive the  
447 following relationships:

$$448 \quad L = 7.13(MH_e)^{0.271} \quad (3)$$

$$449 \quad L = -12.609 + 0.568h + 0.412s \quad (4)$$

450 where  $h$  is the elevation difference between the source and the starting point of deposition,  
451 and  $s$  is the average gradient of the source area in degrees. Lorente et al. (2003) used Eq. (1)  
452 as the basis for Eq. (3), but adjusted both the exponent and the constant to fit their data.  
453 Equation (4) is the result of a linear regression of the variables that had the highest correlation  
454 with total travel distance from Lorente et al.'s (2003) data.

455

456 **[Fig. 8 here]**

457

458 For Rickenmann's (1999) Eq. (1), debris flow 1DF lies well above the line  $x = y$  in Fig.  
459 8, which means its total travel distance is shorter than that predicted by this relationship.  
460 Using Rickenmann's (1999) Eq. (2), our debris flows 1DF, 10DF, and 8DF all lie well above  
461 the  $x = y$  line and therefore have a shorter total travel distance than predicted. This is because  
462 the elevation difference is more important in Eq. (2) than (1), giving a longer predicted total  
463 travel distance for 8DF and 10DF, which have greater elevation differences. For both the  
464 Rickenmann (1999) relationships (Eqs. 1 and 2), our debris flows 2DF, 3DF, 5DF, and 7DF  
465 lie close to the  $x = y$  line: the measured total travel distances match the predicted ones quite  
466 well. All the debris flows in this study lie well below the line for both of the relationships  
467 from Lorente et al. (2003), i.e., all the flows we have studied have larger total travel distances  
468 than would be predicted by Lorente et al. (2003). Existing relationships do not seem to fit our  
469 results very well, so we now proceed to develop our own empirical model in the following  
470 sections.

#### 471 *4.2. Derivation of an empirical relationship for hazard prediction*

472 By treating cumulative packets of the segmented debris flows from top to bottom as  
473 progressively larger subsamples of the main debris flow, we noticed predictable patterns in  
474 the pattern of deposition. Figure 9 shows a plot of cumulative average slope against  
475 cumulative normalised deposition thickness. Cumulative average slope ( $\theta_n$ ) was calculated  
476 for each segment  $n$  as follows:

$$477 \quad \theta_n = \frac{\sum_{i=0}^n S_i}{n} \quad (5)$$

478 where  $S_i$  is the slope within segment  $i$ , and  $n$  is the number of segments counted from the  
479 source of the flow downward. The cumulative normalised deposition thickness ( $Z_n$ ) was  
480 calculated for each segment  $n$  as follows:

481 
$$Z_n = \sum_{i=0}^n \frac{Z_i}{Z_T} \quad (6)$$

482 where  $Z_i$  is the representative thickness for that segment, and  $Z_T$  is the sum of the  
483 representative thicknesses for all segments in the debris flow.

484

485 **[Fig. 9 here]**

486

487 All the debris flows studied fall within a narrow range of cumulative average slope for  
488 a given representative thickness, and most have an initial steep section over which no  
489 deposition occurs. Deposition then begins at a cumulative average slope of 35-40°. The  
490 behaviour of the debris flows then falls into one of three groups: (i) those which then deposit  
491 linearly for the rest of their length (debris flows DF2, DF3, and DF7), (ii) those with a sudden  
492 decrease in deposition before their terminus (debris flows DF1 and DF8), and (iii) those  
493 which show strong initial deposition that tails off into a constant rate of deposition at lower  
494 slope angles (debris flows 5DF and 10DF). We can use these relationships to generate best-fit  
495 curves, allowing us to predict potential future flow behaviour.

#### 496 4.3. *Creating a hazard map from empirical relationships*

497 Enough consistency exists in the relationship between cumulative average slope and  
498 cumulative normalised deposition thickness to fit curves to the envelope of the data points  
499 shown in Fig. 9 (this process is described more fully in Appendix B). We have fitted three  
500 types of curves (Fig. 9): linear (on the lower boundary, labelled 2 in Fig. 9), sigmoidal  
501 (Boltzmann-family, to the highest average slope, labelled 3 in Fig. 9 and lowest average  
502 slope, labelled 4 in Fig. 9), and exponential (to the average, labelled 1 in Fig. 9). These  
503 curves represent the patterns in behaviour labelled (i), (ii), and (iii) described in section 4.1,  
504 respectively. We have then modelled the debris flow behaviours based on these curves along  
505 19 simulated debris flow tracks (Fig. 10). The tracks were generated from the lines of greatest

506 fluid accumulation as derived from hydrological modelling of the LiDAR DEM using Arc  
507 Hydro Tools 9.0. Centrelines were digitised from this accumulation model and then split or  
508 segmented at 5-m intervals, as per the empirical model (see Fig. 3). The underlying slope for  
509 each of these segments was extracted from the DEM. These models require two inputs in  
510 addition to the flow paths: the planimetric area and the debris flow volume.

511 As debris flow 1DF was a relatively small event compared to those in 1999, we used its  
512 volume and planimetric area as an end member to estimate the thickness of deposits reaching  
513 the town on a set of 19 tracks shown in Fig. 10. The results of this modelling show that for  
514 models 2 and 4 upper parts of the town would be at risk from any debris flow; and for models  
515 1 and 3 the flows do not have sufficient mobility to reach the town, no matter what the input  
516 volume and area. To demonstrate how the thicknesses change with increasing volume (and  
517 planimetric area), the thicknesses of debris reaching the town are tabulated for different input  
518 parameters for three example flow-paths (labelled on Fig. 10 Model 1) for all four models in  
519 Table 6. The results from 1 and 3 emphasise that these types of flows rarely have sufficient  
520 mobility to reach the town, no matter what the input volume and area are for these two  
521 models.

522

523 **[Fig. 10 here]**

524

## 525 **5. Discussion**

### 526 *5.1. Reliability of volume data*

527 Our method of estimating pre-flow surfaces has been tested on the debris flows for  
528 which we do have pre-flow data (7DF, 8DF, and 10DF), it seems to underestimate deposition  
529 volumes and greatly over-estimate erosion volumes (Table 4). We do not have a debris flow  
530  $> 1000 \text{ m}^3$  on which we can test this method, but it is likely that the percentage difference in  
531 calculating the deposition volume by this method would decrease with greater volume, as the

532 absolute differences would increase only slowly. It is also likely that the percent difference in  
533 erosion volume would remain large, as the kriging is performed over larger source areas,  
534 leading to the absolute difference increasing with the volume.

535 However, the interpolation on accurate GPS and LiDAR elevation data gives realistic  
536 ranges of volumes for these flows. Considering the inherent bias towards underestimation, the  
537 volume estimates are larger than previous estimates for this area: our “medium” flow 1DF  
538 has a volume of about 8000 m<sup>3</sup> compared to 3000 m<sup>3</sup> calculated by Decaulne et al. (2005) for  
539 a “large” debris flow 2DF in 1999 (Table 5). We have used several different methods to  
540 calculate the deposition volumes of 1DF and have found that all the results are consistent  
541 (Table 5). Debris flow 1DF is a medium-sized flow for this region, and the results are within  
542 realistic bounds for this scale of flow (Innes, 1983). However, debris flow 1DF has the largest  
543 errors from lack of pre-flow data, and hence all other flows are better constrained and have  
544 more reliable volume estimates.

## 545 *5.2. Patterns in deposition and erosion*

546 Debris flows 1DF and 5DF show morphological evidence of the pulsing nature of debris  
547 flows in the patterns of their deposits. The break-off lobe in 1DF is probably a result of the  
548 first pulse, which was able to break over the preexisting levees at the bend in the channel  
549 (Fig. 5B – just above II). Later pulses blocked this path with their own levees and continued  
550 down the path of previous flows. For debris flow 5DF, a major peak in deposition is located  
551 about 50 m from the end of the flow (Fig. 5A – III); this was also probably an original  
552 terminal lobe before a later pulse broke out through a levee above it. This later pulse formed  
553 small levees and then spread out into a sheet deposit, suggesting a higher mobility and, hence,  
554 water content. This demonstrates that a debris flow does not necessarily follow the line of  
555 greatest initial slope, but that earlier pulses can block further flow; this divagation behaviour  
556 of debris flows has been described by several other authors from deposits (e.g., Addison,  
557 1987; Morton et al., 2008) and modelling (Zanuttigh and Lamberti, 2007). These field

558 observations also point to the variable composition of the pulses that form a debris flow  
559 event. Although our model does not incorporate these observations explicitly, we use the  
560 knowledge of this pulsing nature to expand and inform conclusions based on model results.

561 Debris flows continue to be mobile at low slope angles, with debris being transported at  
562 slope angles as small as 7-10°, although initiation seems to require a high slope angle (> 40°).  
563 We have measured little deposition at lower slope angles, and several possible reasons exist  
564 for this:

565 (i) The debris flows studied here exhausted the available material before reaching low  
566 slopes. We have not studied any very large, fresh flows that could perhaps continue  
567 depositing at low slope angles, as their material is not exhausted by deposition on  
568 higher slopes.

569 (ii) Any low-slope deposits within Ísafjörður or on roads remaining from historical flows  
570 would almost certainly have been cleared away.

571 (iii) Urbanisation on low slopes prevents debris flows from progressing unimpeded  
572 downslope.

573 (iv) Morphology of the slopes in Ísafjörður means that very low (<< 10°) slope angles are  
574 not abundant above the shoreline.

575 Previous studies (Decaulne, 2001) have suggested that deposition of lobes does occur at these  
576 low slope angles, but it is unclear if the water content is low enough within these mobile  
577 flows to maintain levees.

578 The ideal slope angles for deposition appear to be around 25°, enabling the outer edge  
579 of the flow to stabilise into levees while the main body of the flow remains mobile.  
580 Deposition begins to occur at much higher slope angles than reported for previous flows (e.g.,  
581 Coe et al., 1997; Lorente et al., 2003). This potentially indicates that the flow deposits in the  
582 Ísafjörður region have a higher angle of dynamic friction or a higher viscosity (possibly



583 related to lower water content or higher clay content) than previously reported for debris  
584 flows. This is supported by field observations that the levees are able to maintain high  
585 external and internal slopes.

586 In the study area a threshold slope of  $19^\circ$  is observed, below which erosion completely  
587 ceases. Whenever this threshold is exceeded lower down the flow, erosion begins again as  
588 shown in Fig. 7. This means that the debris flows are probably bulking (i.e., incorporating  
589 material eroded from along the flow path) as they progress downslope, although we were not  
590 able to estimate the amount of bulking, because of a lack of reliable data in the source areas.

### 591 *5.3. Comparison with previous empirical relationships for debris flow total travel distance*

592 Figure 8 shows how the debris flows studied here compare with empirical  
593 relationships for debris flow run-out distances derived by Rickenmann (1999) and Lorente et  
594 al. (2003).

595 The debris flows studied here fit best with the confined debris flows (Equation 1)  
596 studied by Rickenmann (1999), but the total travel distance is greater than predicted from the  
597 hillslope debris flows studied by Lorente et al. (2003) in Flysch in the Pyrenees. This is  
598 surprising as the debris flows in our study area most closely resemble those of Lorente et al.  
599 (2003), being unconstrained hillslope flows rather than the confined torrent debris flows of  
600 Rickenmann (1999).

601 From this we infer that the larger debris flows in our area are generally more mobile  
602 than hillslope flows studied by Lorente et al. (2003), but less mobile than confined flows  
603 studied in a wide range of settings by Rickenmann (1999). However, the smaller flows have  
604 about the same mobility as Rickenmann's (1999) channelized flows. The higher mobility of  
605 these flows seems counter-intuitive considering their higher angle of dynamic friction or  
606 higher viscosity implied by observed high levee slopes and deposition at high local slope  
607 values (detailed in sections 3.1 and 3.3). However, Iverson (1997) concluded that the  
608 structure of the deposits does not reflect the properties of the original debris flow, and the

609 interplay of the flow's viscosity with the fluid and granular parts of the flow is poorly  
610 understood (Iverson, 1997). We hypothesise that the high mobility compared to Lorente et  
611 al. (2003) is a reflection of the larger scale of the debris flows in this study. Clearly, the  
612 flows in our area do not closely match existing empirical relationships. We conclude that  
613 empirical prediction from simple models is insufficient here; and that without the application  
614 of more complex models, the prediction of future flow lengths in a given area can only be  
615 made by the analysis of detailed measurements of previous flows from the selected area. Here  
616 we present an example of how this can be implemented.

#### 617 *5.4. Developing a new empirical model for debris flow prediction*

618 For the debris flows studied in the Westfjords, the relationship between slope and  
619 deposition does not strongly depend on the overall mass nor the source material's grain size,  
620 grain size distribution, or angularity (detailed in section 3.1). All the flows show similar basic  
621 patterns yet have different masses (Table 4) and comprise different materials (Fig. 4, and  
622 section 3.1). Both field observations and analysis of the isopach and slope profiles (Fig. 5)  
623 point to a strong relationship between slope and deposition-erosion volume. From the isopach  
624 data, we have derived a predictive relationship for flows in this area. Figure 9 shows the data  
625 and trends in cumulative slope and normalised deposition thickness, as derived in section 4.1  
626 and Appendix B, which lead to this predictive relationship. As mentioned in section 4.1,  
627 debris flows 2DF, 3DF, and 7DF do not have the sudden drop in deposition at low cumulative  
628 slope that is shown by most of the other flows. However, we believe that this is not a feature  
629 of the flow mechanics but a result of the deposits being later removed by anthropogenic  
630 mechanical excavation (section 3.1). This removal has affected the normalisation in Fig. 9,  
631 but we estimate that these deposits make up an insignificant fraction of the total deposition  
632 volume and therefore would not push these flows outside the main data envelope. We  
633 attribute the other differences between debris flows in Fig. 9 to gross rheological differences  
634 and to the variation in rheology of their constituent pulses. These differences are surprisingly

635 small, however, considering the variation in topographical setting, source of material, fines  
636 content, clast size, angularity, and grain size distribution between the flows.

