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Abstract: A methodology is presented for the quantification of eskers that uses Canadian digital elevation data (CDED) and legacy esker line-work from Geological Survey of Canada publications. Using ESRI® ArcGIS® and an esker detection module (EDM) coded in Python, the CDED data are smoothed using user-defined filter windows. A difference surface is produced that emphasizes ridge areas and is used to create polygons. The legacy esker line-work is used as a training data set to extract ridge areas within a user-defined buffer. The EDM results have been tested against the input training data and a local data set generated manually from aerial photographic interpretation. Depending upon terrain characteristics, the success of the data extraction ranges from 65 to 81 per cent against the esker line-work and 35 to 72 per cent against the more geographically limited aerial photographic interpretation. The variable success reflects esker size related to both relief and width in the CDED data.

Résumé : Cet article présente une méthodologie pour la quantification des eskers à l'aide de Données numériques d'élévation du Canada (DNEC) et de dessins au trait d'eskers tirés d'anciennes publications de la Commission géologique du Canada. À l'aide du logiciel ArcGIS® d'ESRI® et d'un module de détection des eskers (MDE) codé en langage Python, les données DNEC sont lissées en employant des fenêtres de filtrage définies par l'utilisateur. Ceci produit une surface différentielle mettant en évidence les zones de crêtes, qui est utilisée pour tracer des polygones. Les dessins au trait d'eskers servent d'ensemble de données d'apprentissage pour extraire les zones de crêtes dans un espace tampon défini par l'utilisateur. On a comparé les résultats du MDE aux données d'apprentissage employées et à un ensemble de données locales créé manuellement à partir de l'interprétation de photos aériennes. Le taux de succès d'extraction des données varie en fonction des caractéristiques du terrain : entre 65 et 81 % par rapport aux dessins au trait d'eskers, et entre 35 et 72 % par rapport à l'interprétation des photos aériennes, plus limitée en termes d'étendue géographique. Ce taux de succès variable est fonction de la taille des eskers (relief et largeur selon les données DNEC).

INTRODUCTION

The standard methodology for mapping glacial landforms at the Geological Survey of Canada (GSC) is aerial photographic interpretation. Numerous benchmark products have been published based on this methodology, ranging from 1:50 000 scale to synoptic national-scale coverage (Fig. 1; e.g. Prest, et al.,1968; Aylsworth and Shilts, 1989). This technique offers a number of advantages that have supported its continuous utilization. Aerial photographs provide geologists with a high-resolution, cost-effective portrayal of the landscape upon which interpretations can be based. There is a large inventory of aerial photographs in the National Aerial Photographic Library. The cost to equip an operator with a stereoscope is minimal and information technology (IT) overhead costs are nonexistent. There are, however, a number of disadvantages. The method is time-consuming, largely qualitative, and reliant on highly trained individuals. In the 80 plus years since aerial photographic interpretation became a cornerstone of mapping at the GSC (e.g. Wilson, 1939), numerous technological advances have been made in the capture, analysis, and processing of remotely sensed landscape data. These digital data can improve, and in many cases, may eventually supplant current qualitative mapping methods because they provide an opportunity for more quantitative methods to be employed to extract information on landforms and landscapes. Glacial geomorphologists and glacial geologists, however, have been slow to exploit these technological advances, especially compared with scientists in other disciplines (e.g. soil science, hydrology; *see* Napieralski et al., 2007). Twenty years has passed since the GSC embraced digital cartography, but little progress has been made toward integrating new digital techniques and other remotely-sensed data into the traditional aerial photographic mapping process.

Quantitative mapping of glaciated landscapes involves several challenges: the automated identification of glacial landforms (eskers, moraines, drumlins) and sediment textures (e.g. sand, gravel; Fig. 2), and extraction of specific attributes of these features (e.g. width, length, continuity, volume etc.; e.g. Smith et al., 2009). The automated identification of landforms remains a complex challenge to implement in GIS software at the scale of glacial landforms (e.g. Drăguţ and Blaschke, 2006). For this reason, and reflecting the extensive synoptic data coverage of landform mapping across Canada, one approach is to focus on the derivative task of form extraction and analysis using a training data set to isolate the respective landforms. This permits the optimal use of previously completed work (e.g. Aylsworth and Shilts 1989; Fulton, 1995). This approach also allows us to focus on development of a methodology that can increase the information content of work completed on areas covered by individual National Topographic System (NTS) map sheets mapped by traditional methods of aerial photographic interpretation and field investigation.

The Geological Survey of Canada's Geo-mapping for Energy and Minerals (GEM) Program is mandated with improving the mineral-resource knowledge base of Arctic Canada in a five-year time period. There remain many unanswered questions in the exploration community with respect to both geochemical and heavy-mineral (e.g. kimberlite indicator minerals) dispersion patterns. The potential exists that with new methodologies, the potential

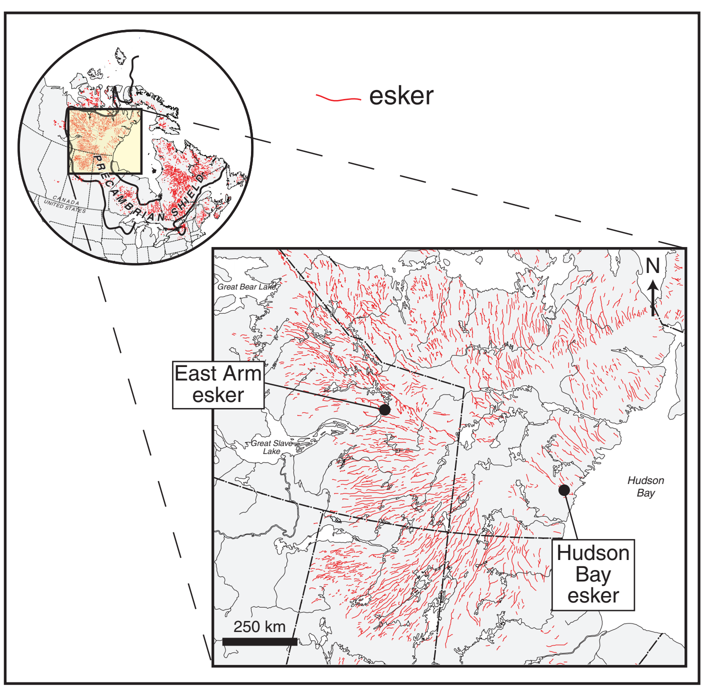

Figure 1. Location map of Canada showing Keewatin study area and esker networks. Main map shows esker network of Keewatin (Aylsworth and Shilts, 1989). Test areas presented in Figures 14 and 15 are Artillery Lake (NTS 75-O/5) and Hudson Bay (NTS 55 K,N).

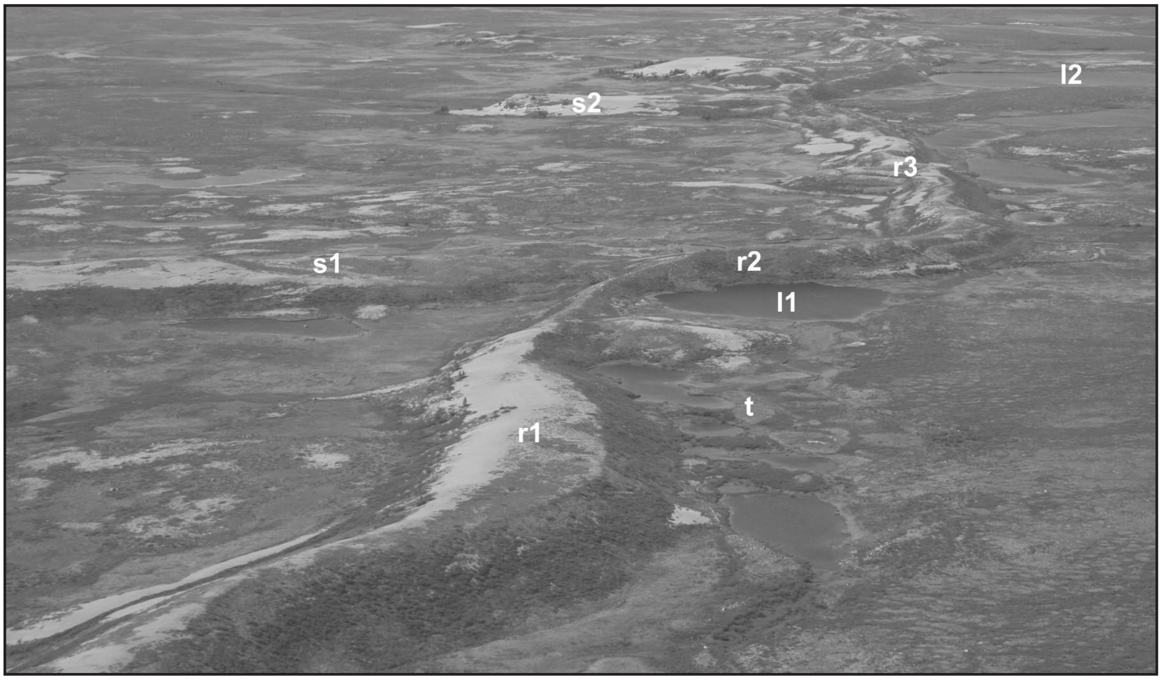

Figure 2. Oblique aerial photo study area to the north of Artillery Lake, NTS 75N, looking west. Note single esker ridge with lateral fans and kettle lakes. Variable esker morphology is apparent and complex vegetation cover illustrates difficulty in classification using multispectral data. Kettle lake designated as l1 is approximately 120 m wide. Key: l1, l2 – lakes; t – till; r1, r2, r3 – esker ridges; s1, s2 – esker spurs. Photograph courtesy of D.I. Cummings.

for new analysis, and improved definition of the glaciated landscape, that some of these unanswered problems can be resolved. Consequently, there is a pressing need for improved remote predictive-mapping technologies (e.g. Shaw et al., 2010a, b) that can exploit modern digital data sets (remotely sensed data, digital elevation models (DEMs), regional geophysical data sets) and complete integrated analysis with legacy GSC data sets and field data.

