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1 **Manual mapping of drumlins in synthetic landscapes to assess operator**  
2 **effectiveness**  
3

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39

40

41

42

43 **Abstract**

44

45 Mapped topographic features are important for understanding processes that sculpt the  
46 Earth's surface. This paper presents maps that are the primary product of an exercise that  
47 brought together 27 researchers with an interest in landform mapping wherein the efficacy  
48 and causes of variation in mapping were tested using novel synthetic DEMs containing  
49 drumlins. The variation between interpreters (e.g., mapping philosophy, experience) and  
50 across the study region (e.g., woodland prevalence) opens these factors up to assessment.  
51 *A priori* known answers in the synthetics increase the number and strength of conclusions  
52 that may be drawn with respect to a traditional comparative study. Initial results suggest that  
53 overall detection rates are relatively low (34-40%), but reliability of mapping is higher (72-  
54 86%). The maps form a reference dataset.

55

56 Keywords: Glacial landform, Synthetic, Drumlin, Mapping, DEM, Objective

57

58 **1. Introduction**

59

60 Mapping the location and distribution of topographic features on the Earth's surface has long  
61 been considered an important means for developing an understanding of the processes that  
62 formed them (e.g., Hollingsworth, 1931; Menard, 1959). Ever since photography has been  
63 used to survey, there has been a requirement to identify features within an image. Aerial  
64 photography facilitated the holistic visualisation of features within the landscape and made  
65 photo interpretation a key tool for academic study. However, it was the military exploitation of  
66 aerial imagery that drove early development in its interpretation (e.g., Anonymous, 1963;  
67 Colwell, 1960), which was later mirrored in the photogrammetric literature (e.g., Thompson,  
68 1966).

69

70 It is against this cultural backdrop of image interpretation that Earth scientists developed  
71 qualitative methodologies for mapping landforms; techniques initially used in aerial

72 photography (e.g., Prest et al., 1968) were transferred to satellite imagery (e.g., Punkari,  
73 1980) and then digital elevation models (DEMs; e.g., Evans, 1972; Smith and Clark, 2005).  
74 The advent of computers and digital spatial data led to the development of algorithms for the  
75 automated identification of landforms (e.g., Behn et al., 2004; Hillier and Watts, 2004; Bue  
76 and Stepinski, 2006). Some landforms offer quantitatively distinct boundaries that make their  
77 identification relatively simple, for example determining flow paths for river channels using  
78 DEMs (e.g., van Asselen and Seijmonsbergen, 2006). However the boundaries of many  
79 landforms are poorly defined (e.g., Fisher et al., 2004; Evans, 2012), requiring complex  
80 visual and analytical heuristics for landform identification. This has also made automated  
81 identification a non-trivial task and it is only in the last decade that significant progress has  
82 been made (e.g., Drăguț and Blaschke, 2006; Hillier, 2008; Anders et al, 2011). Even then,  
83 anecdotal observation of researchers' preferences and its usage in publications suggests  
84 that manual interpretation is generally still considered to be more reliable.

85  
86 If manual interpretative techniques are preferred for some mapping activities it is important to  
87 assess the levels of accuracy and precision that are attainable. However, this is difficult as it  
88 is not possible to know *a priori* the actual number of features in a landscape or their 'true'  
89 boundaries. It is possible to determine a control, a sub-area within a study, within which  
90 interpreters map features that can later be compared with mapping completed for a whole  
91 study (e.g., Smith and Clark, 2005). Likewise, it is also possible to compare the mapping of  
92 different interpreters to ascertain if there are significant differences between individuals (e.g.,  
93 Podwyssocki et al, 1975; Siegal, 1977). This work suggests that variation in mapping by a  
94 single interpreter can be relatively low (Smith and Clark, 2005), but that variation between  
95 interpreters can be high. The absolute, as opposed to relative, accuracies however still  
96 require investigation.

97  
98 The purpose of geomorphological mapping is typically to produce quantitative, repeatable,  
99 observations of features in the landscape, but to what extent can subjective manual  
100 interpretations be reproducible? What is the achievable accuracy of subjective mapping?