637 The data in Fig. 9 form a discrete envelope that describes the way in which we expect a  
638 debris flow to evolve in terms of proportion of overall deposit thickness and hence volume  
639 with cumulative slope. Therefore, with a starting volume, planimetric area, and a DEM, this  
640 relationship can be used to predict overall total travel distance and deposit thickness at a  
641 given location.

#### 642 *5.5. Predicting hazard*

643 We have used the empirical relationships described in section 5.4 to simulate debris  
644 flow deposition and overall total travel distance along synthetic flow paths as explained in  
645 section 4.2. Different flow behaviours are represented by the four models shown in Fig. 9,  
646 and these have been simulated along the synthetic tracks. Models 2 and 4 always reach the  
647 houses no matter what the starting volume (Table 6; Fig. 10). Models 1 and 3 never reach the  
648 houses, and again this is independent of starting volume (Table 6; Fig. 10). As noted in  
649 section 5.4, debris flows 2DF, 3DF, and 7DF do not have the sudden drop in deposition at  
650 low cumulative slope that is shown by most of the other flows; and these flows form the basis  
651 for creating model 1 (exponential). Hence, we can discount this model as being unrealistic  
652 for most debris flows. The sigmoidal (Boltzmann) models 3 and 4 seem to represent the  
653 inherent behaviour of most of the flows: an initial slow increase in deposition, a stable middle  
654 area with approximately constant deposition, and a sharp drop-off at low slope angles.  
655 However, the difference in terms of overall deposit thickness is not great between models 2  
656 (linear) and 4 (sigmoidal), hence a simple linear model would suffice to implement this  
657 method, without the need to fit a precise curve any particular flow.

658 Protective ditches have been dug above the town of Ísafjörður in two locations (marked  
659 in Fig. 2) to protect the population and houses from debris flows. In our modelled flows, the  
660 flow thickness only matches the depth of the protective ditches (i.e., the flow only progresses

661 past the ditches) when the flow is extremely large in volume ( $> 100\,000\text{ m}^3$  is an  
662 exceptionally large flow for this region). We should note that in reality the ditches were  
663 nearly overwhelmed (mud and water reached the houses) in 1999 (Decaulne et al., 2005) by  
664 2DF and 3DF, which have estimated volumes of 3000 and 1000  $\text{m}^3$ , respectively (Table 5).  
665 We note that the ditches have since been widened (Decaulne, 2007). However, our model  
666 results show that medium-sized debris flows result in greater than 1 m of deposits at the  
667 eastern ditch, so two medium flows occurring close to one another in time and space would  
668 overwhelm this ditch and flows would reach the houses. Given that debris flows can be  
669 triggered simultaneously (e.g., Coe et al., 2007; Decaulne and Sæmundsson, 2007), this  
670 appears to be a plausible hazard. However, the frequency of occurrence of these multiple  
671 events is unknown for Ísafjörður, so we assume that this would be a comparatively rare event,  
672 but severe if it does occur. This analysis has enabled us to identify areas of the town at risk  
673 that would not be obvious otherwise. To prioritise any mitigation work done by the  
674 authorities, this model could be combined with estimates of most likely flow areas based on  
675 historical data and cost-benefit considerations. For example, although the electricity  
676 substation is unprotected, damage to it although inconvenient is unlikely to cause loss of life,  
677 compared to residential properties.

678 Our model does not take into account the effect of the relative timings of multiple  
679 events nor the number of pulses in a single flow event. For example, a medium-sized flow  
680 could occur in a single pulse and stabilise on the slope with the terminal lobe at the ditch and  
681 rest of debris backed up behind it. However, such an event could also have many pulses, the  
682 first of which fills the ditch allowing the next pulses to ride over the top. These hypothetical  
683 events could have the same overall volume but very different outcomes. In addition, the flow  
684 paths we have used in our model run down the steepest slope, but as noted previously,  
685 (sections 3.1 and 3.3) debris flows do not necessarily conform to this path. However, the flow

686 routes we have produced are representative of the slopes experienced by a debris flow as it  
687 progresses and therefore can be used as an indication of thickness of deposits expected for the  
688 flow, if not the exact path line.

689 Our model is an oversimplification of the behaviour of the flow, but it is conservative in  
690 its simplifications. The advantage of this model is that it meets the conditions of Hurlimann et  
691 al. (2008), which are (i) the method must specify a spatial distribution, and results must cover  
692 the entire study area; (ii) the method applied should be able to incorporate different volumes  
693 as input data; and (iii) the output of the method should enable intensity determination without  
694 the need for the time and expense of a full two-dimensional flow model, requiring back-  
695 calculation to determine rheology and selection of the most appropriate flow-resistance law.  
696 Our model has a similar philosophy in this respect to Fannin and Wise (2001), although their  
697 model required the additional inputs of length, width, and azimuth of each reach in the debris  
698 flow. Their model also dealt with transitional and confined debris flows in addition to  
699 unconfined debris flows and also included bulking (incorporation of material eroded along  
700 the flow path). Except bulking, none of these additional factors are of importance in purely  
701 hillslope flows.

702

## 703 **6. Conclusions**

704 (i) The length and pattern of deposition of a future debris flow of given volume can be  
705 estimated from slopes measured on DEMs of its predicted flow path. This conclusion  
706 is based on the fact that debris flows above Ísafjörður, in Hnífsdalur and in  
707 Ségandafjörður, consistently showed similar relationships between cumulative  
708 average slope and normalised deposition thickness, despite each flow having wide  
709 differences in source materials and setting. This has allowed us to identify areas of  
710 the town of Ísafjörður previously not acknowledged as being at risk. We recommend

711 areas that have been identified as medium risk or above do not undergo future  
712 development. We suggest that future work should include testing this model with  
713 additional data and extending it in to other areas.

714 (ii) . This model is notable for its simplicity, which allows future debris flow  
715 characteristics to be predicted without the need to determine the precise fluid dynamic  
716 parameters of the flow such as viscosity and velocity, which are required to  
717 implement more complex models.

718 (iii) We have found that erosion occurs when slope angles are  $> 19^\circ$  in any part of the  
719 flow. Hence, any new development should be located in areas with slopes much less  
720 than this, in addition to being located away from areas highlighted as medium to high  
721 risk in the debris flow modelling.

722 (iv) Satisfactory estimates of debris flow volumes can be derived from well-placed cross  
723 profiles, as demonstrated by other authors, however patterns in erosion and deposition  
724 cannot be analysed using this method.

725 (v) Our method of estimating volumes using Krige algorithm produces reasonable  
726 estimates of debris flow deposition volume, even when pre-flow data are absent.  
727 When pre-flow data are absent the deposition volume tends to be underestimated and  
728 the erosion volume greatly over-estimated, but the patterns in deposition and erosion  
729 are preserved and realistic bounds of error are given by this method.

730 (vi) Large hillslope-style debris flows above Ísafjörður, in Hnífsdalur and in  
731 Súgandafjörður, do not fit existing empirical models based on channelized torrent-fan  
732 systems or hillslope flows. Given their significant hazard potential, they therefore  
733 warrant more study. Furthermore, an extended study of the cessation point of erosion  
734 and the onset threshold of deposition in hillslope debris flows in other regions could  
735 lead to more generally applicable relationships, which in turn could provide an

736 important link between the morphometric properties of debris flow deposits and the  
737 fluid dynamics of the flows themselves.

### 738 **Acknowledgements**

739 This work would not have been possible without a postgraduate studentship grant from  
740 the U.K. Natural Environment Research Council (NERC). We thank the NERC ARSF for  
741 obtaining the air photography and LiDAR data on which this paper relies. Additional funding  
742 was awarded to SJC by Earth and Space Awards, the Geological Society's W.G. Fearnside's  
743 Award, The Dudley Stamp Fund, and the British Society for Geomorphology's postgraduate  
744 funds. AD was funded by CNRS-GDR3062 "polar mutations" from Besançon, France, and  
745 by the Natural Research Centre of Northwestern Iceland, Sauðárkrókur, Iceland. We  
746 gratefully acknowledge the contribution of our field assistants, Cynthia Conway, Jessica  
747 Bradley, and Dr. Samantha Hammond.

748

749 **Appendix A – Analysis of Errors**

750 Table 2 summarises the main sources of error in the data collection and data  
751 processing chain. The improvement in the accuracy of the LiDAR data through matching the  
752 tracks using LS3D (Akca, 2007a, b) is clearly shown. The errors associated with data  
753 collection (with the exception of LiDAR data preprocessing) are very small compared to the  
754 errors generated in interpolating the data. This must be taken into consideration when  
755 interpreting the total volume estimates. The best volume estimate would be from a surface  
756 that had densely spaced points both before and after a debris flow occurs (both preferably  
757 from corrected LiDAR data). Given the financial costs associated with collecting LiDAR data  
758 and the unpredictable nature of debris flows, the systematic collections of such data is  
759 unlikely.

760

761 The errors from the upper and lower interpolated surfaces were combined using the  
762 standard formula:

763 
$$\sigma_Z = \sqrt{\sigma_A^2 + \sigma_B^2} \quad (A1)$$

764 where  $\sigma_Z$  is the total uncertainty, and  $\sigma_A$  and  $\sigma_B$  are the uncertainties of the two surfaces.

765 These errors vary spatially and can become large away from data points.

766



## 767 **Appendix B – Model Production**

768 This appendix describes the method by which the curves in Fig. 9 were generated; “x”  
769 refers to cumulative average slope and “y” refers to cumulative deposition thickness. The  
770 parameters derived from the least squares fits described in this appendix, along with their  
771 associated errors, are given in Table 7. The equations used to generate the model curves  
772 shown in Fig. 9 are as follows (with numbering here in the same sequence as in Fig. 9):

$$773 \quad 0.03 + 1876170 x e^{(-x/2.217)} \quad (B1)$$

$$774 \quad (36 - x) / 8.5 (36 - 8.5x) \quad (B2)$$

$$775 \quad -0.03816 + 1.04016 / (1 + e^{((x - 36.30119) / 1.00308)}) \quad (B3)$$

$$776 \quad 1.012 / (1 + e^{((x - 32) / 1.00308)}) \quad (B4)$$

777

778 The shape of Eq. (B1) was derived by performing least squares fit of

$$779 \quad y = A + B * e^{(-x / C)} \quad (B5)$$

780 on the data from debris flow 2DF. The  $\chi^2$  value for the fit is 0.00547, which implies a  
781 significant  $p$ -value of  $\ll 0.001$ . The  $r^2$  value is 0.93652.

782

783 Linear regression of the data from debris flow 5DF was used to derive Eq. (B2) using  
784 the following relation:

$$785 \quad y = A + Bx \quad (B6)$$

786 The  $r^2$  value of this fit is 0.854663, which gives a significant  $p$ -value of  $\ll 0.0001$ .

787

788 The curves from Eqs. (B3) and (B4) were derived by performing a least squares fit of

$$789 \quad y = A + (B - A) / (1 + e^{((x - C) / D)}) \quad (B7)$$

790 using data from debris flow 1DF. The  $\chi^2$  value for the fit is 0.00027, which implies a  
791 significant  $p$ -value of  $\ll 0.001$  and the I value of 0.99828. Equation (B4) is a translation of  
792 Eq. (B3) along the x-axis, an estimate of the lower limit of the data envelope.

793

794 **10. References**

- 795 Addison, K., 1987. Debris flow during intense rainfall in Snowdonia, North Wales: A  
796 preliminary survey. *Earth Surface Processes and Landforms* 12(5), 561-566.
- 797 Akca, D., 2007a. Least squares 3d surface matching, Eidgenössische Technische Hochschule  
798 Zürich, Zürich, 92 pp.
- 799 Akca, D., 2007b. Matching of 3d surfaces and their intensities. *ISPRS Journal of*  
800 *Photogrammetry and Remote Sensing* 62(2), 112-121.
- 801 Arnalds, Þ., Sauer Moser, S., Jóhannesson, T., Grímsdóttir, H., 2002. Hazard zoning for  
802 Ísafjörður and Hnífsdalur, Technical Report VÍ-ÚR15, Veðurstofa Íslands, Reykjavík.
- 803 Arnalds, Þ., Jónasson, K., Sigurðsson, S., 2004. Avalanche hazard zoning in Iceland based on  
804 individual risk. *Annals of Glaciology* 38, 285-290.
- 805 Ballantyne, C.K., Benn, D.I., 1994. Paraglacial slope adjustment and re-sedimentation  
806 following recent glacier retreat, Fabergstolsdalen, Norway. *Arctic and Alpine*  
807 *Research* 26(3), 255-269.
- 808 Berti, M., Simoni, A., 2007. Prediction of debris flow inundation areas using empirical  
809 mobility relationships. *Geomorphology* 90, 144-161.
- 810 Breien, H., De Blasio, F.V., Elverhøi, A., Høeg, K., 2008. Erosion and morphology of a  
811 debris flow caused by a glacial lake outburst flood, western Norway. *Landslides* 5(3),  
812 271-280.
- 813 Carrara, A., Crosta, G., Frattini, P., 2008. Comparing models of debris-flow susceptibility in  
814 the alpine environment. *Geomorphology* 94, 353-378.
- 815 Casali, J., Loizu, J., Campo, M.A., De Santisteban, L.M., Alvarez-Mozos, J., 2006. Accuracy  
816 of methods for field assessment of rill and ephemeral gully erosion. *Catena* 67(2),  
817 128-138.
- 818 Clague, J.J., Evans, S.G., Blown, I.G., 1985. A debris flow triggered by the breaching of a  
819 moraine-dammed lake, Klattasine Creek, British Columbia Canadian *Journal of Earth*  
820 *Sciences* 22(10), 1492-1502.
- 821 Coe, J.A., Glancy, P.A., Whitney, J.W., 1997. Volumetric analysis and hydrologic  
822 characterization of a modern debris flow near Yucca Mountain, Nevada.  
823 *Geomorphology* 20(1-2), 11-28.
- 824 Coe, J.A., Godt, J.W., Wait, T.C., Kean, J.W., 2007. Field reconnaissance of debris flows  
825 triggered by a July 21, 2007, thunderstorm in Alpine, Colorado, and vicinity. Open-  
826 File Report 2007-1237, U.S. Geological Survey.