Objectives

The objective of this paper is to outline the esker detection module (EDM) process by which physical properties of glacial landforms can be extracted semiquantitatively from readily obtained data. Using legacy thematic data of glacial-landform mapping, a workflow is developed to extract selected morphometric parameters from public-domain DEM data available with national coverage. To demonstrate the utility of the approach, case studies using eskers from two widely spaced locations are presented from areas in the central (Keewatin) region of Arctic Canada. The integrity of this data set is demonstrated by comparison to manually interpreted data sets. Various options are presented for the visualization of this glacial morphometric data.

LITERATURE REVIEW

Remote sensing and geographic information systems (GIS) have been applied to studies of glaciated landscapes for more than 30 years (Napieralski et al., 2007). A key component of understanding glaciated landscapes, and more specifically glacial landforms, is the description and analysis of morphological and spatial characteristics of the landforms and deposits (e.g. Napieralski et al., 2007). A particularly valuable data set for landform analysis is the digital elevation model (DEM) (Deng et al., 2007; Iwahashi and Pike, 2007). Much of the research into surface landforms has been completed with high-resolution DEMs, so that derivative measures such as slope, aspect, and curvature can be used (e.g. Evans and Lindsay, 2010; Bates and Metcalfe, 2006). National-scale DEM coverage, however, is generally only available at coarser grid scales greater than 20 m (Canadian Digital Elevation Data, CDED; Shuttle Radar Topography Mission, SRTM) and often contains elevation (z) data in integer format (CDED). Pre-processing of the integer quantization of elevation data means that DEM derivatives (e.g. slope, curvature) do not yield useful information at the required scale of analysis. To circumvent this problem, various researchers have used the difference between the original DEM and a smoothed DEM to isolate specific landscape features (e.g. Brabyn 1997; Weiss, 2000; Hiller and Smith, 2008). This approach has proven to be less sensitive to both horizontal and particularly vertical DEM resolution. Weiss (2000) outlined the use of elevation difference measures and slope to determine a topographic position index (TPI) (*see also* Guisan et al., 1999). Hiller and Smith (2008) outlined a method by which a raw DEM is subtracted from a highly smoothed (1 km × 1 km median filter) regional-elevation DEM to obtain glacial lineaments from the 'residual topography'. They then proceeded to 'normalize' the residual relief for the purposes of visualization. In a related paper, Smith et al. (2009) proposed extracting areal and volumetric statistics from a DEM based on digitized drumlin polygons by creating a drumlin elevation base across the drumlin polygon boundary and subtracting the isolated DEM information from the drumlin elevation base. This method is useful for small study areas, but impractical for mapping large areas and still allows for some subjectivity in the interpretation of the drumlin base by the digitizer.

DATA

The semi-automatic EDM process uses two regional data sets. The base input-data source consists of DEM files from public domain CDED data derived from 1:50 000 topographic maps (http://www.geobase.ca/). The CDED data south of 68°N are stored at 0.75 × 0.75 arc seconds (in x, 11–16 m in ground units, depending on latitude; ca. 23 m in y). The z information is stored to the nearest metre (Clavet and Robitaille, 2008). The CDED data were projected and resampled to the appropriate UTM projection with an x,y resolution of 12.5 × 12.5 m (Fig. 3). The second data set consists of legacy vector esker line-work that was digitized from Aylsworth and Shilts (1989, unpublished). The Aylsworth and Shilts (1989) manuscript data were interpreted from 1:60 000 aerial photographs and transcribed directly to 1:250 000 topographic map bases. For the digital capture, the hardcopy map was georeferenced using a minimum of the four corners of the map sheet. This introduced minimal inaccuracy regarding the exact location of the esker line-work. On most maps many eskers consisted of two components, a line delineating the esker ridge, and an adjacent polygon delimiting associated glaciofluvial sediment that forms part of the eskerine system. Only the esker ridge was digitized; the polygon information was not captured. A supplemental, third data set — the 1:50 000 scale National Topographic Database (NTDB) eskers — were used to check for inconsistencies between the CDED data and the esker line-work from Aylsworth and Shilts (1989) (Fig. 3). A significant data issue with the esker — data set from Aylsworth and Shilts is an inconsistent lateral x,y co-ordinate shift of 100–200 m relative to the 1:50 000 scale topographic base. This shift is apparently related to generalization and positional inconsistencies between the 1:50 000 NTDB base and the 1:250 000 topographic base upon which the interpretation was originally plotted.

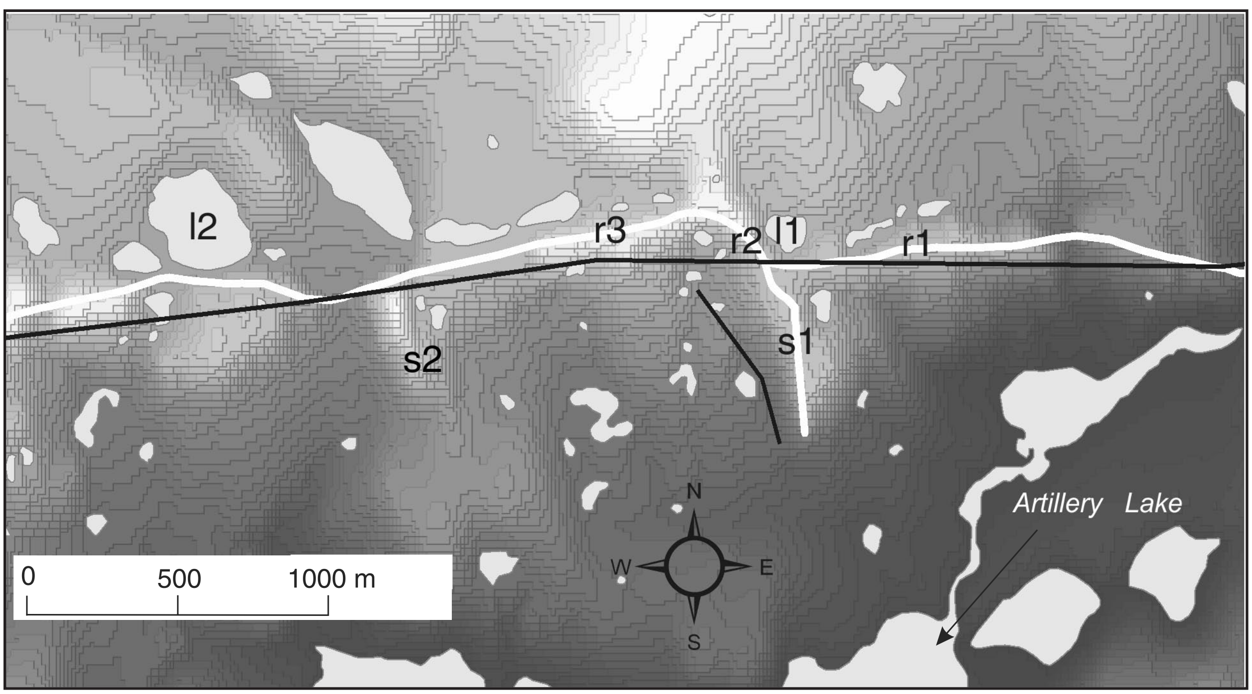

Figure 3. Background image is hillshaded integer value CDED resampled to 12.5 m × 12.5 m grid size. Esker line-work as interpreted by Aylsworth and Shilts (1989) shown in black. For reference esker line-work from NTDB 075O05 1:50 000 map sheet shown in white. Key: l1, l2 – lakes; r1, r2, r3 – esker ridges; s1, s2 – esker spurs.

METHODS

To sample and manipulate the data sets, the semi-automated EDM was coded as a custom ArcGIS toolbox consisting of a series of scripts in the Python programming language. The toolbox can be loaded into ArcGIS and run from dialogue boxes. Models combining scripts in commonly used sequences are provided in the toolbox for batch processing. The toolbox requires an ArcInfo licence and the Spatial Analyst extension. The algorithm operates on the DEM data set and esker line work in five distinct operations (Fig. 4).

Step 1: pre-process ('smooth') DEMs

The CDED data stores the elevation value as an integer. This introduces an artifact to the data that is particularly noticeable in low-relief terrain and prevents the use of the data for generation of any useful derivatives. To address the integer imposed distortion of the landscape, the DEM was smoothed using a n × n filter and the centre pixel integer value replaced with the mean value stored as a floating point value. This partially removes the step-elevation artifact from the CDED data and provides a continuous elevation range of the topography. As the term 'smoothing' implies, peaks become more subdued and rounded and valleys fill in; local elevation differences become less extreme. In this study, two derivative surfaces were generated, a moderately smoothed surface (3 × 3 or 5 × 5 pixel window) and a highly smoothed surface that reflects a regional mean elevation (13 × 13 to 25 × 25 pixel window, Fig. 5).