101 What is the variation in accuracy and which characteristics of the interpreter and landscape  
102 govern any variation? Are there any systematic biases in the mapping, and how do these  
103 relate to the definition of the feature's boundary being used in practice? These are important  
104 questions to understand when making inferences from data and should guide the  
105 development of clear and consistent methodologies for interpretative mapping, yet their  
106 investigation is difficult without *a priori* knowledge of landscapes and the variability between  
107 both interpreters and the landforms they map. Synthetic DEMs (e.g., Hillier and Smith, 2012),  
108 on the other hand, are designed terrains within which key components are known *a priori*,  
109 and so they have facilitated some progress on these and related questions. Specifically,  
110 synthetic DEMs were used to determine an optimal semi-automated method for drumlin  
111 extraction (Hillier and Smith, 2014) and to assess multi-resolution segmentation algorithms  
112 for delimiting drumlins (Eisank et al, 2014). In addition, a pilot study on manual mapping  
113 tentatively indicated that drumlin amplitude may be the key dimension governing drumlin  
114 detectability (Fig. 1c) (Arumgam et al., 2012).

115

116 This paper and the accompanying maps present the outcomes of an exercise that brought  
117 together a variety of researchers with an interest in landform mapping where the efficacy and  
118 variation of interpretation between individuals was tested using synthetic DEMs. Initial  
119 findings from this work are presented, and the maps form a reference dataset for future work.

120

## 121 **2. Methods**

122

### 123 **2.1 Research Design**

124

125 In order to test aspects of interpreter mapping, such as 'completeness' (defined below), it is  
126 necessary to know with certainty exactly which landforms exist in a landscape and where  
127 they are, but for incompletely defined landforms in a real landscape this is unknowable.

128 Thus, a sufficiently realistic DEM containing an *a priori* known answer is required to give  
129 these absolute measures of effectiveness (see 'Results'), which traditional mapper inter-

130 comparisons simply cannot provide or estimate. One way to generate this might be to use a  
131 'landscape evolution model' (e.g., Chase, 1992; Braun and Sambridge, 1997) to generate an  
132 artificial landscape that is both realistic and statistically comparable to a real landscape  
133 including all factors such as vegetation and anthropogenic alteration, but this has not yet  
134 been achieved for glacial bedforms. Hillier and Smith (2012) therefore proposed an  
135 alternative hybrid method. They used an existing DEM of real terrain and inserted synthetic  
136 landforms of known size and shape into it. The locations and orientations of the landforms  
137 are set differently for each synthetic DEM. Synthetic DEMs created in this way make it  
138 possible to assess the ability of interpreters to identify landforms in an absolute sense,  
139 something that is not possible with a real landscape. Any number of synthetic variants of a  
140 landscape can be produced for interpreters can map. Then, comparing and contrasting the  
141 mapped outputs allows conclusions to be drawn that include quantitative error estimates  
142 about properties such as absolute accuracy, variability, repeatability, and systematic biases.  
143 Thus, subject to establishing the representativeness of the synthetic DEMs used in each  
144 case study, this increases the number and strength of conclusions that may be drawn with  
145 respect to a traditional comparative study. An experimental approach employing synthetic  
146 DEMs is used here. These currently insert only one landform type (i.e., drumlins), however  
147 this is sufficient to support the aims of the paper and there is no reason why more complex  
148 synthetics could not be constructed in the future.

149

## 150 **2.2 Choice of landform**

151

152 For this work drumlins were selected as the landform to be mapped. Drumlins are elongate  
153 hills, typically 100s m long and up to a few 10s of metres high (Menzies, 1979; Wellner,  
154 2001; Smith et al., 2007; Clark et al, 2009; Spagnolo et al, 2012; Hillier and Smith, 2014).  
155 They are very likely formed subglacially, parallel to ice flow (Smith et al, 2007; King et al,  
156 2009; Johnson et al, 2010), and, as they can persist in the landscape, they encode  
157 information on the location and direction of flow of former ice cover (e.g., Hollingsworth,  
158 1931; Kleman and Borgström, 1996; Finlayson et al, 2010) and perhaps even the nature and

159 velocity of ice flow (e.g., Colgan and Mickelson, 1997; Smalley et al, 2000; Stokes and Clark,  
160 2002). Such information is valuable for understanding the histories of past ice-sheet change.  
161 Thus, they are of scientific interest. Commonly, drumlins are mapped manually, often by an  
162 individual interpreter (e.g., Hughes, et al, 2010). However, their exact form has not yet been  
163 definitively, robustly and quantitatively defined and so a drumlin's spatial footprint is open to  
164 interpretation and differs between interpreters (see e.g., Fig 1a of Hillier and Smith, 2014).  
165 Despite this there has been some limited success in the use of automated algorithms to map  
166 drumlins (e.g., Saha et al, 2011). As such, drumlins seem likely to be able to be mapped  
167 accurately, reproducibly and objectively, and are regularly interpreted upon this basis, yet  
168 making this operational remains a challenge.