- 827 Decaulne, A., 2001. Dynamique des versants et risques naturels dans les fjords d'Islande du  
828 nord-ouest l'impact geomorphique et humain des avalanches et des debris flows. PhD  
829 Thesis, Université Blaise Pascal, Clérmont-Ferrand, 263 pp.
- 830 Decaulne, A., Sæmundsson, Pétursson, O., 2005. Debris flow triggered by rapid snowmelt: A  
831 case study in the Gleiðarhjalli area, northwestern Iceland. *Geografiska Annaler Series*  
832 *A-Physical Geography* 87A(4), 487-500.
- 833 Decaulne, A., 2007. Snow-avalanche and debris-flow hazards in the fjords of north-western  
834 Iceland, mitigation and prevention. *Natural Hazards* 41(1), 81-98.
- 835 Decaulne, A., Sæmundsson, 2007. Spatial and temporal diversity for debris-flow  
836 meteorological control in subarctic oceanic periglacial environments in Iceland. *Earth*  
837 *Surface Processes and Landforms* 32, 1971-1983.
- 838 Fannin, R.J., Wise, M.P., 2001. An empirical-statistical model for debris flow travel distance.  
839 *Canadian Geotechnical Journal* 38(5), 982-994.
- 840 Favalli, M., Fornaciai, A., Pareschi, M.T., 2009. Lidar strip adjustment: application to  
841 volcanic areas. *Geomorphology*, in press.
- 842 Gabet, E.J., Bookter, A., 2008. A morphometric analysis of gullies scoured by post-fire  
843 progressively bulked debris flows in southwest Montana, USA. *Geomorphology* 96(3-  
844 4), 298-309.
- 845 Gardner, J.S., 1989. High magnitude geomorphic events in the Canadian rocky mountains.  
846 *Studia Geomorphologica Carpatho-Balcanica* 23, 39-51.
- 847 Gartner, J.E., Cannon, S.H., Santi, P.M., Dewolfe, V.G., 2008. Empirical models to predict  
848 the volumes of debris flows generated by recently burned basins in the western U.S.  
849 *Geomorphology* 96(3-4), 339-354.
- 850 Hurlimann, M., Rickenmann, D., Medina, V., Bateman, A., 2008. Evaluation of approaches  
851 to calculate debris-flow parameters for hazard assessment. *Engineering Geology*  
852 102(3-4), 152-163.
- 853 Innes, J.L., 1983. Debris flows. *Progress in Physical Geography* 7, 469-501.
- 854 Iverson, R.M., 1997. The physics of debris flows, *Reviews of Geophysics*, pp. 245-296.
- 855 Iverson, R.M., Schilling, S.P., Vallance, J.W., 1998. Objective delineation of lahar-  
856 inundation hazard zones. *Bulletin of the Geological Society of America* 110(8), 972-  
857 984.
- 858 Jakob, M., 2005. A size classification for debris flows. *Engineering Geology* 79(3-4), 151-  
859 161.
- 860 Johnson, A. M., J. R. Rodine, 1984. Debris flow. In: Brundsen, D., Prior, B. (Eds.), *Slope*  
861 *Instability*. John Wiley, Hoboken, NJ, pp. 257-361.

- 862 Kanji, M.A., Cruz, P.T., Massad, F., 2008. Debris flow affecting the Cubatão oil refinery,  
863 Brazil. *Landslides* 5(1), 71-82.
- 864 Larsson, S., 1982. Geomorphological effects on the slopes of Longyear valley, Spitsbergen,  
865 after a heavy rainstorm in July 1972. *Geografiska Annaler Series A-Physical*  
866 *Geography* 64(3-4), 105-125.
- 867 Lorente, A., Beguería, S., Bathurst, J.C., García-Ruiz, J.M., 2003. Debris flow characteristics  
868 and relationships in the central Spanish Pyrenees. *Natural Hazards and Earth System*  
869 *Science* 3(6), 683-692.
- 870 Luckman, B.H., 1992. Debris flows and snow avalanche landforms in the Lairig Ghru,  
871 Cairngorm Mountains, Scotland. *Geografiska Annaler Series a-Physical Geography*  
872 74(2-3), 109-121.
- 873 Matthews, J.A., Shakesby, R.A., McEwen, L.J., Berrisford, M.S., Owen, G., Bevan, P., 1999.  
874 Alpine debris-flows in Leirdalen, Jotunheimen, Norway, with particular reference to  
875 distal fans, intermediate-type deposits, and flow types. *Arctic Antarctic and Alpine*  
876 *Research* 31(4), 421-435.
- 877 Morton, D.M., Alvarez, R.M., Ruppert, K.R., Goforth, B., 2008. Contrasting rainfall  
878 generated debris flows from adjacent watersheds at forest falls, southern California,  
879 USA. *Geomorphology* 96(3-4), 322-338.
- 880 Norðdalh, H., 1990. Late Weichselian and early Holocene deglaciation history of Iceland.  
881 *Jökull* 40, 27-50.
- 882 Okuda, S., 1989. Recent studies on rapid mass movement in Japan with reference to debris  
883 hazards. *Studia Geomorphologica Carpatho-Balcanica* 23, 5-22.
- 884 Prochaska, A.B., Santi, P.M., Higgins, J.D., Cannon, S.H., 2008. Debris-flow runout  
885 predictions based on the average channel slope (ACS). *Engineering Geology* 98(1-2),  
886 29-40.
- 887 Rapp, A., 1960. Recent development of mountain slopes in Kärkevagge and surroundings,  
888 northern Scandinavia. *Geografiska Annaler Series A-Physical Geography* 42(2-3), 65-  
889 200.
- 890 Rapp, A., Stromquist, L., 1976. Slope erosion due to extreme rainfall in the Scandinavian  
891 mountains. *Geografiska Annaler Series a-Physical Geography* 58(3), 193-200.
- 892 Rapp, A., Nyberg, R., 1981. Alpine debris flows in northern Scandinavia - morphology and  
893 dating by lichenometry. *Geografiska Annaler Series A-Physical Geography* 63(3-4),  
894 183-196.
- 895 Rickenmann, D., 1999. Empirical relationships for debris flows. *Natural Hazards* 19(1), 47-  
896 77.
- 897 Santi, P.M., deWolfe, V.G., Higgins, J.D., Cannon, S.H., Gartner, J.E., 2008. Sources of  
898 debris flow material in burned areas. *Geomorphology* 96, 310-321.

- 899 Scheidl, C., Rickenmann, D., Chiari, M., 2008. The use of airborne LiDAR data for the  
900 analysis of debris flow events in Switzerland. *Natural Hazards and Earth System*  
901 *Sciences* 8, 1113–1127.
- 902 Staley, D.M., Wasklewicz, T.A., Blaszczyński, J.S., 2006. Surficial patterns of debris flow  
903 deposition on alluvial fans in Death Valley, CA using airborne laser swath mapping  
904 data. *Geomorphology* 74(1-4), 152-163.
- 905 Wilkerson, F.D., Schmid, G.L., 2008. Distribution of debris flows in Glacier National Park,  
906 Montana, U.S.A. *Journal of Mountain Science* 5(4), 318-326.
- 907 Zanuttigh, B., Lamberti, A., 2007. Instability and surge development in debris flows.  
908 *Reviews of Geophysics* 45(3) .
- 909

910 **Figure legends**

911 **Fig. 1.** Inset: Map of Iceland showing location of main image (thick grey box). Main:

912 hillshade representation of the NERC ARSF's LiDAR data collected in 2007 for

913 Ségandafjörður and Skutulsfjörður, with locations in Fig. 2 marked A, B, C.

914

915 **Fig. 2.** Air photographs of the study area obtained by NERC ARSF in 2007, with debris

916 flows in this study marked with black outlines. Contours are at 20-m intervals. (A) Debris

917 flows 8DF and 10DF are located on the east side of Ségandafjörður, north of Botn on the

918 road to Selárdalur. (B) Debris flow 5DF is located to the south of Hnífsdalur above the valley

919 road. (C) Debris flows 1DF, 2DF, 3DF, 4DF, and 7DF are located above the town of

920 Ísafjörður, sourced from the Gleiðarhjalli bench. White arrows indicate the extents of the two

921 main drainage ditches mentioned in the text.

922

923 **Fig. 3.** A schematic oblique three-dimensional illustration of how analysis was performed by

924 segmenting the debris flows along-track. This figure shows debris flow 1DF, which has been

925 split into segments 5 m wide at the channel centre-line. Summary statistics were derived for

926 each of the segments from underlying data sets, such as isopach maps of erosion, deposition,

927 and an underlying DEM.

928

929 **Fig. 4.** (A-C) Maps of the spatial relation between erosion and deposition as derived by

930 differencing the LiDAR generated topography from the post-flow DEM for debris flows

931 10DF, 8DF, and 7DF, respectively. (A'-C') Maps for the same flows, however, the base-

932 topography used for differencing was derived by Krige interpolation over the area of the

933 debris flow (method described in section 2.3).

934

935 **Fig. 5.** (A) Long profile and isopach map of debris flow 5DF. (B) Long profile and isopach  
936 map of debris flow 1DF. Contours on the isopach maps are at 5-m spacing. MA10 in the long  
937 profiles is the abbreviation for Moving Average over 10 data points. Black points correspond  
938 to elevation on the right-hand axis, and pink/blue points correspond to slope represented on  
939 the right-hand axis.

940

941 **Fig. 6.** Box-plots showing the distribution of normalised representative deposition thickness  
942 (A) and representative erosion thickness (B) thickness plotted in 2° slope bins. Normalised  
943 thickness is calculated by taking the thickness of the flow in a given segment and dividing it  
944 by the total thickness for all segments (described in detail in section 2.4). All data from all  
945 debris flows are included. The boxes represent the first and the third quartiles of the  
946 distribution, with the black bar marking the median. The narrow bars mark the maximum and  
947 minimum of the distribution, with the circle symbols representing “mild” outliers (between  
948 1.5 and 3 interquartile ranges beyond the bars) and the stars representing “extreme” outliers  
949 (above 3 interquartile ranges beyond the bars). The erosion slope threshold of 19° is marked  
950 by a vertical line in (B). In (A), X marks the region where data are artefacts from the  
951 interpolation technique, rather than a true signal. This problem occurred within the alcoves.

952

953 **Fig. 7.** (A) The base of the northernmost debris flow sourced from Gleiðarhjalli bench. (B)  
954 The base of debris flow 4DF. White arrows indicate the extent of the eroded channels. (C)  
955 Large black arrows indicate locations of photos (A) and (B) on a slope map of the 5-m DEM,  
956 with small black arrows showing increases in local slope that correspond to erosional sections  
957 picked out by the white arrows in (A) and (B).

958



959 **Fig. 8.** Plot of the total travel distance predicted for the debris flows in this study by the  
960 empirical relationships derived by Rickenmann (1999) and Lorente et al. (2003), against our  
961 measured total travel distance for the same debris flows. Rickenmann-1 refers to the  
962 relationship given in Eq. (1); Rickenmann-2 to Eq. (3); Lorente-1 to Eq. (3), and Lorente-2 to  
963 Eq. (4). The diagonal line is the equality line  $x = y$ .

964

965 **Fig. 9.** Graph showing normalised cumulative deposition thickness  $Z_n$  against cumulative  
966 average slope  $\theta_n$  for all the debris flows in this study. The curves used in each of the models  
967 are 1 – exponential fit to debris flow 2DF, 2 – linear interpolation of data from flow 5DF, 3 –  
968 sigmoidal curve fitted to flow 1DF to delineate the upper limit of the envelope of curves, and  
969 4 – sigmoidal curve following the lower limit of the envelope of curves, derived by  
970 translating curve 3 along the  $x$ -axis. See section 4.1 and appendix B for details.

971

972 **Fig. 10.** Graphic displaying the air photo mosaic of Ísafjörður taken by NERC ARSF overlain  
973 with model debris flow paths derived from different curves fitted to the normalised  
974 cumulative deposition thickness against cumulative average slope plot (Fig. 9), using starting  
975 values given in Table 6, column 1. Arrows in upper left refer to tracks in Table 6.

976

977

978 **Table 1**

979 Dates of activity of the debris flows and dates of surveys described in this study<sup>a</sup>

980

<b>Date</b>	<b>June 1999</b>	<b>June 2006</b>	<b>spring 2007</b>	<b>summer 2007</b>	<b>spring 2008</b>	<b>summer 2008</b>
<b>Event</b>	2DF (1) 3DF (4) 4DF (5)	1DF	5DF	LiDAR and GPS survey	7DF (2DF*) 8DF 10DF	GPS Survey

981 <sup>a</sup>See Fig. 2 for geographical locations of numbered debris flows. Numbers in brackets  
 982 indicate the debris flow identification number in Decaulne et al. (2005) and \* indicates debris  
 983 flow occurred along the same track as the debris flow in the brackets.