Step 2: subtract DEMs

The highly smoothed surface was then subtracted from the moderately smoothed surface to create an elevation-difference surface. This step essentially sets the regional elevation variation as defined by the more smoothed surface to zero and shows only the local elevation variation (Fig. 6).

Step 3: isolate hilltop polygons

Ridge-like hilltops were then isolated by selecting positive values on the elevation-difference surface. The optimal cutoff elevation difference value in this study was found to be between 0.5 and 2 m depending upon the window sizes used in step one (above). No quantitative rule was defined; rather visual assessment formed the basis for the selected value. Choosing cutoff values closer to zero results in selection of more esker area, but also more potential confusion between eskers and non-esker features (Fig. 7, 8).

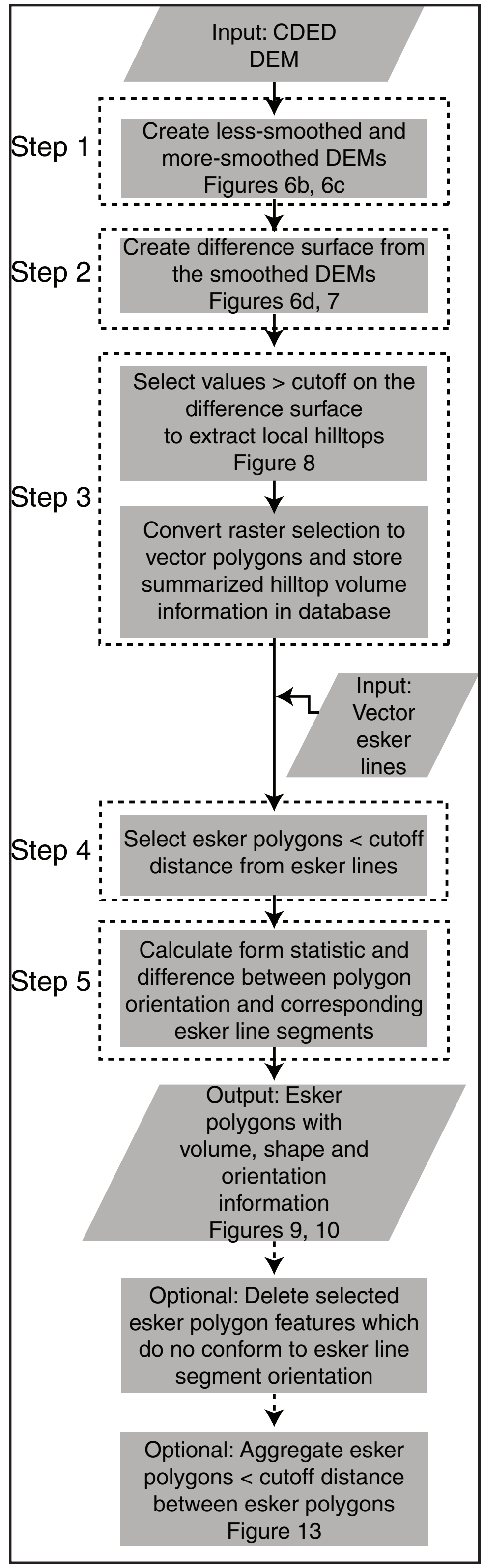

Figure 4. Flow diagram highlighting esker-polygon calculation process in the Esker Detection Module (EDM).

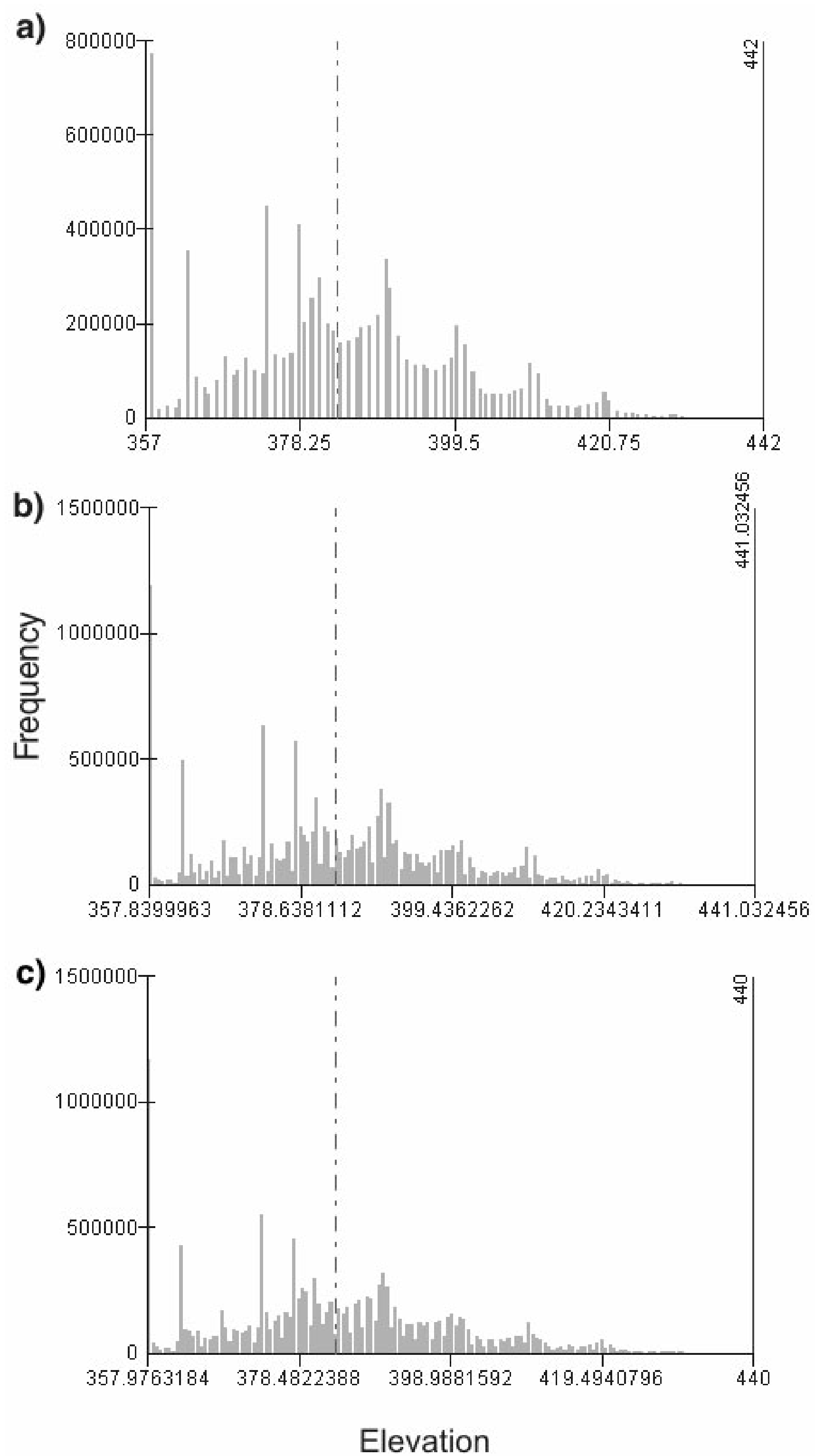

Figure 5. Histograms of CDED data and smoothed CDED. **a)** Original CDED. **b)** CDED smoothed using a 5 × 5 pixel mean value rectangular filter. **c)** CDED smoothed using a 13 × 13 pixel mean value rectangular filter. With increased smoothing the histogram becomes less 'spiky' as elevation gaps between integer Z values are filled in. Dashed line represents the mean of the data set and is almost identical in all three data sets.