169

### 170 **2.3 Generation of Synthetic Landscapes**

171

172 In order to generate synthetic DEMs using the method of Hillier and Smith (2012), a 'donor'  
173 DEM is required. This study uses the NEXMap<sup>®</sup> Britain DEM, which is an interferometric  
174 synthetic aperture radar (IfSAR) product with a spatial resolution of 5 m and vertical accuracy  
175 of ~0.5-1 m (Intermap, 2004). Once the DEM is selected it is then necessary to manually  
176 identify the drumlins present. In this case the identification is that done by Smith et al (2006)  
177 (Fig. 1b), who used different visualisations of the landscape (i.e., relief shaded in two  
178 orthogonal directions, gradient, curvature, local contrast stretch). This mapping approach  
179 was employed by Smith et al (2006) on multiple occasions in order to both check the  
180 repeatability of the mapping and to reduce bias that may have been introduced in any one  
181 session. The mapping stage serves two purposes: (1) to parameterise the synthetic drumlins  
182 to be inserted in to the DEM, and (2), to allow the removal of the original drumlins.

183

184 The population of originally mapped drumlins were parameterised in terms of their shape  
185 (i.e., Gaussian) and dimensions - height ( $H$ ), width ( $W$ ), and length ( $L$ ). These were then  
186 used to generate a set of synthetic, idealised, drumlins; each mapped drumlin created one  
187 synthetic drumlin, which retained the same identification number and parameter triplet ( $H$ ,  $W$ ,

188 *L*) wherever it was placed. Visually selected median filters (see Hillier and Smith, 2014) were  
189 used to quantify and remove the original drumlins. The synthetic features were then  
190 randomly inserted in a non-overlapping fashion back into the DEM, which also preserved  
191 their spatial density and the distribution of their orientations. These measures are sufficient  
192 to ensure that errors associated with recovery of *H*, *L* and *W* are the same in the synthetics  
193 as the original landscape, at least for semi-automated techniques (Hillier and Smith, 2012).  
194 This, combined with the use of a real DEM, ensured that the synthetics were statistically  
195 representative of the real landscape. Full details of the procedure are outlined in Hillier and  
196 Smith (2012). It was intended that drumlin-shaped landforms were equally as difficult to find  
197 in the synthetics as they are in reality. The perfect Gaussian shape of the synthetics and their  
198 ability to cut across landscape features in an unnatural way may tend to act to make them  
199 easier to identify. Conversely, their lack of alignment with each other may make them more  
200 difficult to find than natural drumlins. The lack of local parallel alignment was highlighted as  
201 a disadvantage during the workshop. As a result, five additional DEMs were created wherein  
202 drumlins were aligned perpendicular to the original flow field, which also avoids confusion  
203 with any incompletely removed glacial texture in the DEM. If anything, these synthetic DEMs  
204 including parallel alignment represent a limiting best case for drumlin detection. None of the  
205 synthetics used include parabolic, ovoid or crosscutting drumlins (e.g., Rose and Letzer,  
206 1977; Shaw, 1983; Shaw and Kavill, 1989; Hillier and Smith, 2008; Boyce and Eyles, 1991;  
207 MacLachlan and Eyles, 2013), which could complicate mapping.

208

## 209 **2.4 Study Area**

210

211 This work used the same study area as Hillier and Smith (2012) (Fig. 1a), which has been  
212 mapped in detail by other researchers studying the glacial geomorphology of the region (e.g.,  
213 Rose and Letzer, 1975, 1977; Smith et al, 2006; Rose and Smith, 2008; Finlayson et al,  
214 2010; Hughes et al., 2010). This area of Scotland sits between the Grampian Highlands to  
215 the north and the Southern Uplands to the south and was glaciated during the Last Glacial  
216 Maximum (LGM) and Younger Dryas (YD). It contains two identifiable suites of features



217 interpreted as "classically shaped" drumlins, namely of approximately leminscate or elliptical  
218 footprints (e.g., Chorley, 1959; Reed, 1962). The drumlins mark the presence of flowing ice  
219 during these time periods, broadly west to east during the LGM and north to south during the  
220 YD. Drumlin dimensions are broadly comparable to those of other drumlins in the UK (Hillier  
221 and Smith, 2014). The study area is similar to many previously glaciated regions of the UK in  
222 that it contains topographic complexity in the form of regional relief (e.g., hills; Hillier and  
223 Smith, 2008) and non-glacial anthropogenic 'clutter' (e.g., trees, houses; Sithole and  
224 Vosselman, 2004), which vary in their amplitude and spatial density, respectively; it is  
225 intended that these variations across the study area will allow their impacts upon mapping to  
226 be isolated.