984 **Table 2**  
 985 Summary of estimated measurement and processing error generated during GPS data  
 986 collection and processing.  
 987

	<b>Vertical Error (m)</b>	<b>Horizontal Error (m)</b>
Human Error	0.05	0.05
GPS calculation error	max = 0.121	max = 0.043
-wobble of antenna	mean = 0.01	mean = 0.005
-constellation of satellites (number and position)		
LiDAR	~ 0.25 (extremes up to 2 considering the horizontal error)	~ 1-2
LiDAR (post adjustment)	~0.1	< 0.25
Kriging Error 1DF	Variable, max = 0.85, mean = 0.11	Not calculated
Kriging Error 5DF	Variable, max = 0.42, mean = 0.07	Not calculated
Kriging Error – GPS only	max ~ 1.0 mean ~ 0.3	Not calculated
Kriging Error –LiDAR + GPS	max ~ 1.4 mean ~ 0.5	Not calculated
Kriging Error – from buffer	max ~ 1.6 mean ~ 0.9	Not calculated

988

989 **Table 3**  
 990 Summary of materials and drainage areas for each of the debris flows in this study.  
 991

<b>Debris flow ID</b>	<b>Source material</b>	<b>Estimated clast-size range (estimated median) m</b>	<b>Estimated percent fines</b>	<b>angularity</b>	<b>Upstream area</b>
<b>1DF</b>	Glacial deposits	0.01 - 4 (0.3)			
<b>2DF</b>	Glacial deposits	0.01 - 4 (0.3)	10-30	subrounded to subangular	Gleiðarhjalli bench
<b>3DF</b>	Glacial deposits	0.01 - 4 (0.3)			
<b>4DF</b>	Glacial deposits	0.01 - 4 (0.3)			
<b>5DF</b>	Talus and soil	0.01 - 0.2 (0.05)	30-50	mainly angular	Rock chute
<b>7DF</b>	Weathering of bedrock and reworked material	0.01 - 1.5 (0.2)	< 5	subangular to angular	Rock chute
<b>8DF</b>	Weathering of bedrock	0.01 - 0.8 (0.1)			
<b>10DF</b>	Weathering of bedrock	0.01 - 0.8 (0.1)			

992

993 **Table 4**  
 994 Summary of measured and estimated volumes and the other measured parameters of debris  
 995 flows in this study  
 996

<b>Debris Flow ID</b>	<b>Measured deposition m<sup>3</sup> (Standard Error)</b>	<b>Measured erosion m<sup>3</sup> (Standard Error)</b>	<b>Estimated deposition m<sup>3</sup> (Standard Error)</b>	<b>Estimated erosion m<sup>3</sup> (Standard Error)</b>	<b>Elevation Drop (m)</b>	<b>Length (m)</b>	<b>Area (m<sup>2</sup>)</b>	<b>Mean Width (m)</b>
<b>1DF</b>			8000 (±66%)	41 000 (±38%)	391	756	20 087	26
<b>2DF</b>			2000 (±134%)	16 000 (±62%)	322	732	13 323	19
<b>3DF</b>			1000 (±124%)	6000 (±100%)	396	728	9327	13
<b>5DF</b>			100 (±136%)	400 (±81%)	88	198	1427	7
<b>7DF*</b>	800 (±105%)	600 (±160%)	500 (±76%)	2000 (±70%)	394	721	3858	9
<b>8DF*</b>	1000 (±94%)	200 (±195%)	700 (±100%)	700 (±123%)	571	797	3192	7
<b>10DF*</b>	1000 (±91%)	500 (±105%)	800 (±88%)	2000 (±60%)	590	866	4029	10

997 \* indicates that the calculations performed do not include the debris flow source areas.

998 **Table 5**  
 999 Comparison of the results of Decaulne et al. (2005) with those from this study<sup>a</sup>  
 1000

<b>Debris Flow ID</b>	<b>Decaulne et al. (2005) estimated deposition (m<sup>3</sup>)</b>	<b>Deposition (m<sup>3</sup>) – this study</b>	<b>Deposition from linear lower surface (m<sup>3</sup>) - this study</b>	<b>Deposition extrapolated from all cross sections (m<sup>3</sup>) - this study</b>	<b>Deposition extrapolated from 3 cross sections (m<sup>3</sup>) - this study</b>
<b>1DF</b>	-	8287 (±66%)	11 584	7977	8359
<b>2DF (1)</b>	3000	1925 (±134%)	-	1770	2804
<b>3DF (4)</b>	1000	1119 (±124%)	-	-	-
<b>5DF</b>	-	136 (±136%)	128	-	-
<b>7DF</b>	-	562 (±160%)	531	-	-
<b>8DF</b>	-	211 (±195%)	918	-	-
<b>10DF</b>	-	495 (±105%)	806	-	-

1001 <sup>a</sup>Numbers in brackets in the first column indicate the debris flow identification number in  
 1002 Decaulne et al. (2005).  
 1003

1004 **Table 6**  
 1005 Model results for three example flows, marked on Fig. 10, showing depth of the simulated  
 1006 flow on reaching buildings for various starting volumes and planimetric areas<sup>a</sup>  
 1007

<b>Starting volume (m<sup>3</sup>) :</b>		<b>8 287 : 16 000</b>	<b>15 000 : 30 000</b>	<b>20 000 : 30 000</b>
<b>area (m<sup>2</sup>)</b>				
<b>flow 1</b>	<b>model 1 (m)</b>	0	0	0
	<b>model 2 (m)</b>	1.22*	1.22*	1.5*
	<b>model 3 (m)</b>	0	0	0
	<b>model 4 (m)</b>	1.16*	1.16*	1.6*
<b>flow 2</b>	<b>model 1 (m)</b>	0	0	0
	<b>model 2 (m)</b>	0.96	0.96	1.28*
	<b>model 3 (m)</b>	0	0	0
	<b>model 4 (m)</b>	0.73	0.73	0.97
<b>flow 3</b>	<b>model 1 (m)</b>	0	0	0
	<b>model 2 (m)</b>	0.99	0.99	1.32*
	<b>model 3 (m)</b>	0	0	0
	<b>model 4 (m)</b>	0.12	0.12	0.16

1008 <sup>a</sup>The first data column shows results from using the volume and area for debris flow 1DF in  
 1009 the models. Starred entries indicate where the thickness of the flows is > 1 m.  
 1010

1011 **Table 7**  
1012 Parameter values derived from least squares fits of functions given by Eqs. B5-B7 with their  
1013 associated errors  
1014

Equation	Parameter	Value	Error
B5	A	0.03267	0.01601
B5	B	$1.87617 \times 10^6$	$1.54541 \times 10^6$
B5	C	2.21702	0.1269
B6	A	35.04498	0.17543
B6	B	-8.52036	0.3586
B7	A	0.9834	0.00339
B7	B	-0.03816	0.00453
B7	C	36.30119	0.01725
B7	D	1.00308	0.01641

1015



Figure 1  
[Click here to download high resolution image](#)

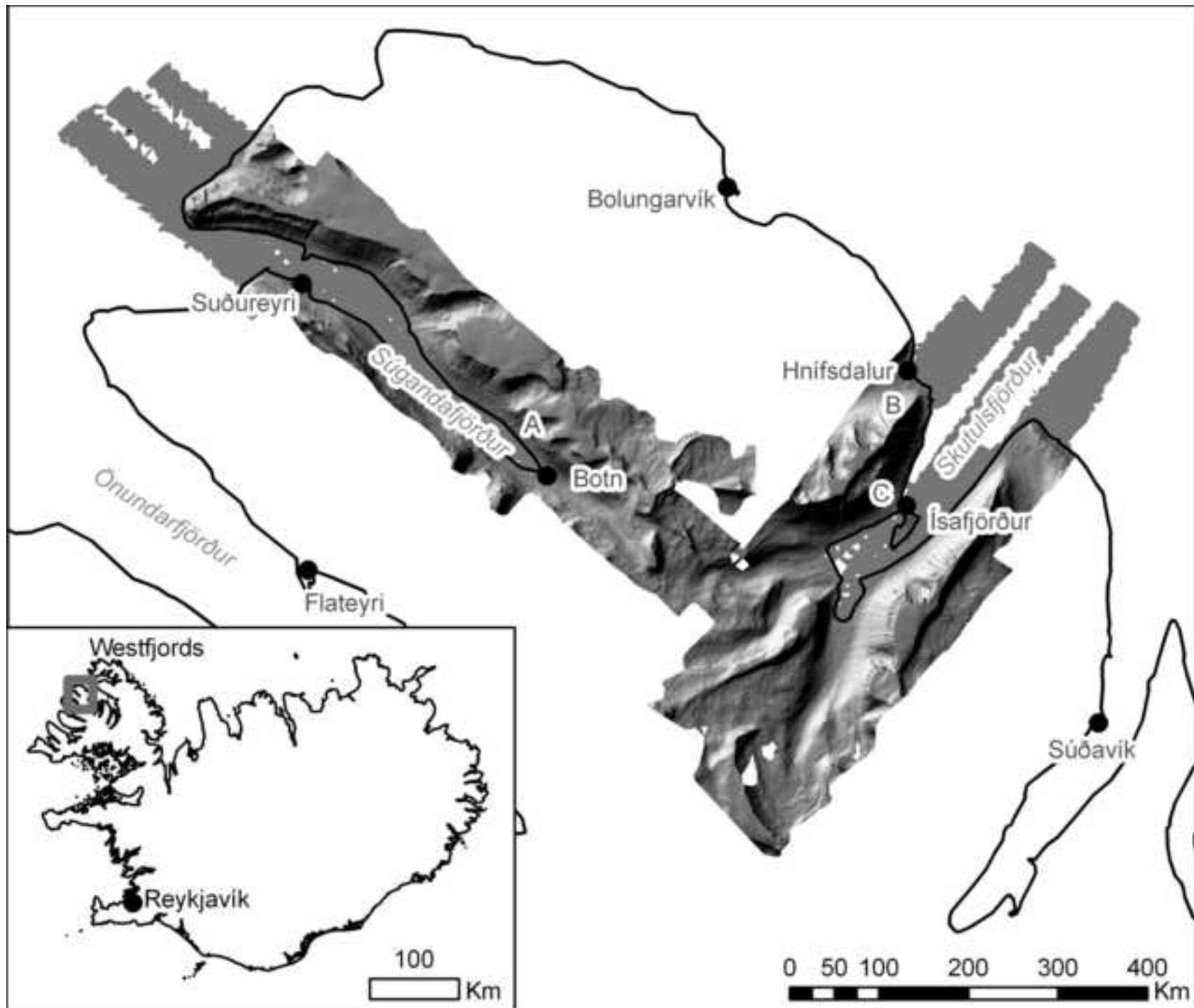


Figure 2  
[Click here to download high resolution image](#)

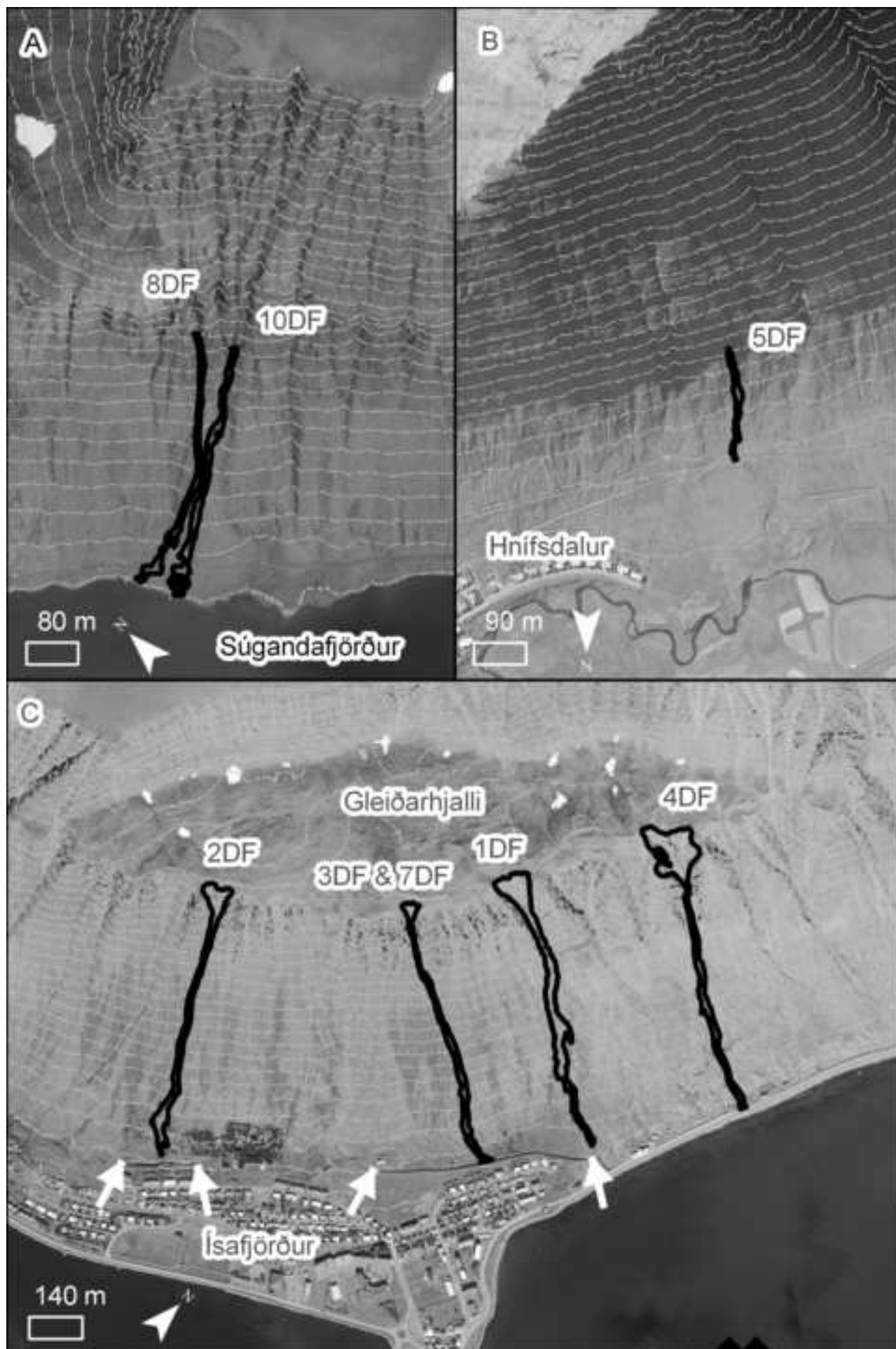


Figure 2 (colour for online)  
[Click here to download high resolution image](#)