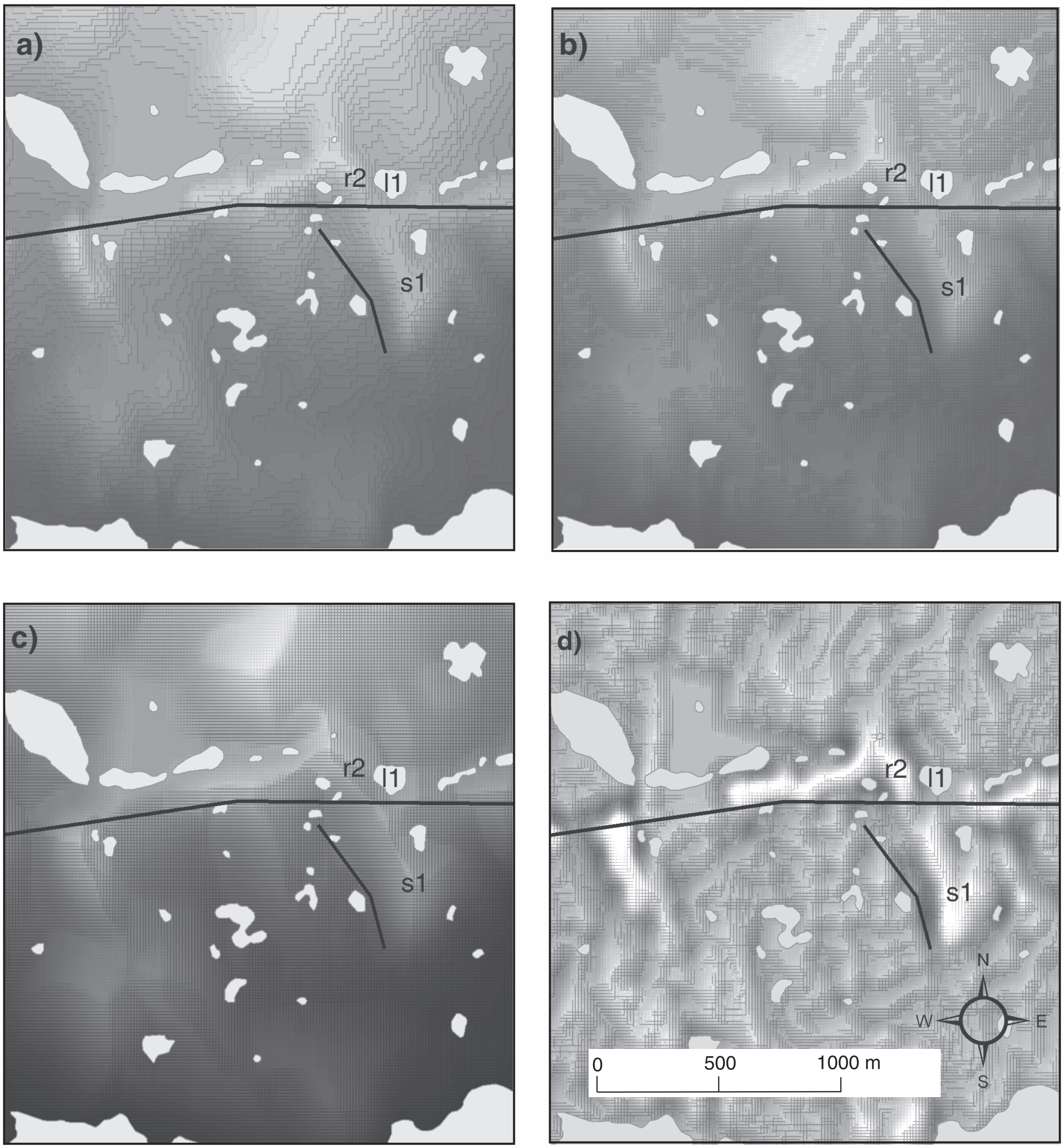

Figure 6. Creation of elevation-difference surface from CDED data. **a)** Original CDED. **b)** Less-smoothed surface using a 5 × 5 pixel mean value rectangular filter. **c)** More-smoothed surface using a 13 × 13 pixel mean value rectangular filter. **d)** Difference between less-smoothed surface and the more-smoothed surface. Difference surface shows localized elevation variation independent of the more global trend. Key: l1 – lake; r2 – esker ridge; s1 – esker spur.

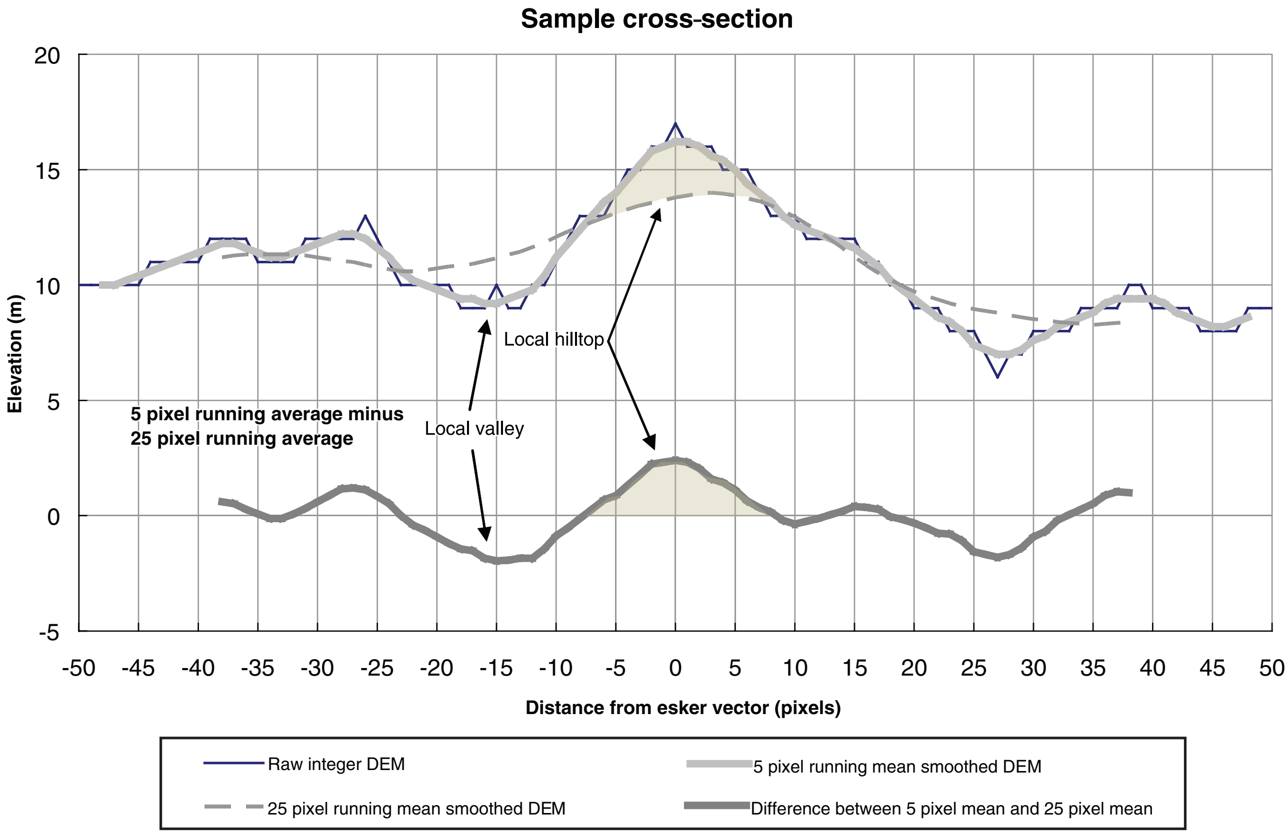

Figure 7. Cross-section of conceptual esker. Top line shows esker based on hypothetical DEM along with less-smoothed and more-smoothed filters. The bottom line is the corresponding difference surface, where the more-smoothed filter surface is set to 0. One local hilltop is shaded as an example. The darker shading indicates the 'volume' of the hilltop based on a cutoff value of 0.5 m. The lighter shading on either side of the hilltop represents the additional 'volume' included with a cutoff of 0. This representation is based on the cross-section values only, whereas the algorithm itself uses a rectangular (e.g. 5 × 5 pixel) window.

Step 4: extract hilltop polygons

The hill-top polygons that fall within a specified distance of the vector esker line were then extracted. The optimal value was found to depend on the registration and generalization of the esker line-work relative to the DEM resolution and the width of the eskers. For this study 100 m was used. Aggregated polygons may be created by merging adjacent esker polygons within a given tolerance distance of each other (e.g. Slocum et al., 2009).

Step 5: quantify hilltop (esker) dimensions

A number of parameters can be extracted from the DEM layers and derived vector polygon, such as maximum range of elevation difference values, area, and the volume between the two surfaces. The maximum elevation range indicates whether the esker is relatively flat topped or peaked. The volume between the two surfaces is a minimum estimate of esker volume (assuming limited extension of the esker beneath the adjacent land surface). This 'volume' may be normalized by esker polygon area or by the distance of the long axis of the fitted ellipse of each polygon, so that the glacial deposit may be interpreted independent of esker polygon area or length (Fig. 9). Other polygon shape measures (Davis, 2002, p. 356) may be calculated as polygon areas and perimeters are stored in the database.

QUALITY ASSURANCE

A series of quality-assurance steps were performed to ascertain the success of the semi-automated hilltop (esker) extraction process. The steps used empirical relationships generated from the digital data sets, and compared results against traditional aerial photographic interpretations and field observations.

Selection based on form and orientation

As part of the validation process, the form and orientation of each esker polygon was quantified. To accomplish this, a standard deviational ellipse (Mitchell, 2005) was fitted to each polygon. Following Davis (2002), the form statistic, essentially a measure of circularity, was defined as