227

## 228 **2.5 Interpretive Mapping**

229

230 In order to test the variability of interpretive mapping individual researchers were invited to  
231 map drumlins in the synthetic DEMs. There were a total of 27 respondents who had a range  
232 of experiences and expertise within geomorphology, glaciology, Earth science and remote  
233 sensing. They included undergraduate and postgraduate students, faculty and post-doctoral  
234 researchers from a range of countries and of different nationalities, although all from Europe  
235 or North America with a bias towards the United Kingdom.

236

237 In addition, whilst this manuscript and its associated maps present the outputs of this  
238 mapping, a workshop was organised in order to present the draft results to participants and  
239 to drive discussion. The ultimate goal of the project is to highlight the nature of differences  
240 between interpreters and to begin the development of objective criteria for mapping. In total  
241 25 people completed mapping for the project, with an overlapping set of 24 participants who  
242 attended the workshop.

243

244 Interpreters were supplied with five raw synthetic DEMs and guidelines clearly stating that  
245 each DEM contained exactly 173 drumlins, creating a total dataset of 865 landforms.

246 Interpreters were requested to prepare the DEMs for mapping using their software of choice  
247 and whilst there was an assumption that relief shading, gradient and curvature (Smith and  
248 Clark, 2005) may be prominent visualisation techniques, they were not restricted in the use  
249 of any particular manipulation. In order to generate a statistically significant number of results  
250 interpreters were requested to map:

- 251 • drumlin outlines for each DEM using their preferred or 'best' visualisation
- 252 • separate sets of outlines individually using each of the relief shaded, gradient and  
253 curvature visualisation for two randomly selected DEMs
- 254 • mapping of drumlin ridge crests and high points for two randomly selected DEMs  
255 using their 'best' method.

256

257 Mapping results were returned as individual shapefiles and a questionnaire completed,  
258 qualitatively surveying individual approaches to mapping. Synthetic drumlins were,  
259 simplistically, considered to be 'found' if their centre points lay within a digitised outline; when  
260 multiple synthetics were encompassed, the closest to the digitised outline's centre was  
261 selected. Subsequently, all mapped polygons (outlines, ridges, centre points) within  
262 shapefiles were re-numbered so their ID numbers matched those of the relevant synthetic  
263 drumlin. Thus, the behaviour of each drumlin's *H*, *W*, *L* triplet can be compared between  
264 interpreters, DEMs and visualisations.

265

### 266 **3. Results**

267

268 The five main synthetic DEMs were mapped by 25 interpreters giving a total of 21,625  
269 drumlins to be identified by the group. 12,121 outlines were mapped in interpreters' preferred  
270 visualisations, 8,667 of which were coincident with the original synthetic drumlins. Table 1  
271 presents an error matrix in the standard format used in remote sensing (e.g., Lillesand et al,  
272 2008) reporting these results. For accessibility, the equivalent terminology from information  
273 retrieval theory is also given (e.g., Manning et al, 2008). The matrix shows that whilst the  
274 'overall accuracy' is relatively low (8667/25,079) at 34%, the producer's accuracy, 'reliability'

275 or 'precision' (8,667/12,121) is relatively high at 72% (i.e., few false positives). This reflects  
 276 the conservative number of drumlins generally mapped, but the high confidence in their  
 277 accuracy. As a result, the user's accuracy, 'completeness', or 'recall' is also relatively low at  
 278 40% (8,667/21,625). Figure 2 shows the number of drumlins mapped by individual  
 279 interpreters across all five DEMs; there is some variability in the totals mapped which is likely  
 280 dependent upon the visualisation method and mapping philosophy employed by the  
 281 individual. However, the number of correct drumlins is much more stable, typically between  
 282 300 and 500 landforms with a mean of 347 and standard deviation of 97.