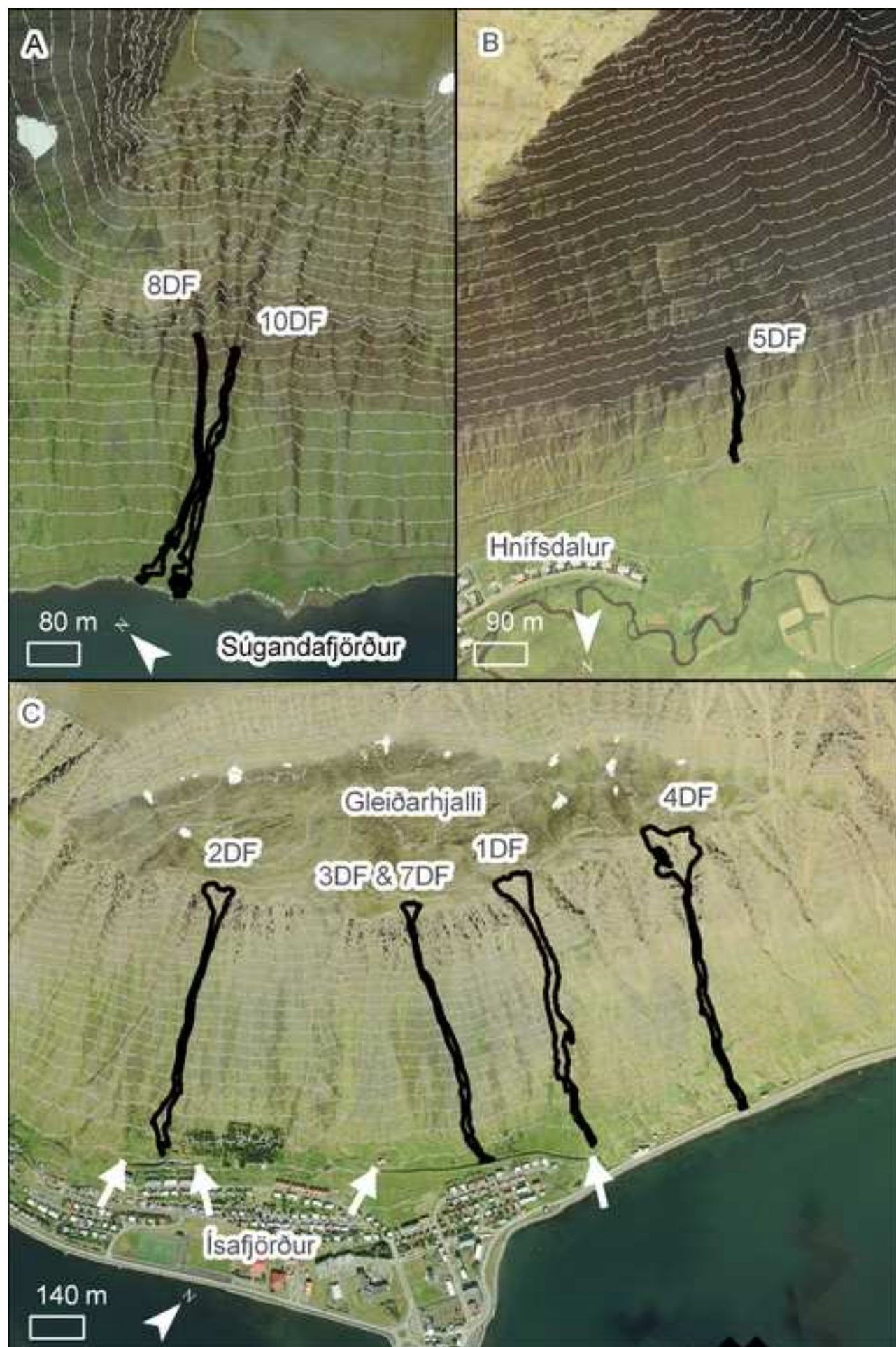


Figure 3

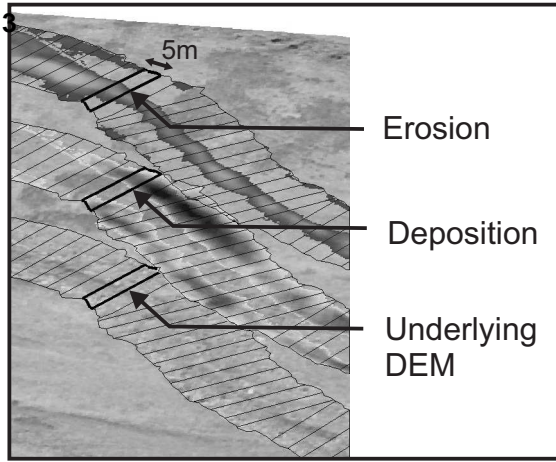


Figure 3 (colour for online)

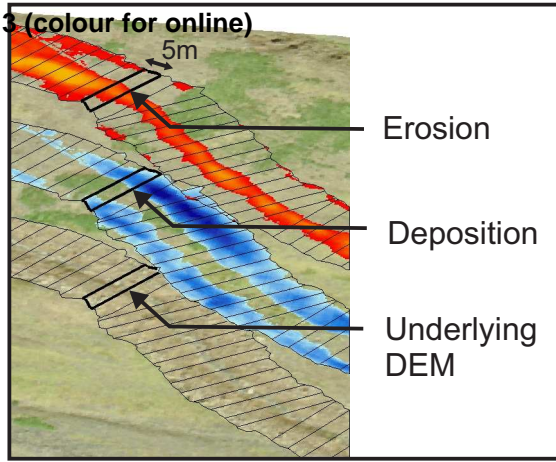


Figure 4  
[Click here to download high resolution image](#)

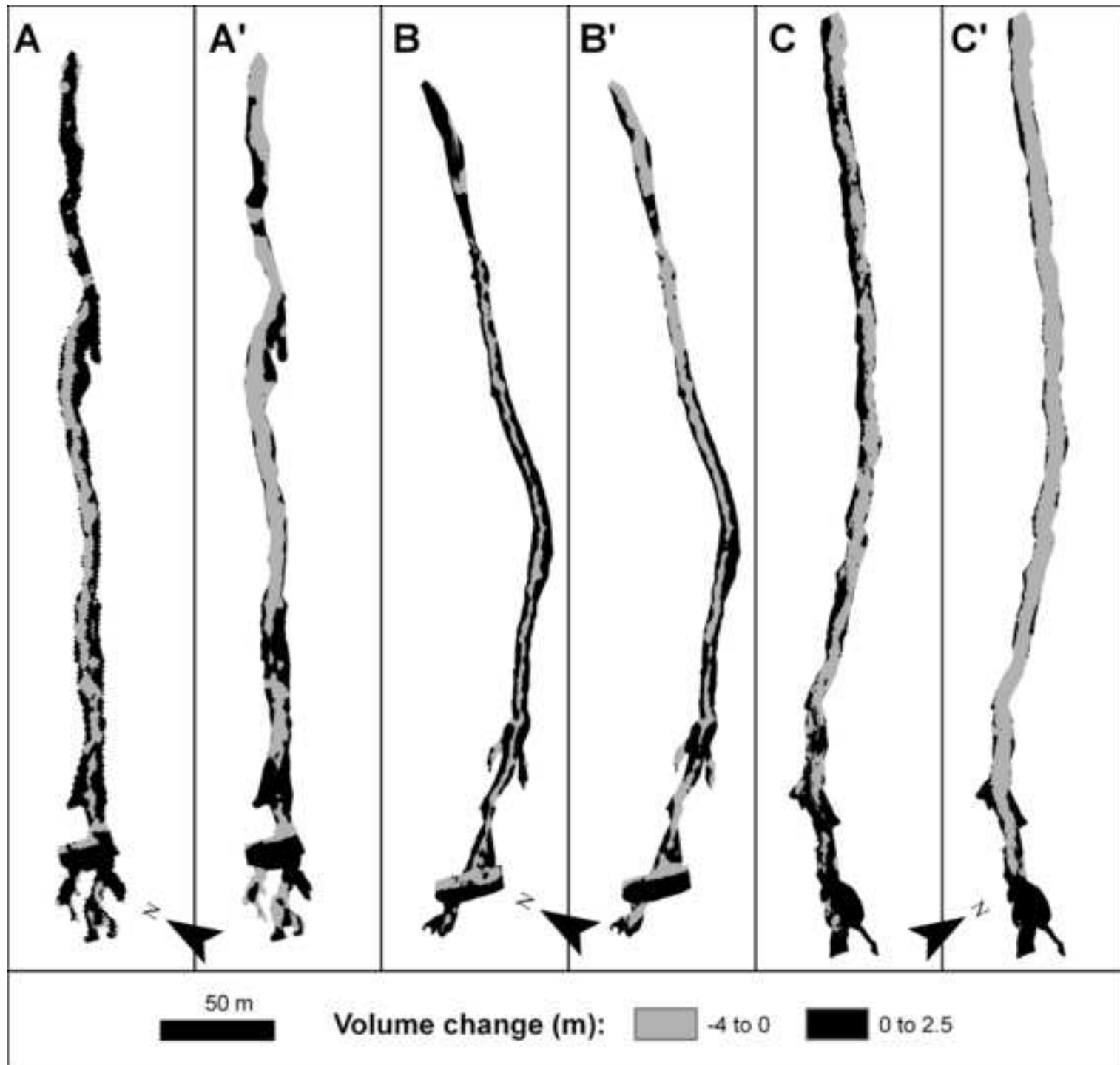


Figure 5  
[Click here to download high resolution image](#)