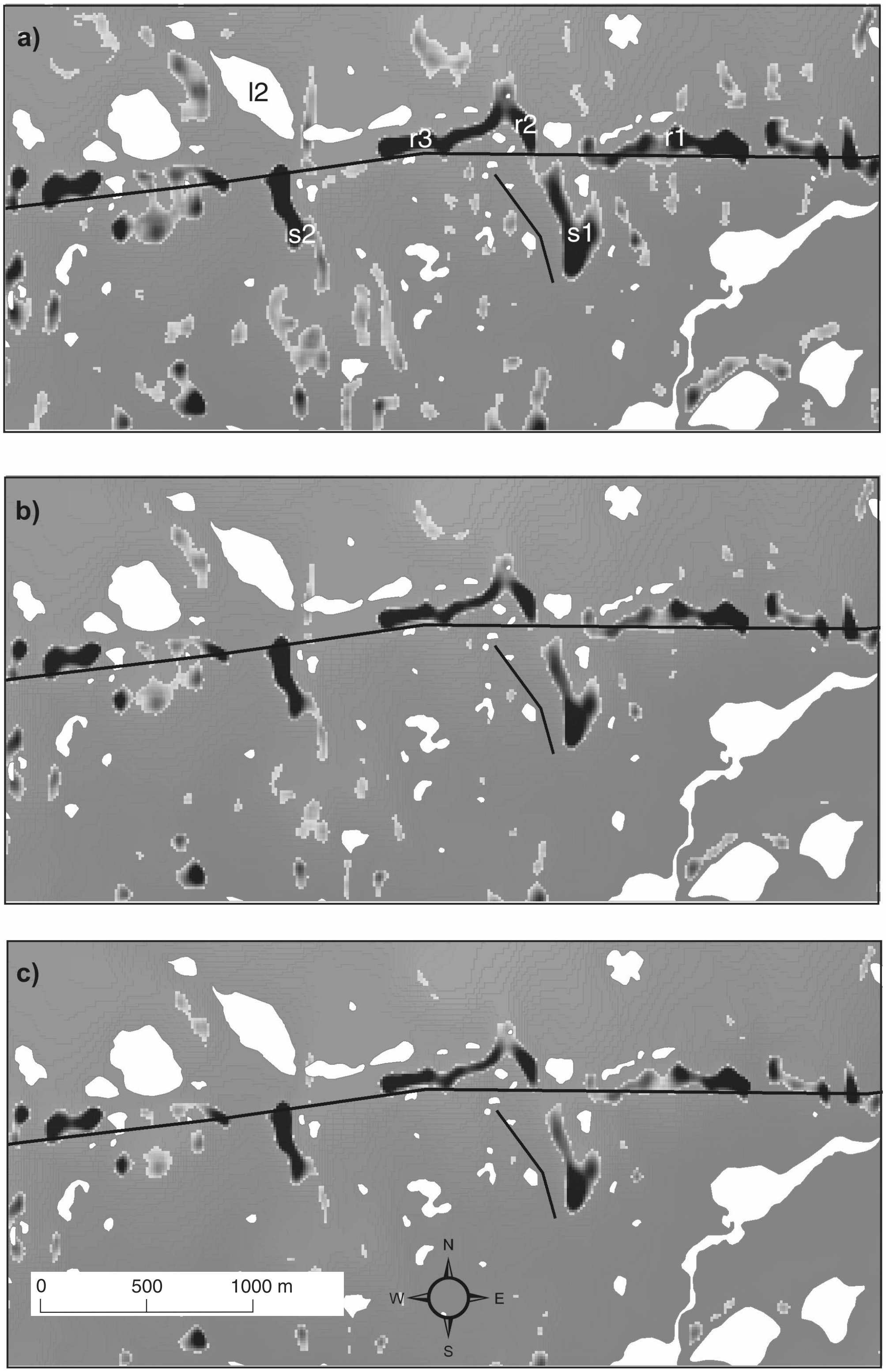

Figure 8. Effect of varying cutoff values. Intensity of local hilltop shading indicates elevation difference between less-smoothed and more-smoothed surface. Elevation difference values range from the cutoff value displayed as light [0.5 m for **a)**, 0.8 m for **b)**, or 1 m for **c)**] to 7.9 m (dark). These elevation-difference values are multiplied by the area of each pixel within a polygon, and then summed to produce a summary 'volume' for each esker polygon. Key: l2 – lake; r1, r2, r3 – esker ridges; s1, s2 – esker spurs.

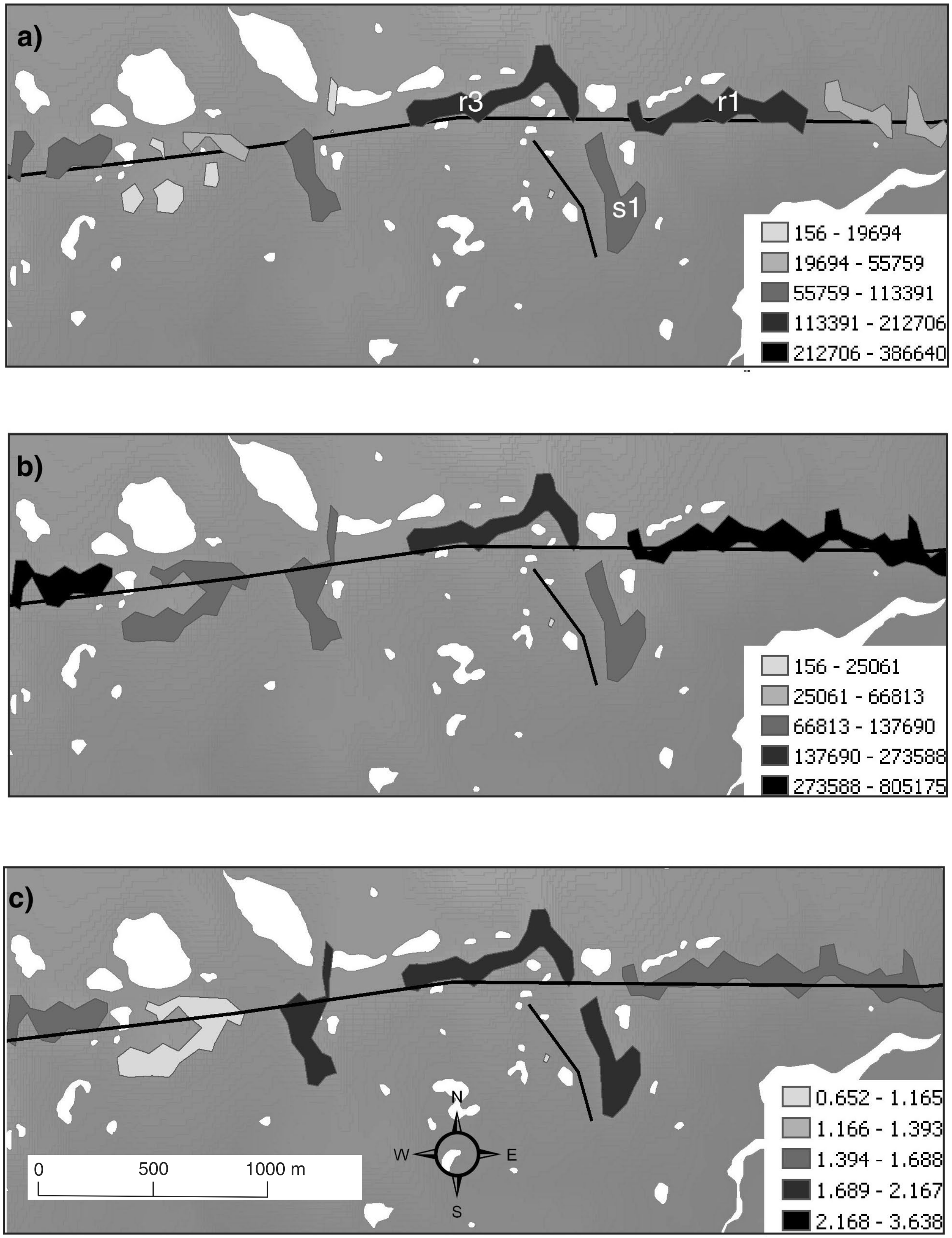

Figure 9. Esker polygons from the local hilltop polygons in Figure 8c within 100 m of the esker lines. Unaggregated **a)** and aggregated (**b** and **c**) esker polygons show raw 'volume' in cubic metres (**a** and **b**) and 'volume' measures normalized by area in square metres **c)**. Normalization of 'volume' by the length of the long axis of the polygon yields similar results to normalization by area. Key: r1, r3 – esker ridges; s1 – esker spur.

