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Abstract

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

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

1. Introduction

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

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

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

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

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

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

2. Methods

2.1 Research Design

In order to test aspects of interpreter mapping, such as 'completeness' (defined below), it is necessary to know with certainty exactly which landforms exist in a landscape and where they are, but for incompletely defined landforms in a real landscape this is unknowable. Thus, a sufficiently realistic DEM containing an *a priori* known answer is required to give these absolute measures of effectiveness (see 'Results'), which traditional mapper intercomparisons simply cannot provide or estimate. One way to generate this might be to use a ‘landscape evolution model’ (e.g., Chase, 1992; Braun and Sambridge, 1997) to generate an artificial landscape that is both realistic and statistically comparable to a real landscape including all factors such as vegetation and anthropogenic alteration, but this has not yet been achieved for glacial bedforms. Hillier and Smith (2012) therefore proposed an alternative hybrid method. They used an existing DEM of real terrain and inserted synthetic landforms of known size and shape into it. The locations and orientations of the landforms are set differently for each synthetic DEM. Synthetic DEMs created in this way make it possible to assess the ability of interpreters to identify landforms in an absolute sense, something that is not possible with a real landscape. Any number of synthetic variants of a landscape can be produced for interpreters can map. Then, comparing and contrasting the mapped outputs allows conclusions to be drawn that include quantitative error estimates about properties such as absolute accuracy, variability, repeatability, and systematic biases. Thus, subject to establishing the representativeness of the synthetic DEMs used in each case study, this increases the number and strength of conclusions that may be drawn with respect to a traditional comparative study. An experimental approach employing synthetic DEMs is used here. These currently insert only one landform type (i.e., drumlins), however this is sufficient to support the aims of the paper and there is no reason why more complex synthetics could not be constructed in the future.

2.2 Choice of landform

For this work drumlins were selected as the landform to be mapped. Drumlins are elongate hills, typically 100s m long and up to a few 10s of metres high (Menzies, 1979; Wellner, 2001; Smith et al., 2007; Clark et al, 2009; Spagnolo et al, 2012; Hillier and Smith, 2014). They are very likely formed subglacially, parallel to ice flow (Smith et al, 2007; King et al, 2009; Johnson et al, 2010), and, as they can persist in the landscape, they encode information on the location and direction of flow of former ice cover (e.g., Hollingsworth, 1931; Kleman and Borgström, 1996; Finlayson et al, 2010) and perhaps even the nature and velocity of ice flow (e.g., Colgan and Mickelson, 1997; Smalley et al, 2000; Stokes and Clark, 2002). Such information is valuable for understanding the histories of past ice-sheet change. Thus, they are of scientific interest. Commonly, drumlins are mapped manually, often by an individual interpreter (e.g., Hughes, et al, 2010). However, their exact form has not yet been definitively, robustly and quantitatively defined and so a drumlin's spatial footprint is open to interpretation and differs between interpreters (see e.g., Fig 1a of Hillier and Smith, 2014). Despite this there has been some limited success in the use of automated algorithms to map drumlins (e.g., Saha et al, 2011). As such, drumlins seem likely to be able to be mapped accurately, reproducibly and objectively, and are regularly interpreted upon this basis, yet making this operational remains a challenge.

2.3 Generation of Synthetic Landscapes

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

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

2.4 Study Area

This work used the same study area as Hillier and Smith (2012) (Fig. 1a), which has been mapped in detail by other researchers studying the glacial geomorphology of the region (e.g., Rose and Letzer, 1975, 1977; Smith et al, 2006; Rose and Smith, 2008; Finlayson et al, 2010; Hughes et al., 2010). This area of Scotland sits between the Grampian Highlands to the north and the Southern Uplands to the south and was glaciated during the Last Glacial Maximum (LGM) and Younger Dryas (YD). It contains two identifiable suites of features interpreted as "classically shaped" drumlins, namely of approximately leminscate or elliptical footprints (e.g., Chorley, 1959; Reed, 1962). The drumlins mark the presence of flowing ice during these time periods, broadly west to east during the LGM and north to south during the YD. Drumlin dimensions are broadly comparable to those of other drumlins in the UK (Hillier and Smith, 2014). The study area is similar to many previously glaciated regions of the UK in that it contains topographic complexity in the form of regional relief (e.g., hills; Hillier and Smith, 2008) and non-glacial anthropogenic ‘clutter’ (e.g., trees, houses; Sithole and Vosselman, 2004), which vary in their amplitude and spatial density, respectively; it is intended that these variations across the study area will allow their impacts upon mapping to be isolated.