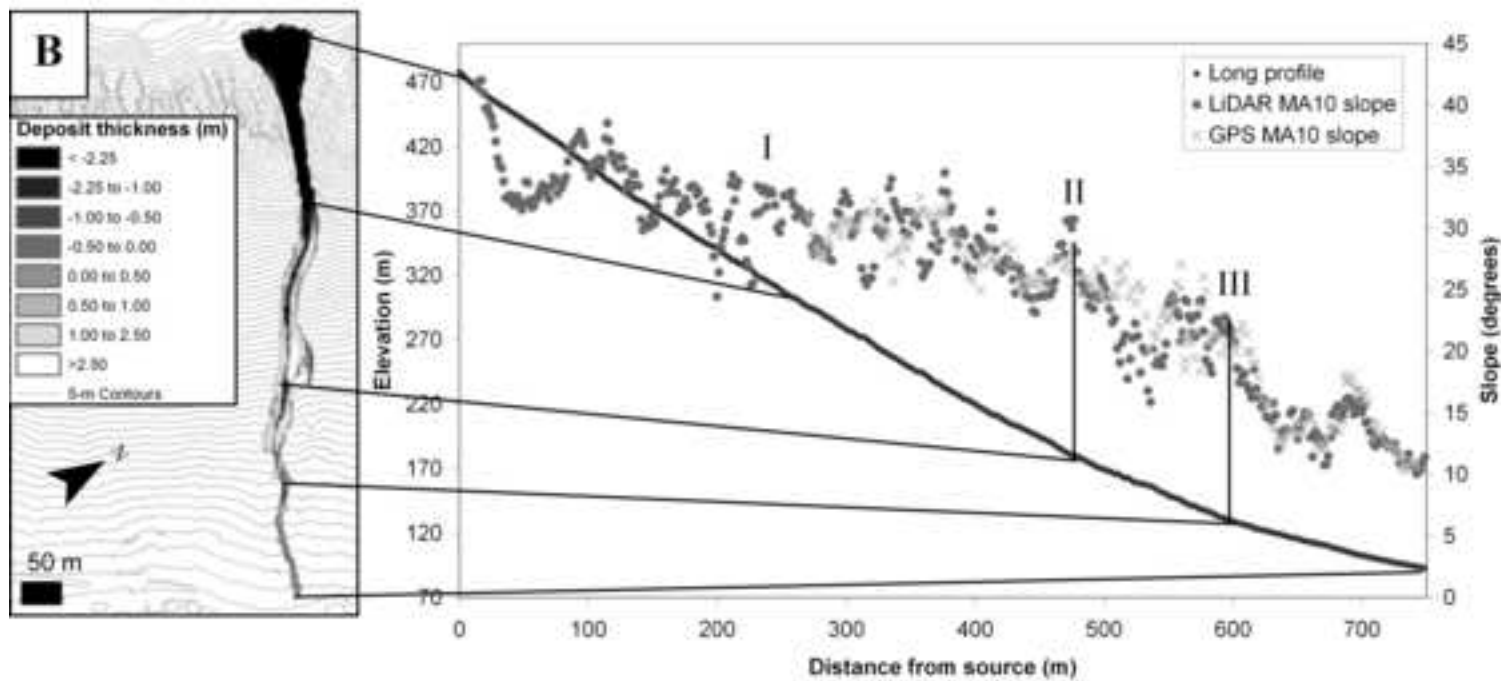
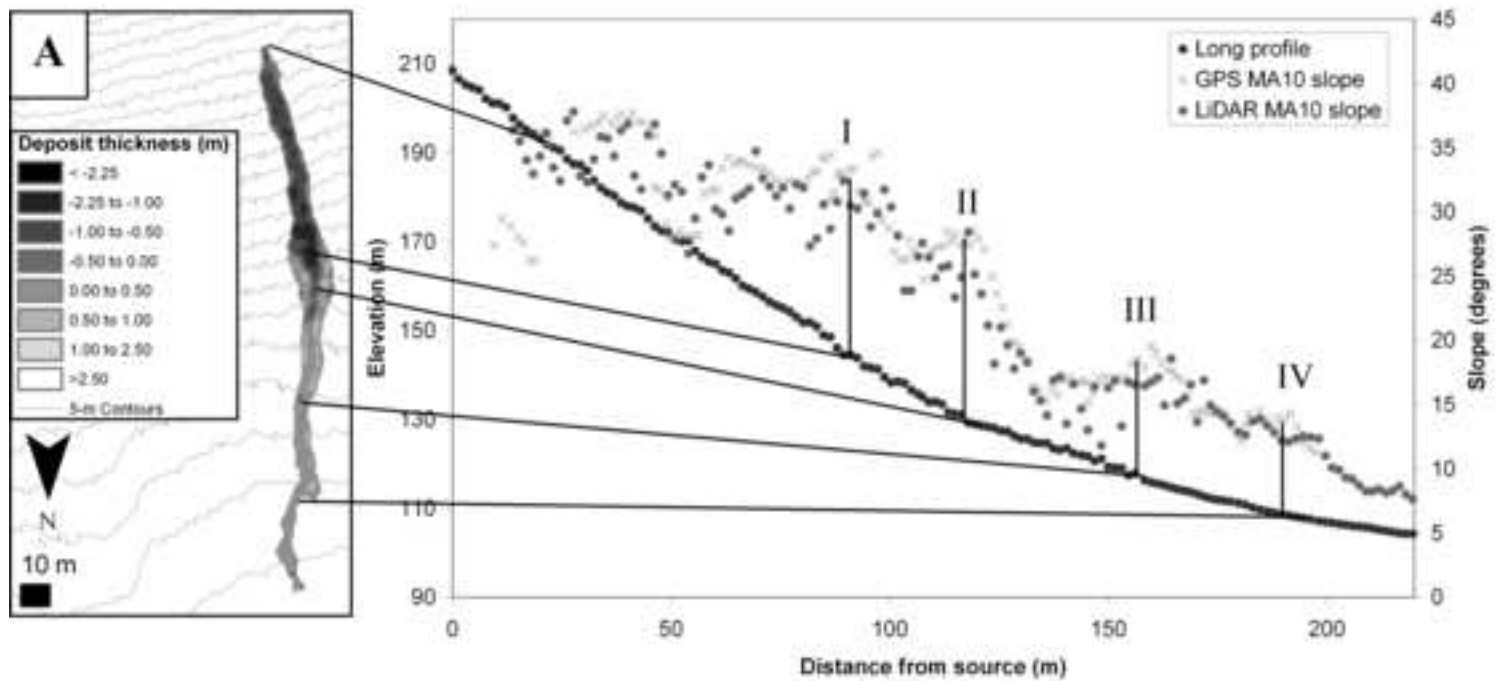
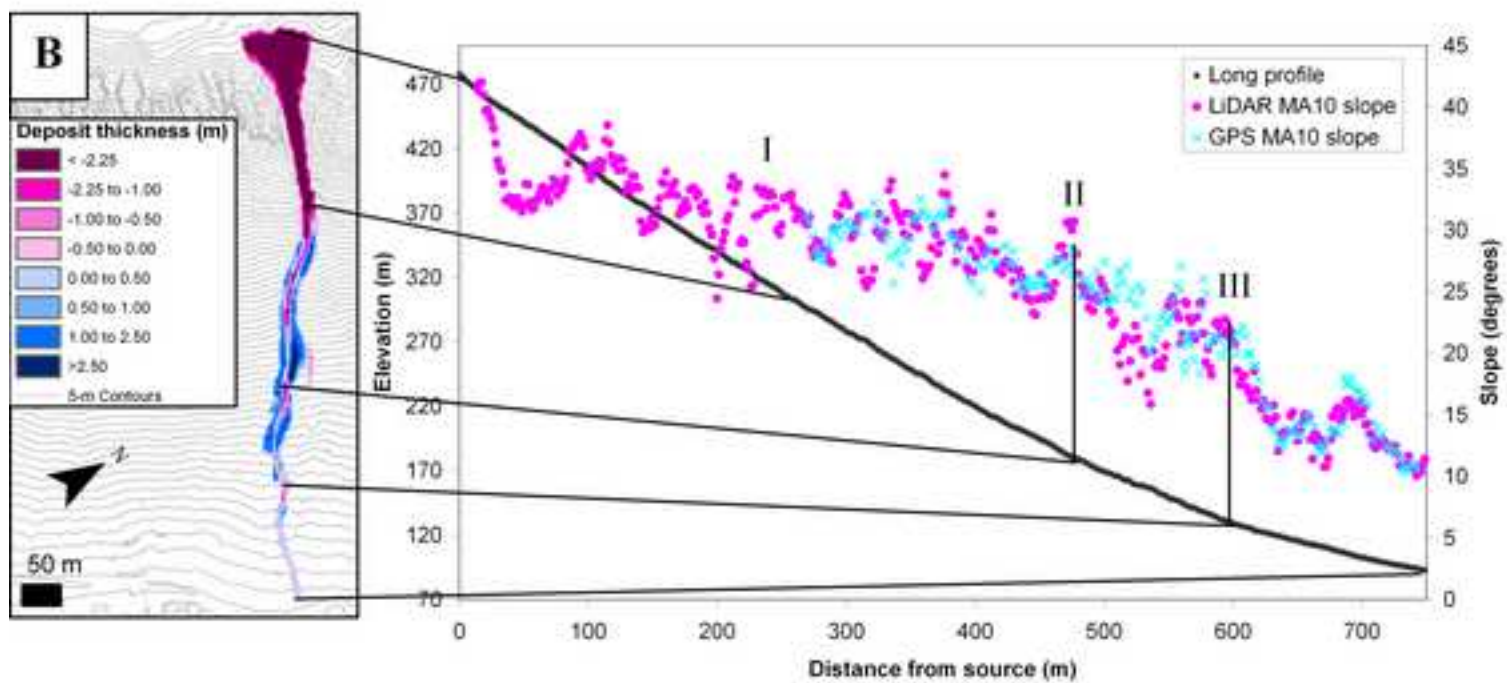
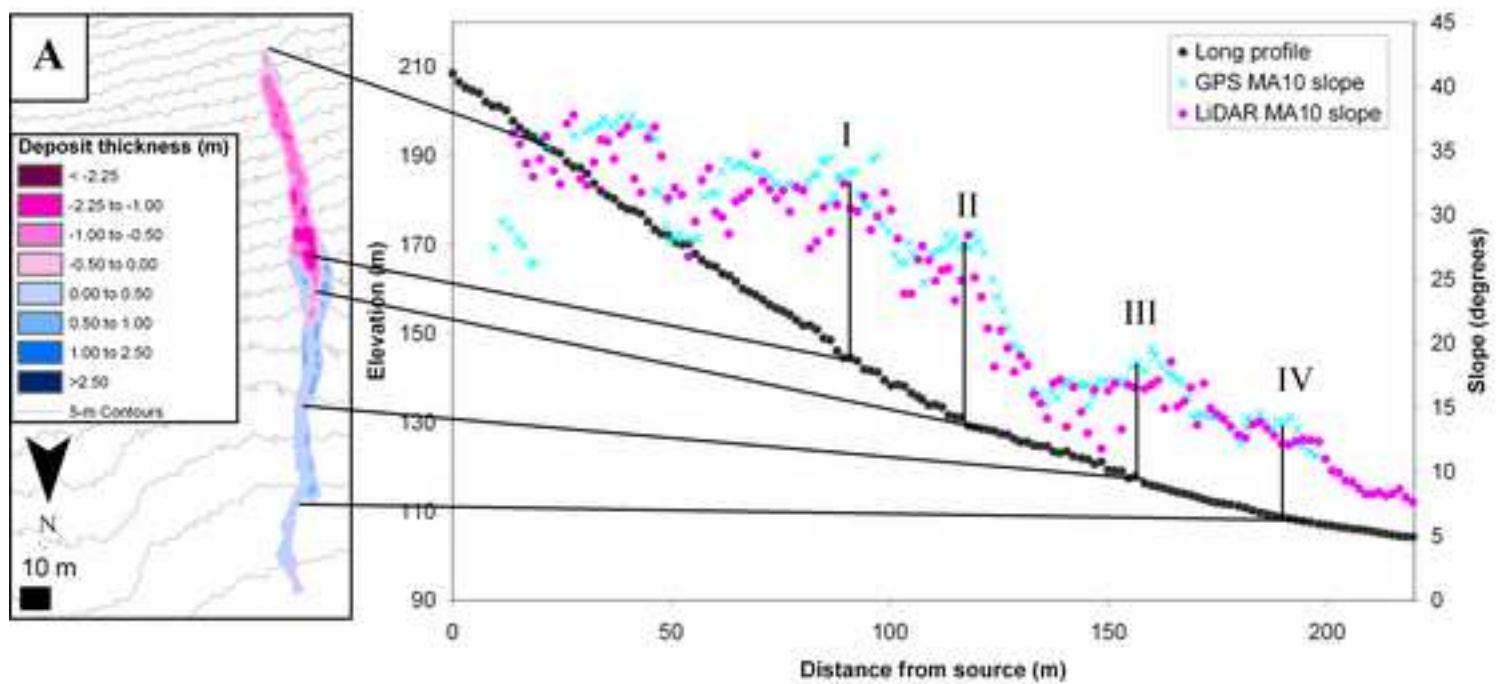


Figure 5 (colour for online)  
[Click here to download high resolution image](#)