283

284 To supplement the main mapping, 12 interpreters mapped one of four additional synthetic  
 285 DEMs containing parallel alignment, a total of 2076 drumlins. Fig. 2 shows numbers scaled  
 286 (x5) to allow comparison with the main mapping. The number of correctly mapped drumlins  
 287 likely increases a little (t-test, unequal variance,  $p=0.11$ ) for these DEMs to 402 with a  
 288 standard deviation of 82, with the variability likely arising for similar reasons to that in maps  
 289 1-5. The increase in correctly mapped drumlins is driven by a moderately sized but notable  
 290 increase in 'reliability' (885/1028) to 86%, leaving 'completeness' (885/2076) at the slightly  
 291 raised level of 43% and 'overall accuracy' (885/2219) up to 40%, both still relatively low.  
 292 Thus, mappers are able to make some use of parallel alignment although perhaps less than  
 293 expected from the strength of feeling about this at the workshop. Idealised drumlin shapes  
 294 combined with parallel alignment, especially when using a necessarily smoothed (2 km mean  
 295 filter) flow field, arguably represents a best case scenario for detection.

296

297 **Table 1:** Error Matrix showing the number of correctly mapped drumlins in addition to errors  
 298 of omission and commission. See text for an interpretation of the matrix. Figures for DEMs  
 299 containing parallel alignment are given in brackets.

	Mapped	Not Mapped 'omission'	Total
Correct	8667 (885) [True positive]	12958 (1191) [False negative, Type II error]	21625 (2076)
Incorrect (commission)	3454 (143)		3454

	[False positive, Type I error]		(143)
	12121 (1028)	12958 (1191)	25079 (2219)

300  
301

302 The maps present the outcomes of mapping from each of the individual interpreter's  
303 digitisation of drumlin outlines using their 'best' attempt based upon their preferred  
304 visualisation. Each of the five synthetic DEMs (Maps 1-5) is presented separately as part of  
305 an interactive PDF, as are the DEMs containing parallel conformity (Maps 6-9). The PDF is  
306 designed to be a digital product that the reader interacts with; map layers within the PDF can  
307 be turned on and off allowing the original synthetic drumlins to be viewed, along with  
308 mapping by each of the interpreters. This allows direct comparison by switching between  
309 layers. The underlying topography is displayed as relief-shaded terrain illuminated from 315°.   
310 Additionally there are **two** layers that display the outlines of the synthetic drumlins: (1) the  
311 'Number of Times Identified' layer shows the frequency with which the drumlin was correctly  
312 identified and (2) the 'Height' layer shows the amplitude of the drumlin classified using a  
313 Jenk's Natural Breaks algorithm.

314

315 **4. Conclusions**

316

317 Manual mapping of landforms from remotely sensed imagery remains a common task in the  
318 Earth sciences because it both seems effective and is practical to implement. In contrast,  
319 whilst automated and semi-automated detection methods have significantly improved, they  
320 remain difficult to implement and are of variable quality. Yet the objectiveness and  
321 repeatability of manual interpretation can be questioned. Testing the efficacy of mapping in  
322 an absolute sense is difficult as it is not possible to know, *a priori*, the landforms that actually  
323 exist in the landscape.

324

325 To this end, this work utilises innovative synthetic landscapes. The current process takes a  
326 DEM, removes existing landforms (specifically drumlins) and then uses the metrics from this  
327 landform population to parameterise a new idealised set that are inserted back in to the  
328 model DEM. Five variations of this landscape were generated and 25 interpreters with  
329 varying ability, experience, preferences, and time available mapped the drumlins within them.  
330 This provides a first assessment of mapper capabilities with respect to a known baseline.  
331 Each individual interpreter's mapped boundaries are overlaid on the DEMs and presented  
332 within the maps accompanying this manuscript. As such, the maps form a reference dataset.  
333 Initial results suggest that overall detection rates are relatively low, but reliability of mapping  
334 can be high.

335

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337

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341 Mather's quantitative MSc work, co-supervised by N. Woodcock, on drumlin morphology  
342 (Mather, 2008) acted as an early driver for this project. The NEXTMap DEM data were  
343 supplied to MS.

344

### 345 **Software**

346

347 Esri ArcGIS 10 was used for the production of the accompanying maps, with many of the  
348 individual mappers also using it to digitise the outlines of the synthetic drumlins. GMT  
349 (Wessel and Smith, 1998) was used for the underlying analysis; e.g., DEM production,  
350 outline renumbering.