2.5 Interpretive Mapping

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

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

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

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

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

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

3. Results

The five main synthetic DEMs were mapped by 25 interpreters giving a total of 21,625 drumlins to be identified by the group. 12,121 outlines were mapped in interpreters' preferred visualisations, 8,667 of which were coincident with the original synthetic drumlins. Table 1 presents an error matrix in the standard format used in remote sensing (e.g., Lillesand et al, 2008) reporting these results. For accessibility, the equivalent terminology from information retrieval theory is also given (e.g., Manning et al, 2008). The matrix shows that whilst the 'overall accuracy' is relatively low (8667/25,079) at 34%, the producer's accuracy, 'reliability' or ‘precision’ (8,667/12,121) is relatively high at 72% (i.e., few false positives). This reflects the conservative number of drumlins generally mapped, but the high confidence in their accuracy. As a result, the user's accuracy, ‘completeness’, or ‘recall’ is also relatively low at 40% (8,667/21,625). Figure 2 shows the number of drumlins mapped by individual interpreters across all five DEMs; there is some variability in the totals mapped which is likely dependent upon the visualisation method and mapping philosophy employed by the individual. However, the number of correct drumlins is much more stable, typically between 300 and 500 landforms with a mean of 347 and standard deviation of 97.

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

Table 1: Error Matrix showing the number of correctly mapped drumlins in addition to errors of omission and commission. See text for an interpretation of the matrix. Figures for DEMs 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)