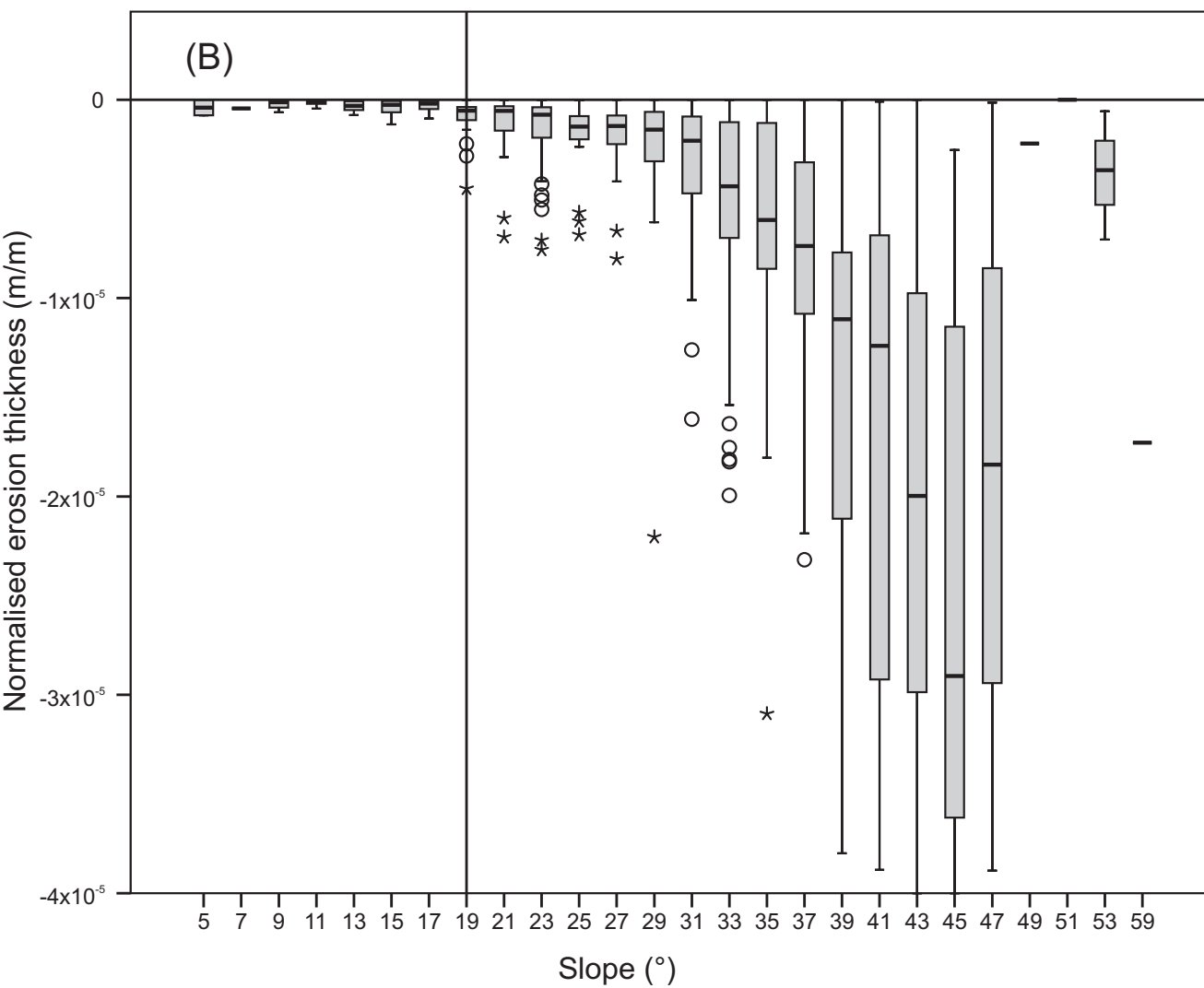
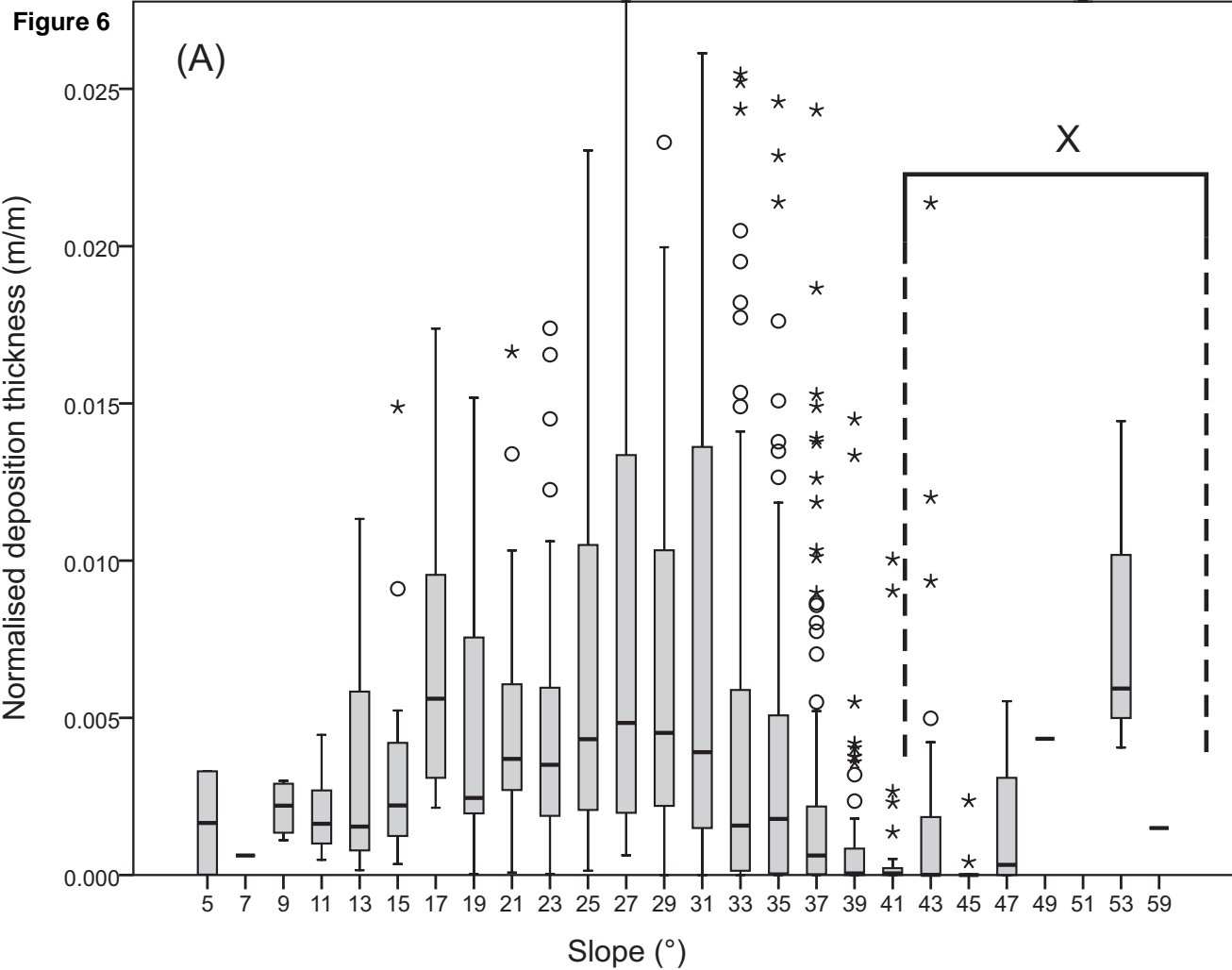
**Figure 6**

Figure 7  
[Click here to download high resolution image](#)

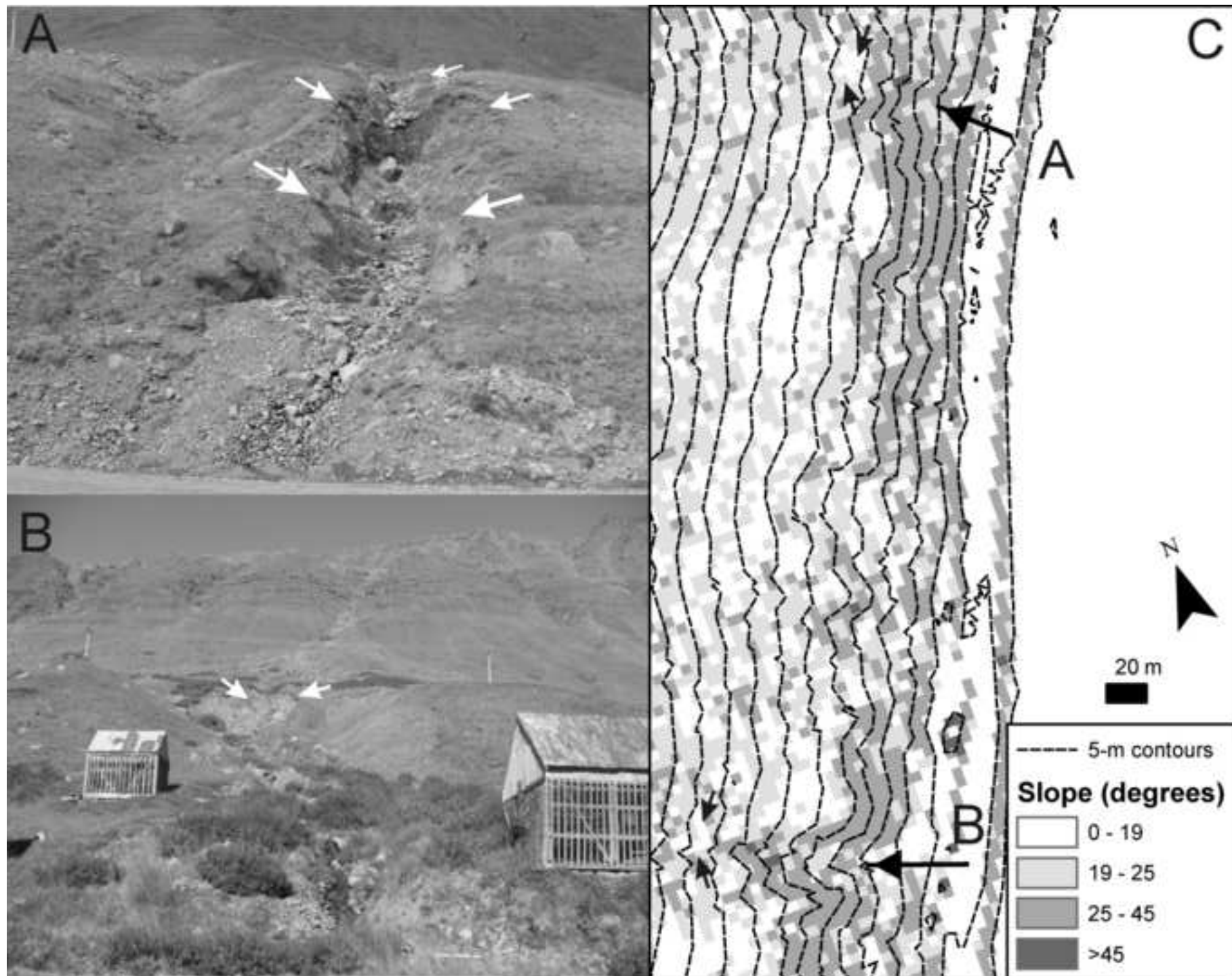


Figure 7 (colour for online)  
[Click here to download high resolution image](#)