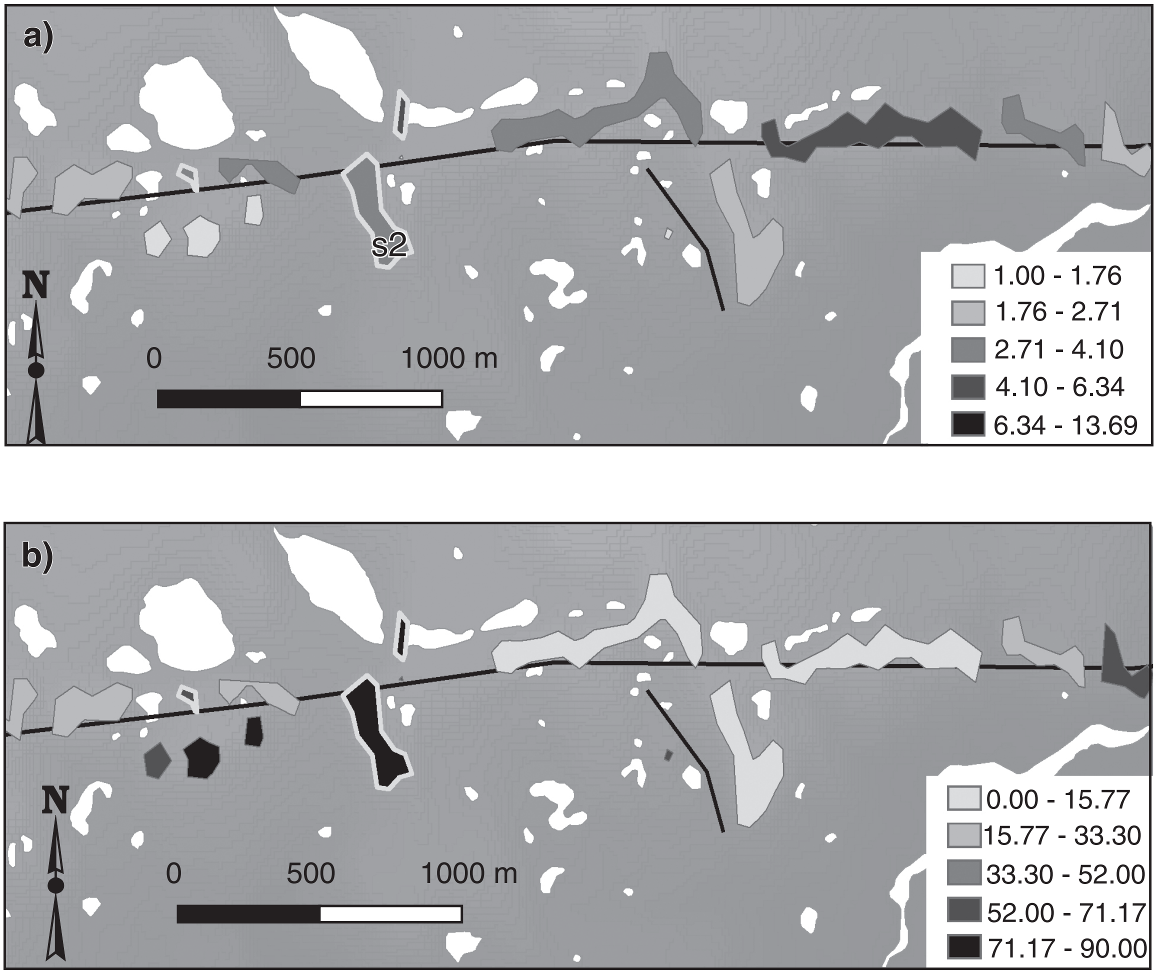

Figure 10. Polygon error assessment. **a)** Form statistic, the length of the long axis of an ellipse fitted to the polygon divided by the short axis of the fitted ellipse. **b)** Difference in absolute orientation between the esker polygon and the corresponding esker line segment. Three polygons (outlined in light grey) have been flagged as being sufficiently elongated and oriented differently from the corresponding esker segments. This may be due to deficiencies in the esker vector network (esker spur s2 not included in the esker lines) or confusion with non-esker landscape features (smaller polygon to the north of esker spur s2).

the ratio of the long axis versus the short axis of the ellipse. The absolute difference of the orientation of the long axis of the standard deviational ellipse and the orientation of the nearest segment of the esker lines was also calculated. The form statistic and the difference in orientation were mapped and used to check the probability of a given hilltop polygon being an esker polygon (Fig. 10). Given common esker geomorphologies (e.g. Brennand, 2000), if the form is elongated and its orientation significantly different than the corresponding esker line segment, the polygon may represent i) an esker spur not indicated as part of the esker line network, ii) a part of the esker that has a different orientation than the trunk esker, or; iii) a non-esker landscape element that is confounding the algorithm.

Percentage correspondence between esker line segments and esker polygons

In order to calculate the orientation difference described in the previous section, the esker polygons were buffered by the distance tolerance that was used to select esker polygons within a certain distance of the esker lines (Step 4, above). These buffered polygons are spatially intersected with the esker lines to create a series of esker line segments corresponding to esker polygons, which are then used to calculate the absolute difference in orientation between a given esker polygon and the corresponding esker line segment. The esker line segments that intersect buffered esker polygons were compared to non-intersecting esker line segments, either visually or as a summary measure (percentage

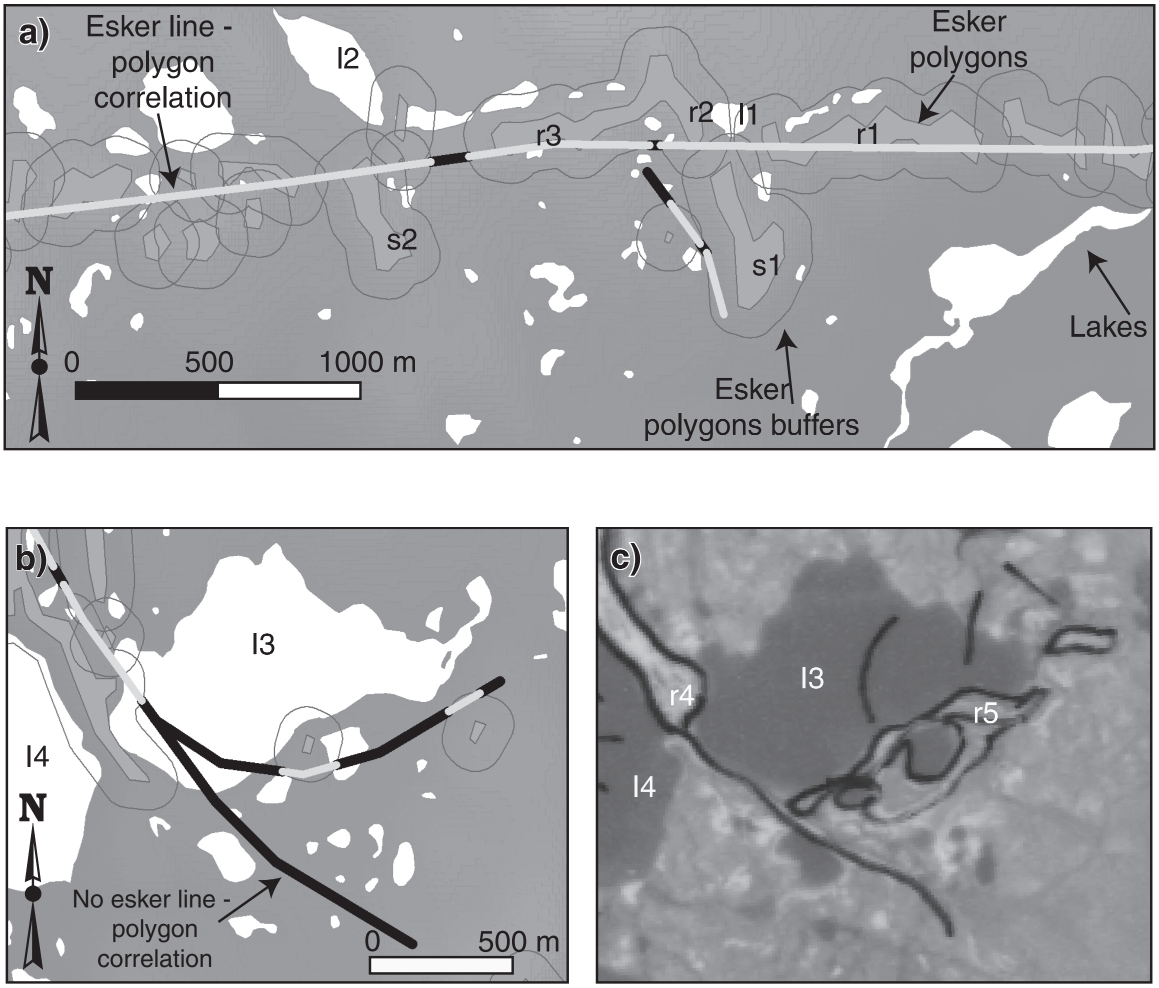

Figure 11. Correspondence of esker lines to esker polygons in the study area. **a)** Elements of esker delineation process north of Artillery Lake, esker line, esker polygons, and buffers based on esker polygons. Annotated lakes (e.g. l1, l2), esker ridgelines (e.g. r1, r3) and esker spurs (e.g. s1, s2) correspond to locations in Figure 2, note change in orientation. **b)** Area to the west of Artillery Lake with lower correspondence of extracted eskers with line work. **c)** Independent manual aerial photographic interpretation of area in Figure 11b. A single black line indicates a narrow esker ridge, no wider than the width of the line on the photograph.

length of the length of esker line segments associated with extracted esker polygons relative to the total length of esker line segments). Such summary measures might be indicators of the performance of the algorithm: the algorithm performance may be related to the average height and width of esker polygons relative to the DEM x, y, and z resolution, or to the degree to which non-esker landscape elements intersect the eskers, confounding the identification of esker features. Select eskers were chosen from two 1:50 000 NTS sheets (75-O/5, 75-O/6) to assess the veracity of the technique. For NTS sheet 75-O/5, the EDM approach quantified 81% of the length of the esker line segments with corresponding esker polygons (section shown in Fig. 11a). For NTS sheet 75-O/6, an area with more confounding nonglacial features and less medium-scale relief, the length correspondence was 65% (section shown in Fig. 11b).