351

### 352 **Map Design**

353

354 The accompanying atlas was designed as an interactive document that the reader can  
355 explore. It represents the output from the first ever attempt to objectively compare mapping  
356 of landforms by individual interpreters. An A1 page size was selected in order to maximise  
357 the resolution of the underlying raster topography, which is presented as a Swiss-type  
358 hillshade. **Each** map has a unique underlying DEM, varying according to where the synthetic  
359 drumlins are. Ancillary elements surround the map providing location, scale, title and  
360 legends. Palatino was selected for typography as a readable, "classic", style typeface.

361

362 The key part of the maps is the interactive layers; with the layer tab visible each layer within  
363 each page is visible. Any of these elements can have their visibility toggled on or off. There  
364 are three primary layers under "Main Map". "Mapping" shows all mapping of the individual  
365 interpreters; this whole layer, or individual sub-layers, can have their visibility toggled. "Times  
366 Identified" shows the actual synthetic drumlins and is symbolised based upon the number of  
367 times they were identified. "Drumlin Height (m)" is symbolised to show the amplitude of the  
368 synthetic drumlins and is specifically included to emphasise the link with the number of times  
369 forms were identified; compare this to Fig. 1c.

370

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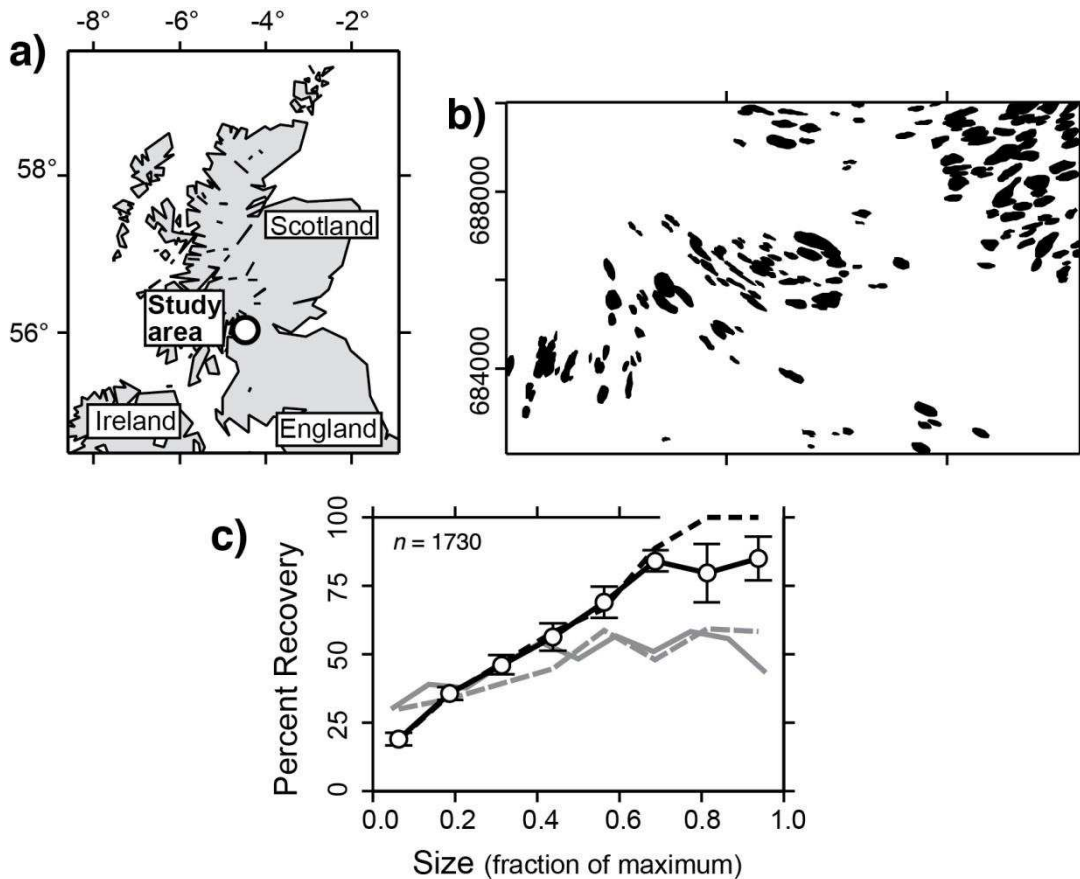
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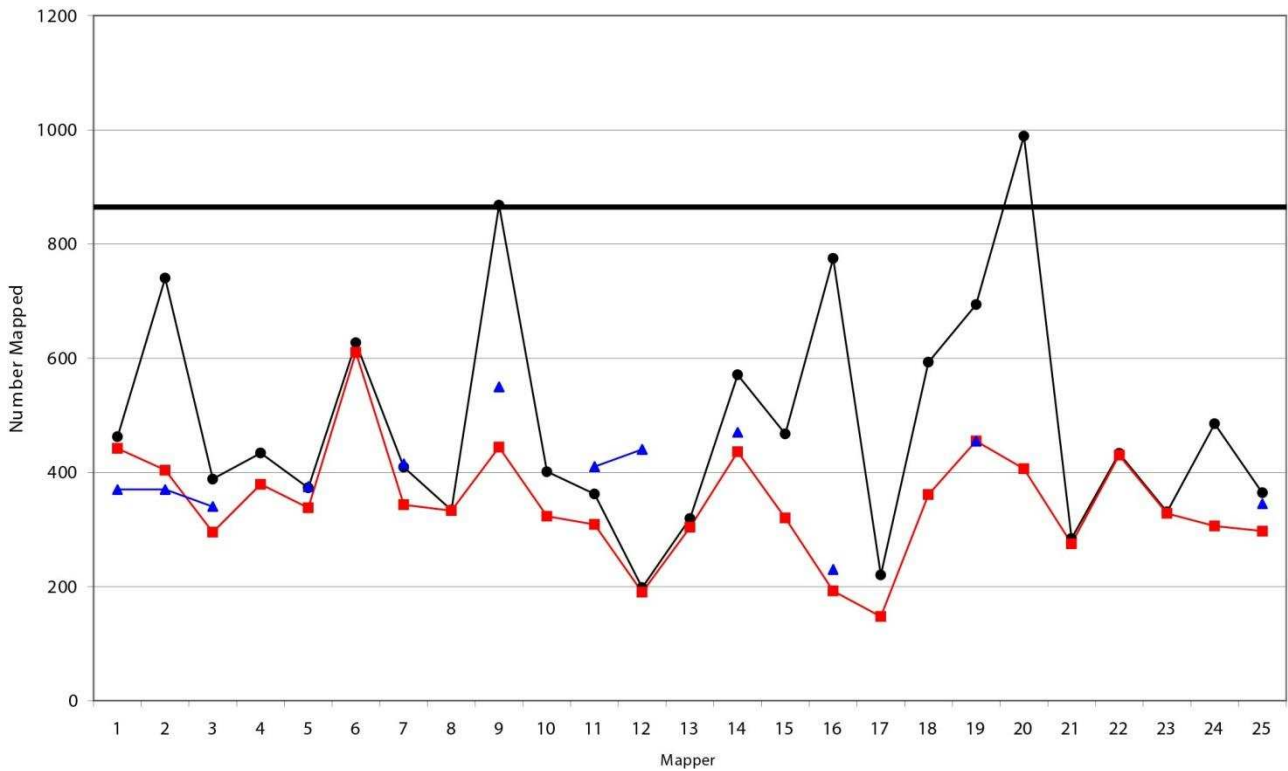
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563 **Fig 1:** a) Location of the study area. b) Drumlins (black) in the area as mapped by Smith et al  
 564 (2006). c) Recovery (i.e., 'completeness') as a function of size; synthesis of a manual  
 565 mapping pilot study for which the methodology was as here (see 'Interpretive Mapping') but  
 566 applied to 10 DEMs equivalent to Maps 1-5 using only one mapper (Armugam). Black line is  
 567 for height,  $H$ , and grey lines are for width  $W$  (solid) and length  $L$  (dashed). Circles are means  
 568 with their standard errors for the 10 DEMs, and dashed line is for medians.  $H$ ,  $W$ , and  $L$  have  
 569 bin widths of 2.5, 25, and 100 m, respectively. At the upper end, bins with two or fewer input  
 570 data are omitted, giving maxima of 20, 275 and 800 m, respectively. All data are plotted  
 571 centrally within bins.



574  
 575 **Fig. 2:** Number of drumlins mapped per individual interpreter (black) and the number correct  
 576 (red). Blue triangles are for the number correctly mapped in synthetic DEMs with parallel  
 577 conformity, scaled (x5) to allow comparison. Horizontal black line is the number of drumlins  
 578 in the synthetics. This was known to the mappers.  
 579