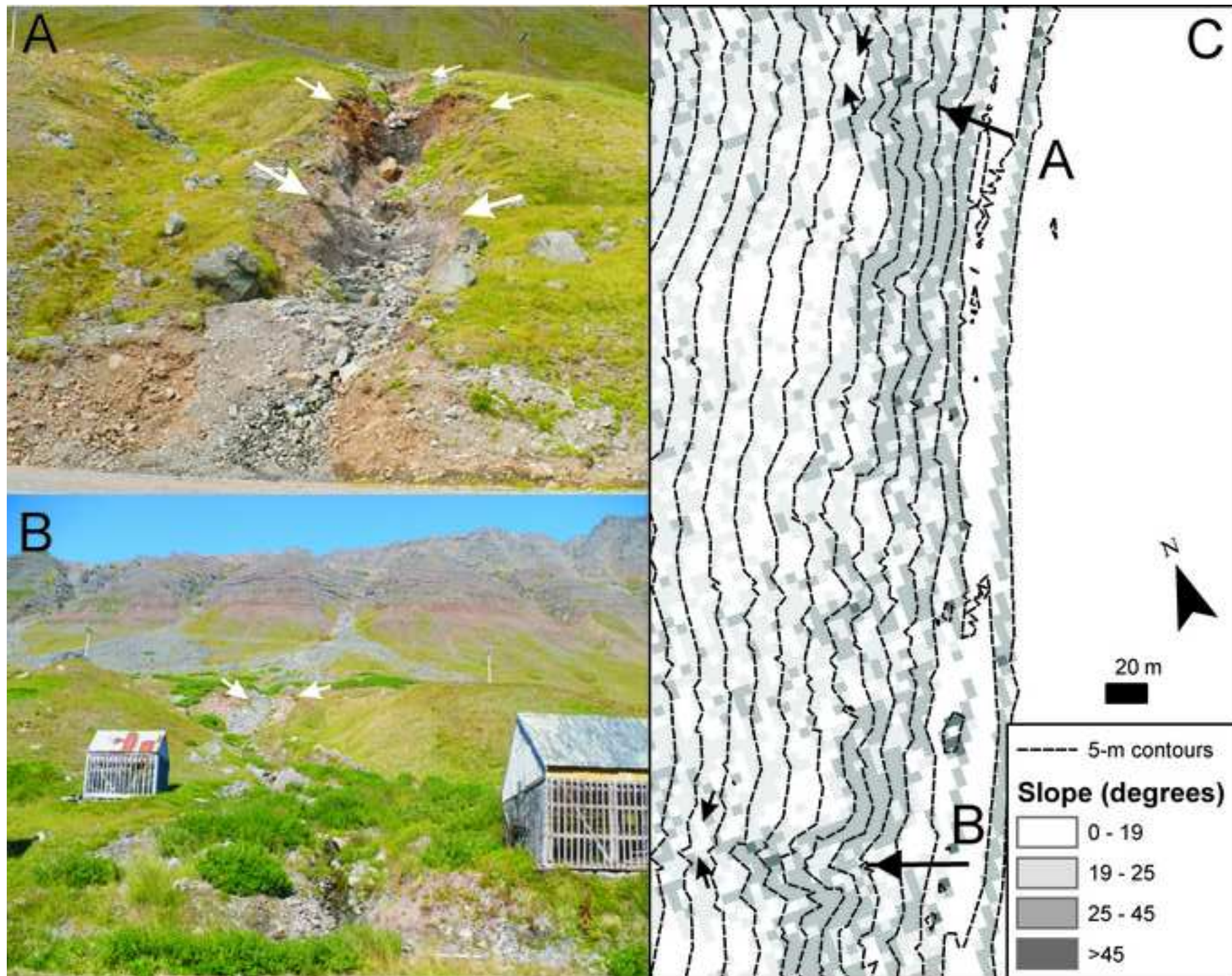


Figure 8

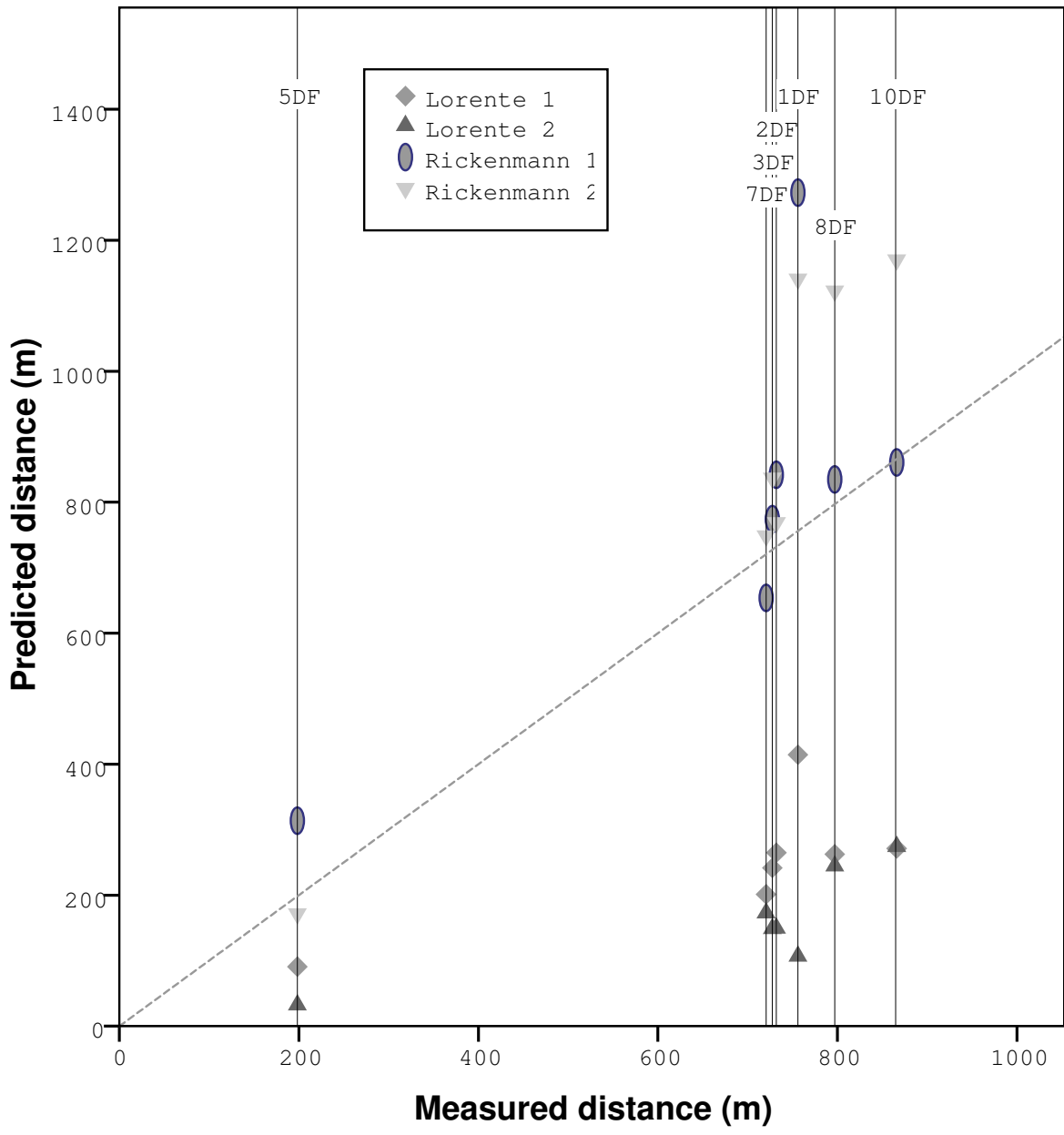


Figure 9  
[Click here to download high resolution image](#)

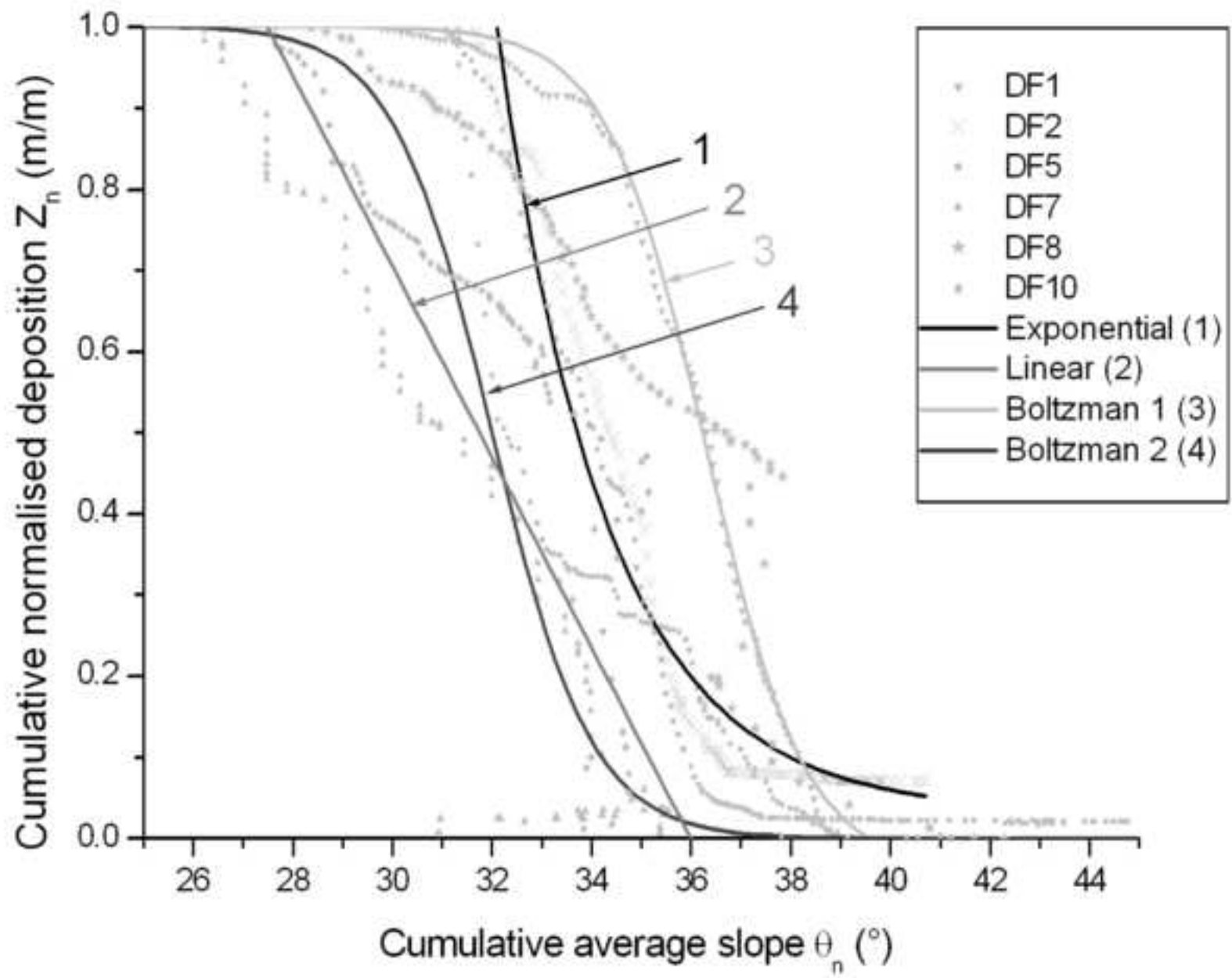


Figure 9 (colour for online)  
[Click here to download high resolution image](#)

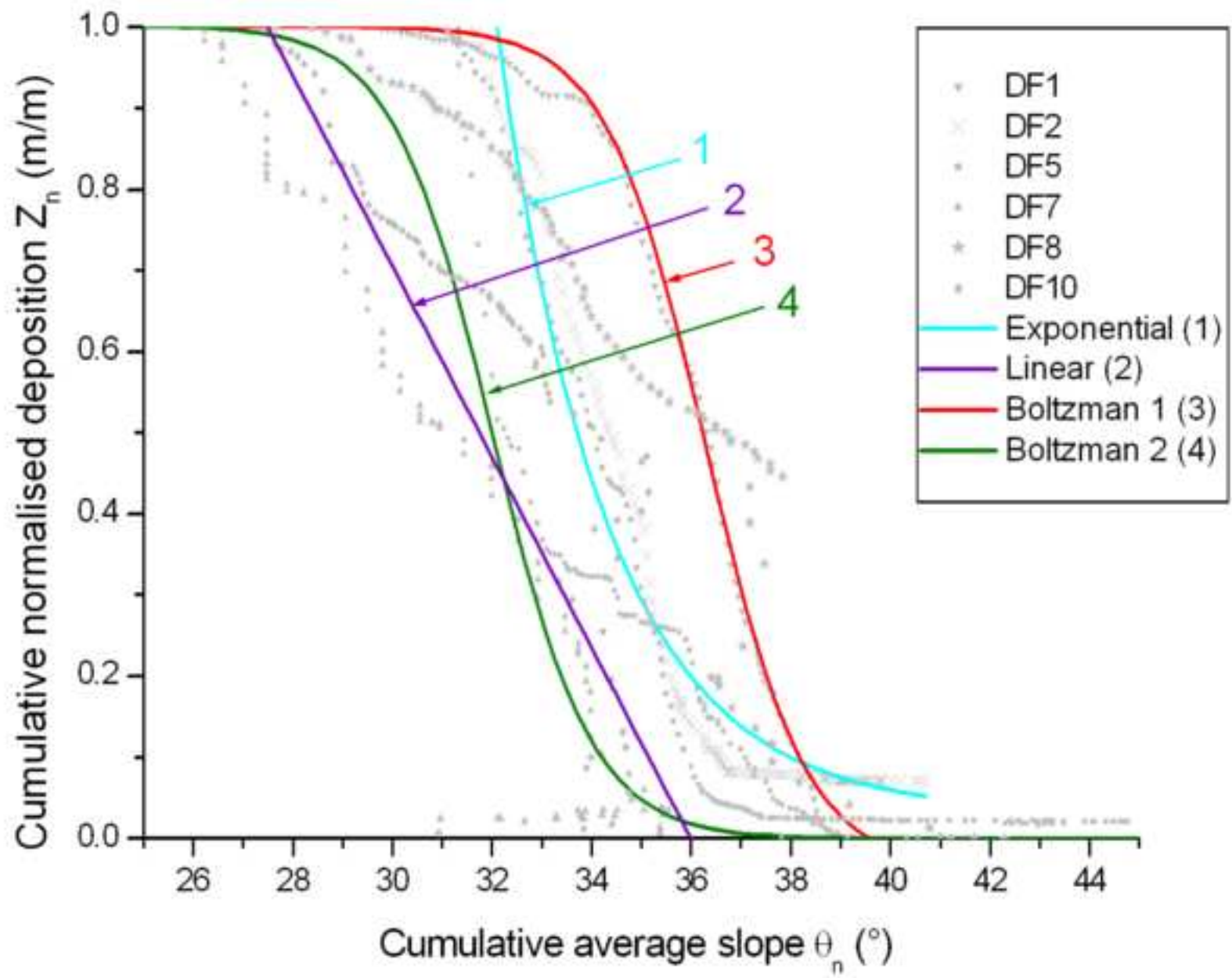


Figure 10  
[Click here to download high resolution image](#)

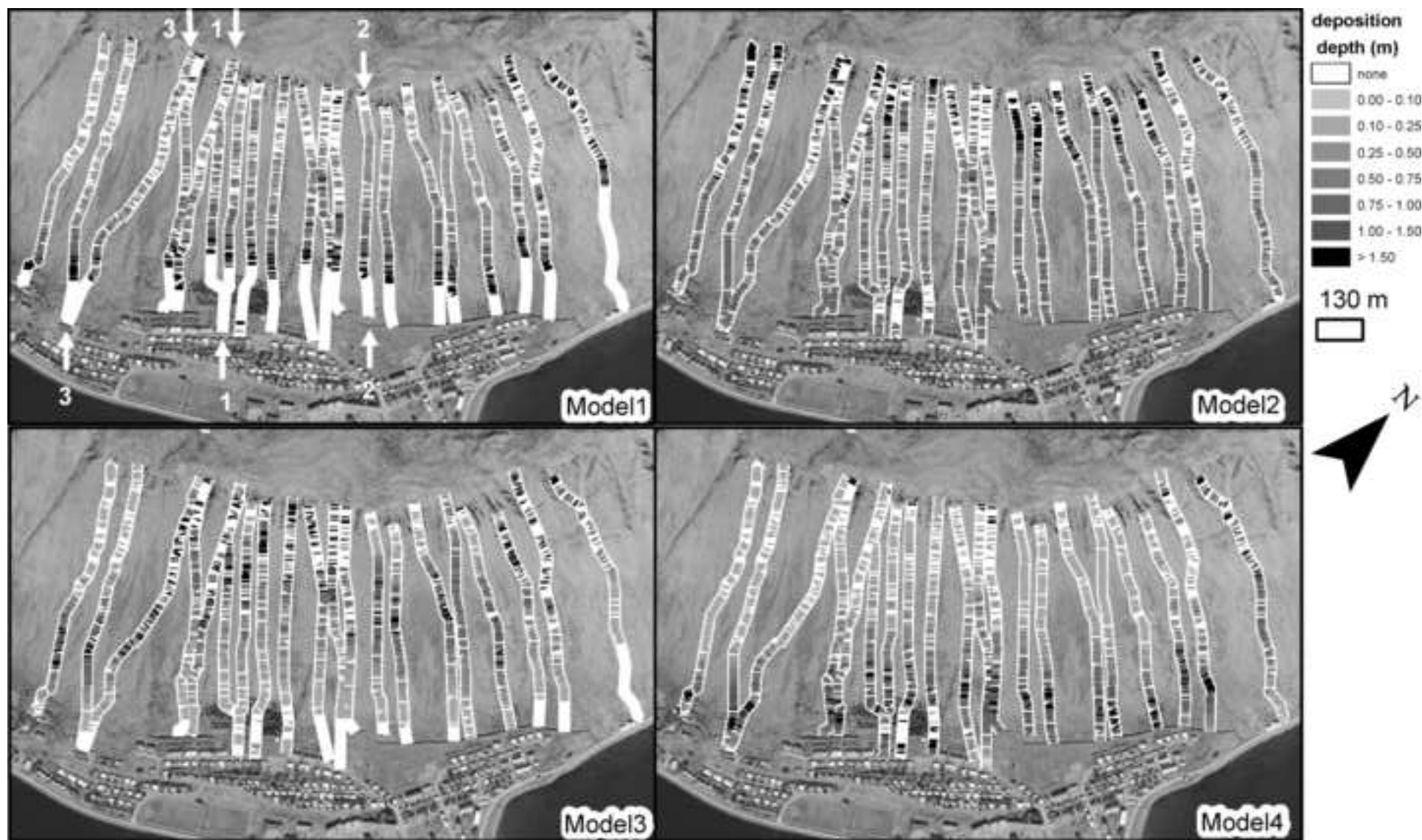


Figure 10 (colour for online)  
[Click here to download high resolution image](#)