Comparison to independent interpretation of aerial photography

To test the accuracy of the esker classification, the esker features were interpreted using 1:60 000 monochrome aerial photographs (Fig. 12, 13a). The interpretation was recorded on the photographs and the interpreted photos were registered locally to the 1:50 000 scale map base. The results of the automated classification were overlaid on the photos to allow visual comparison (Fig. 13b, c). The success of EDM is directly related to the width and height of the esker ridge in the CDED data. In areas of well defined peaked eskers, the method yielded 68 to 72% linear correspondence to the interpreted air photos (Fig. 13). In areas where eskers were not as peaked, the correspondence was less: approximately 35% (Fig. 11c). Most eskers higher than ~15 m were captured, whereas smaller eskers were generally not. As such,

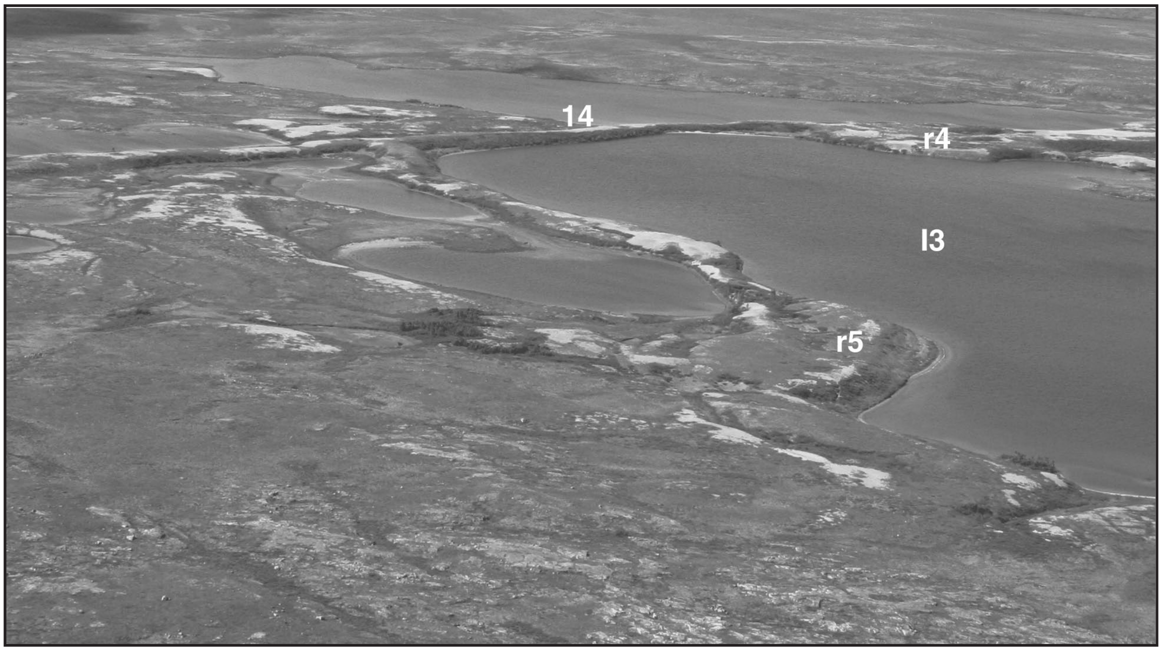

Figure 12. Oblique aerial photograph of an area to the east of Artillery Lake, looking to the south-west. Annotation as per Figure 11. This area is not as well captured using the EDM methodology due to narrower and less elevated esker features relative to those esker features in the study area portrayed in Figure 2. *See* Figures 11b and 11c for the corresponding map and interpretation. Photograph courtesy of D.I. Cummings.

in most cases the method will provide a minimum estimate of esker volume (Fig. 13b). To account for the low resolution of the CDED data, classified polygons with a proximity of 100 m of each other were aggregated on the assumption that EDM picks up local hilltops, but does not delimit the flanks to the base of the hill; therefore areas between identified hill-tops are likely to contain esker material as well (Fig. 13b, c).

Regional context

Brennand (2000) introduced a morphological classification of Laurentide eskers. Three esker morphologies were identified: a) long, dendritic eskers, b) short, subparallel eskers, and c) short, deranged eskers. Long dendritic eskers form networks that are up to hundreds of kilometres long, up to 50 m high, and can be up to kilometres wide. Short subparallel eskers are up to tens of kilometres long, less than 30 m high, and hundreds of metres wide. Short deranged eskers are generally hundreds of metres long, less than 20 m high, tens of metres wide, and may occur in isolation or as disorganized swarms. Based on the CDED resolution and the residual surface approach of EDM, it is likely that EDM will be most successful quantifying long dendritic eskers (Fig. 14), moderately successful delineating subparallel eskers (Fig. 15), and have relatively poor success with type short deranged eskers. The example from 75-O/5 is an example of a long dendritic esker and was successfully delineated along 81 per cent of the esker-line work length. The esker on 75-O/6 is more likely a short subparallel esker and was delineated along 65% of the line length. Short deranged eskers rarely, if ever, have a morphological expression in CDED data. Consequently no test has been run against these eskers. On the basis of the limited test data presented, EDM has the potential for quantifying esker geometry and longitudinal changes in the long dendritic eskers at a regional scale.

VISUALIZATION OF ESKER DATA

Variables associated with esker polygons ('volume', area, elevation difference, and form) may be classified and displayed on a map at a selected scale (e.g. 1:50 000). Summarizing esker polygon information over specified distances along the esker 'network' allows for a visual picture of the esker polygon information over the length of longer eskers. The implementation involves the creation of a route from selected esker line features, summarizing the attributes of the esker polygon over a given distance interval along the esker route, and creation of point symbols at those given intervals along the route. One can display variation in esker-polygon attributes over the length of the esker, visually identify areas of relatively high and low glacial deposits along a route, compare attributes for 'trunk' and 'tributary' eskers, or summarize attributes for an entire network (Fig. 14 and 15)

Esker polygons and summary esker-point features, symbolized by a given attribute, may be exported to .kml format and visualized in Google Earth. This allows access to

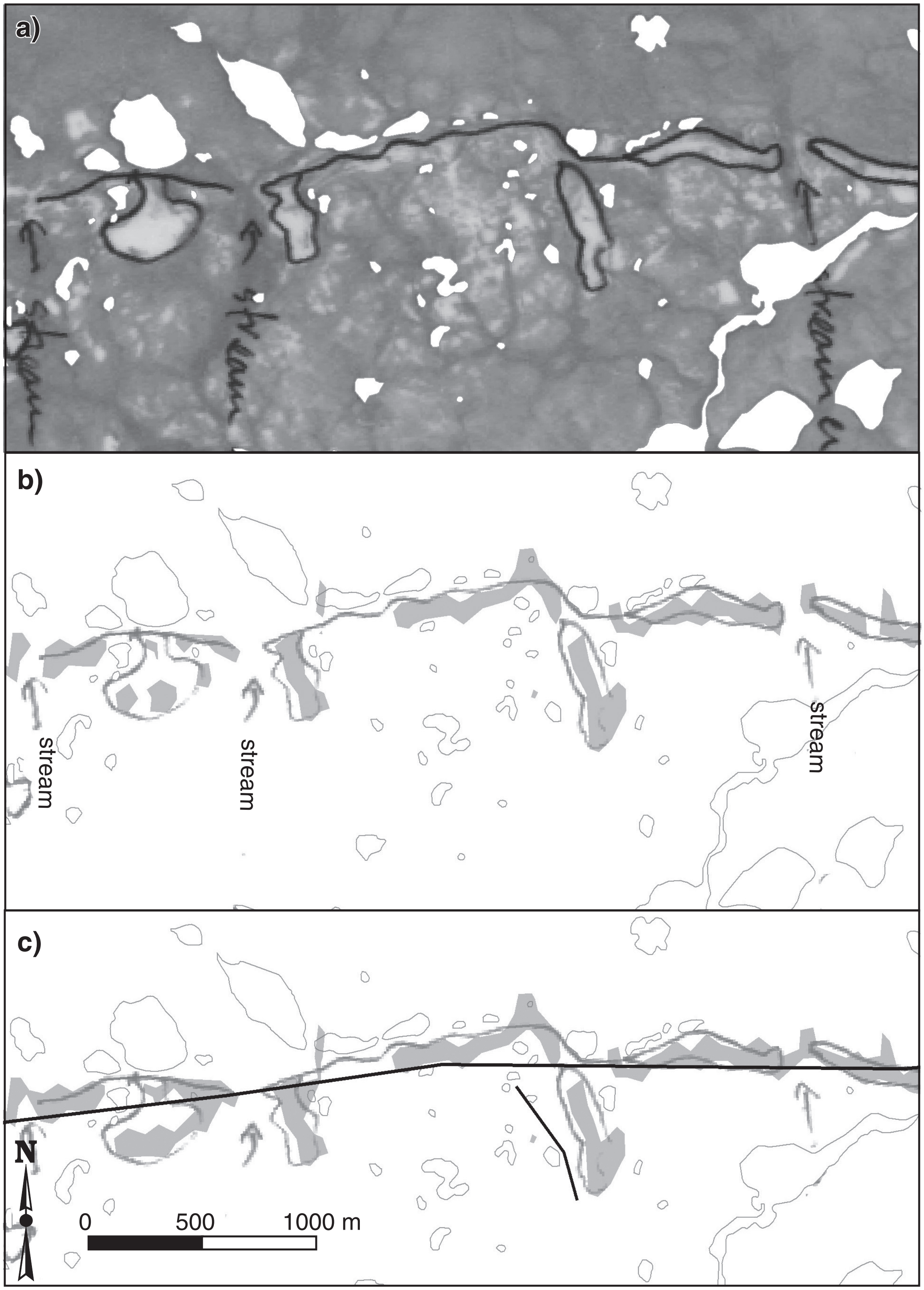

Figure 13. Validation of EDM analysis against manual 1:60 000 monochrome aerial photographic interpretation completed on esker north of Artillery Lake. **a)** Aerial photographic interpretation showing narrow esker ridge (line) and broader esker areas (polygons). **b)** Esker polygon areas derived by EDM using a cutoff value of 1 m and buffer of 100 m of esker line. **c)** Aggregation of esker polygons within 100 m buffer.