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

4. Conclusions

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

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

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Software

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

Map Design

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

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

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Figures

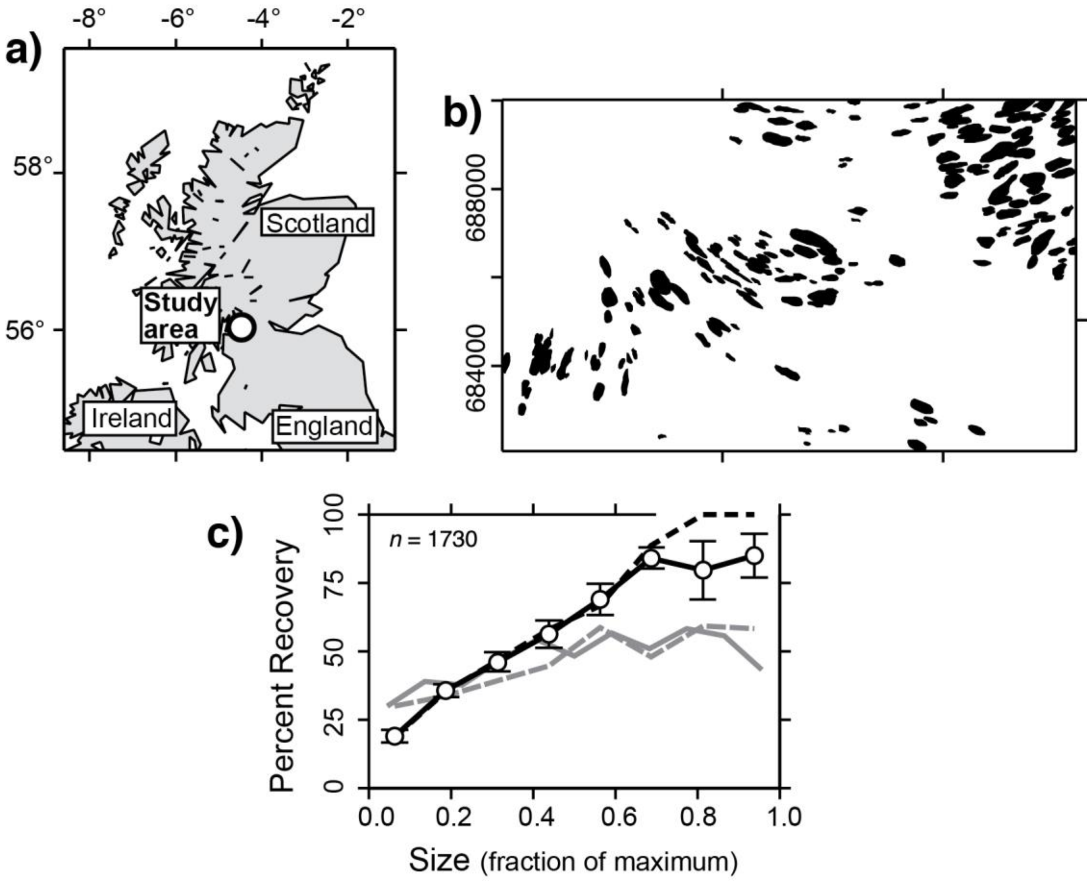

Fig 1: a) Location of the study area. b) Drumlins (black) in the area as mapped by Smith et al (2006). c) Recovery (i.e., `completeness') as a function of size; synthesis of a manual mapping pilot study for which the methodology was as here (see 'Interpretive Mapping') but applied to 10 DEMs equivalent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

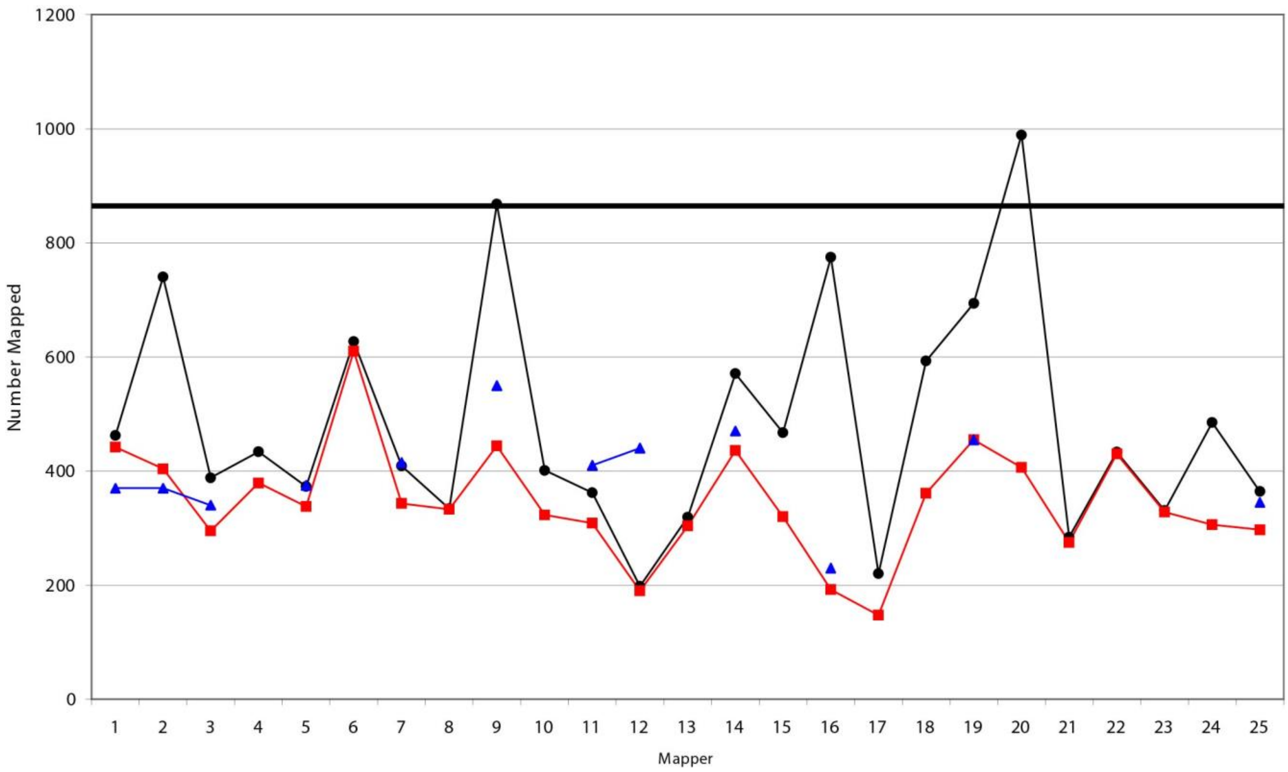

Fig. 2: Number of drumlins mapped per individual interpreter (black) and the number correct (red). Blue triangles are for the number correctly mapped in synthetic DEMs with parallel conformity, scaled (x5) to allow comparison. Horizontal black line is the number of drumlins in the synthetics. This was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