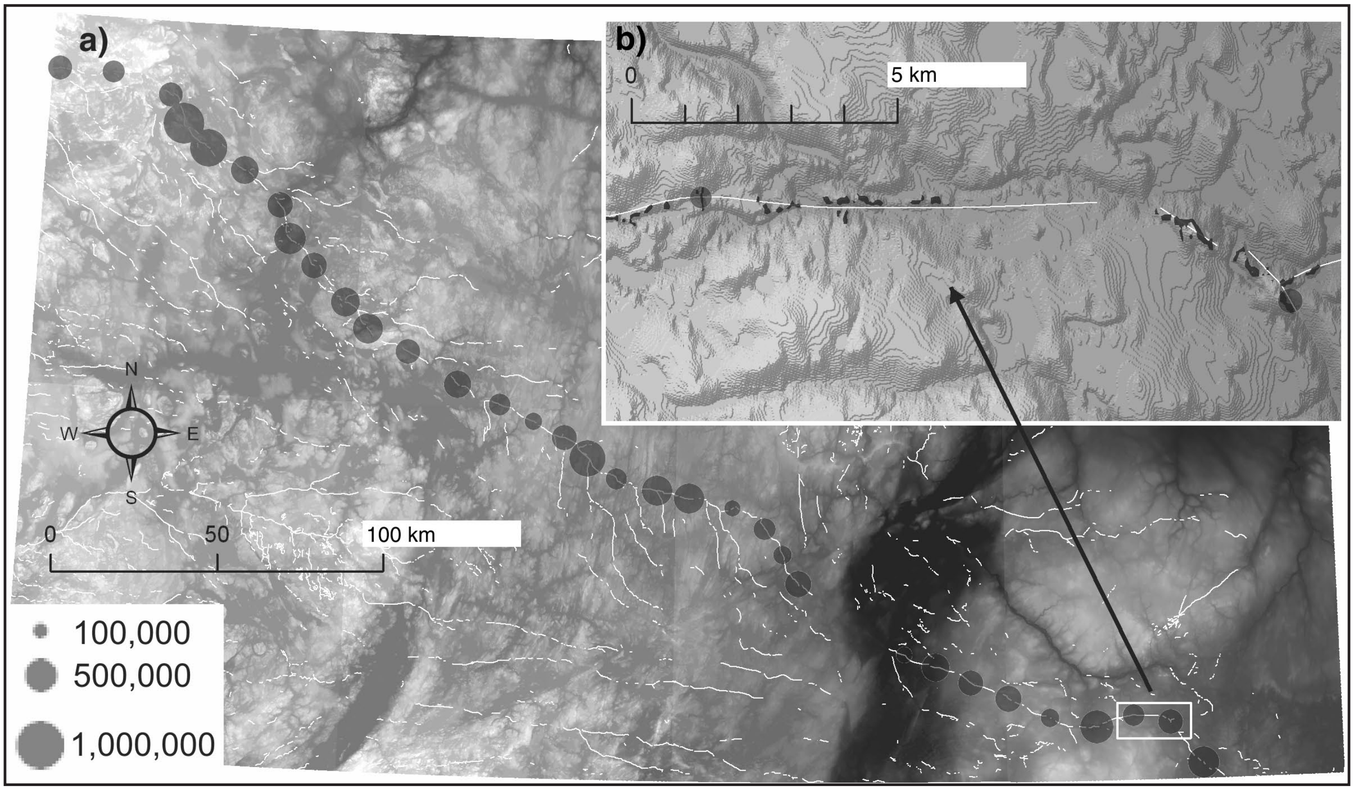

Figure 14. a) A 400 km long section of esker extending across six 1:250 000 NTS map sheets (76 B, 76 C, 75 N, 75-O, 75 P, 65 M) from near Dubawnt Lake to north of Lac de Gras. Proportional circle symbols show 'volumes' in cubic metres summarized for every 10 km along the esker line . **b)** Map shows esker polygons overlaid on esker lines and CDED DEM along with proportional dot position.

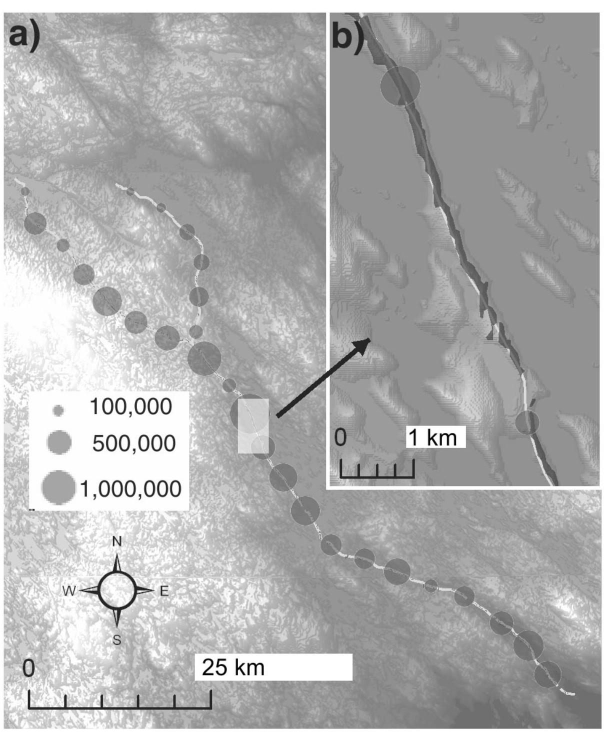

Figure 15. EDM information for esker near western shore of Hudson Bay (portions of 1:250 000 NTS sheets 55 K and 55 N). **a)** Volumes measures in cubic metres are summarized for every 5 km of the esker line and displayed as proportional symbols. **b)** Map shows esker polygons overlaid on esker lines and CDED DEM along with proportional dot position. Note much greater continuity of polygon coverage for this esker.

quantitative esker information without the requirement for a GIS licence and visualization with respect to Google Earth imagery.

ISSUES AND FURTHER RESEARCH

Issues of manipulation of the digital data

This study evaluated the feasibility of using 1:50 000 CDED data and legacy esker line-work to delineate and to quantify esker areas and volumes. A serious shortcoming of the CDED data is the integer quantization of elevation, resulting in a stair-step appearance in areas of relatively low relief. This integerization results in a data set that does not represent the land surface as a continuously varying surface, but rather imposes a stepped function to the surface. This prevents the use of standard DEM derivatives.

To address the integer problem in the CDED data an elevation-difference surface was the key input in the process. In order to produce esker polygons which more closely resembled the character of those identified during the manual airphoto interpretation, it was found that rather than using the raw elevation surface, a closer correspondence to the manual interpretation resulted from smoothing the DEM slightly using a 5 × 5 pixel filter to produce a less-smoothed surface, then subtracting the more-smoothed regional-elevation surface from the less-smoothed surface. Subtracting the regional-elevation surface from the raw DEM resulted in a jagged, fragmented elevation-difference surface.

It could be argued that this smoothing compromises the 'volume' measures. It is acknowledged that an additional smoothing step in the process alters the original DEM and reduces accuracy of the DEM; however, it creates an elevation model that more closely represents the continuous character of the actual surface. The 'volume' measures are referenced in inverted commas as the volume measures will represent an approximation of the actual esker volumes, given the limitations of the original data and the algorithm. These 'volume' measures, however, are calculated in a consistent way and do provide an automated way of comparing and ranking volumes of eskers in different locations. Even in the best of circumstances, manual interpretation and field sampling both have issues with subjectivity.

Eskers

This method has been compared to conventionally produced aerial photographic interpretation, and a relatively good correlation was found where the esker features are of sufficient size and relief relative to the DEM resolution (Fig. 13). Interpreted aerial photography, however, can at best act as a spot check, given the massive length of esker networks in northern Canada. Comparing results to those obtained with higher resolution DEMs and a more nuanced methodology would be instructive, but in this region there are no alternate DEM data sets to the CDED.

Proposed research involves extraction of esker features in an area of southern Canada based on Ontario Ministry of Natural Resources DEMs (10 × 10 m x,y resolution, decimal metres in z) using DEM derivatives including slope and curvature. Results of that analysis will be compared to data extracted from CDED DEMs as described in this paper.

Additional data sets are being explored for mapping of the eskers beyond the limit of the derivative difference surface. Eskers often are broader and more areally extensive than defined by this approach; however low relief and/or lack of peakedness does not enable the approach documented here to detect their continuation. A preliminary attempt with Landsat using a supervised classification found that regionally there was no characteristic difference between the spectral signatures within the esker polygons and laterally beyond the polygon. This reflects varying substrate of the eskers (gravel vs. sand), variable substrate mobility (gravel lags vs. sand blowouts), and differences in surface relief and consequently moisture content and vegetation cover. One direction of proposed research is to determine the local spectral signature within individual polygons, then search outward from each polygon for cells with similar spectral signatures. This method could refine the estimated polygon coverage of the esker by reducing the reliance on topographic expression in the CDED data.

CONCLUSIONS

Esker ridges with adequate relief, breadth and peakedness have been extracted from CDED data using legacy GSC vector esker line work as a training data set. The extracted areas, delimited by a polygon, can then be used to query the CDED data and additional attribute data stored in a database. Additionally a variety of statistical measures can be applied to quantify shape parameters of the polygon data set. The data can then be used to improve quantitative understanding of variability along the esker network. The veracity of the process has been tested against the input training data and a local data set generated manually from aerial photographic interpretation. Depending upon terrain characteristics, the success of the data extraction ranges from 65 to 81% against the esker line-work and 35 to 72% against the more geographically limited aerial photographic interpretation. This comparison against two independent data sets demonstrates that the method can successfully be applied for esker analysis in the barren lands of Keewatin; however, the process has the best success with larger eskers that form the trunk components of regional dendritic eskers. This reflects the low resolution of the CDED data that the method used which only captures a landform signature for larger eskers.

Refinement of this method is likely to successfully delineate significant portions of esker networks in northern Canada for quantitative analysis.

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