

AN EVALUATION OF SRTM DIGITAL ELEVATION DATA FOR GLACIAL LANDFORM MAPPING IN NEWFOUNDLAND

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ABSTRACT

The availability of Shuttle Radar Topography Mission (SRTM) digital elevation data has the potential to revolutionize glacial landform mapping and eliminate many of the shortcomings of more traditional methods, such as aerial photograph interpretation. Although widely used, there has been limited testing of the suitability of SRTM data for such glacial landform mapping. This paper describes a comparative study of glacial landform mapping from northeast Newfoundland, Canada, using aerial photograph interpretation and a SRTM digital elevation model (DEM). It forms part of a larger study aimed at identifying sectors of fast flow (ice streams) within the late Wisconsinan Newfoundland Ice Cap.

The study assessed the amount and type of overlap between landform data derived from a SRTM DEM and aerial photographs and explored systematic mapping biases that may negatively affect data quality. Results indicate that the interpretation from 1:50 000 aerial photographs produced more detailed landform maps than that from the SRTM DEM. This was likely the result of large differences in horizontal resolution between mapping sources (≤ 10 m for aerial photographs and 90 m for SRTM DEM). The SRTM data permitted identification of larger scale landforms, particularly ribbed moraine, which were only selectively recorded on aerial photographs. Analysis of landform distribution and surficial geology provided similar results for the two datasets: mapped-landform concentrations were highest in areas of thick till and lower in till veneer and bedrock.

The SRTM DEM was successful in the identification of regional ice-flow trends and landform patterns. The use of multiple illumination angles avoided bias in the mapping of linear features in the SRTM DEM, while the integration of supplemental data, such as bedrock and surficial geology, improved overall mapping quality, particularly for flow-parallel landforms. Although lacking the finer detail of aerial photographs, the efficiencies offered by SRTM data for reconnaissance mapping of glacial landforms are confirmed.

INTRODUCTION

Traditional methods of mapping glaciated terrain, including field mapping and aerial photograph interpretation of 1:50 000 map sheets, are generally time intensive, subjective, and lead to the development of bottom-up approaches to large-scale ice-sheet reconstruction. Recent developments in remote-sensing technologies have made available digital elevation models (DEMs) that allow landscape visualization at a variety of scales. With these products it is possible to conduct glacial mapping across larger areas in a systematic manner, thus promoting a top-down approach that allows greater analysis and synthesis of evidence at the ice-sheet scale (Clark, 1997).

With the release in 2003 of an almost globally extensive topographic dataset from the Shuttle Radar Topography Mission (SRTM), high resolution DEMs for Newfoundland

and Labrador became readily available. Application of these DEMs has the potential to increase mapping speed and to promote a better understanding of regional ice-flow histories (e.g., reconnaissance-level mapping of large areas of Labrador). In an effort to begin such systematic, cost-effective mapping, the Geological Survey of Newfoundland and Labrador has developed a preliminary glacial landform dataset for the Island of Newfoundland, interpreted from SRTM data (D. Liverman, unpublished data, 2008). Although SRTM data may significantly increase the efficiency of landform mapping, there has been no systematic attempt to assess product quality, nor has there been an evaluation of how best to employ the data in combination with other geological products.

This paper reports on a comparative study of landform mapping from northeast Newfoundland using data derived from three sources: aerial photographs, SRTM DEM, and a

combination of aerial photographs and SRTM data. These are evaluated to assess the amount and type of overlap between landform data derived from SRTM DEMs and aerial photograph interpretation and to explore systematic mapping biases that may negatively affect data quality. The results of this study will assist in the preparation of regional ice-flow maps based on landform data derived from interpretation of traditional aerial photographs and recent SRTM data.

SHUTTLE RADAR TOPOGRAPHY MISSION (SRTM)

The Shuttle Radar Topography Mission was flown by the Space Shuttle Endeavour during February 2000, producing the first global, large-scale topographic dataset. The SRTM provides a high-quality DEM at 3-arc-second (~90 m) resolution between latitudes 58°S and 60°N. To capture elevation data of Earth's surface, SRTM used interferometry, a technique in which two images of the same area are taken from different vantage points. In the case of SRTM, this was achieved by using two antennas: one within the cargo bay of the shuttle and another on the end of a 60-m-long mast deployed from the shuttle. The interferometry radar used phase/range differences measured from the two different vantage points to obtain elevation data with an absolute accuracy of ± 16 m and relative accuracy of ± 6 m (Farr *et al.*, 2007). The SRTM radar contained two types of antenna panels, C-band and X-band. The near-global topography was generated from the C-band radar data, which were processed at the Jet Propulsion Laboratory and distributed through the United States Geological Survey's EROS Data Center (<http://edc.usgs.gov/srtm/data/obtainingdata.html>).

The SRTM data differ from traditional remote-sensing data in several key characteristics. For example, the horizontal resolution of 1:50 000 aerial photographs, while not explicitly stated, is likely less than 10 m compared to the 90 m resolution provided by a SRTM DEM. Also, aerial photographs have elements of image interpretation in the form of tonal and textural data that aid in landform identification (Campbell, 2002). In contrast, SRTM DEMs lack surface textural data, and tonal variations reflect slope angle and aspect rather than surface reflectance properties.

GLACIAL MAPPING USING SRTM

The use of SRTM data for glacial and surficial mapping is an increasingly common practice in Canada since its release in 2003 (Table 1). The SRTM data address the need for rapid, reconnaissance-level geological mapping of remote areas (*e.g.*, Matile *et al.*, 2003; Mei *et al.*, 2005; Matile and Keller, 2007) and regional-scale reconstructions of ice-sheet dynamics from mapped glacial lineations and

their crosscutting patterns (*e.g.*, Lowell and Fisher, 2005). Although some of these studies have limited ground-truthing, and in some cases the DEMs are supplemented with other remote-sensing data (*e.g.*, Mei *et al.*, 2005; Hickin and Levson, 2008), interpretations from SRTM data appear to be largely untested against traditional mapping sources.

STUDY AREA

The study area covers approximately 13 000 km² and includes 13 1:50 000-NTS map sheets in northeastern Newfoundland (2D/11, 2D/12, 2D/13, 2D/14, 2D/15, 2E/2, 2E/3, 2E/4, 2E/5, 2E/6, 2E/7, 12A/9 and 12A/16; Figure 1). The largest communities in the study area are Gander and Grand Falls–Windsor. Several smaller communities, including Lewisporte, Botwood and Norris Arm, are located along the coast. The study area extends inland 60 km from the most southerly arm of the Bay of Exploits, the modern basin for the Exploits River.

BEDROCK GEOLOGY AND PHYSIOGRAPHY

Bedrock in the study area typically increases in age from east to west. Eastern and southeastern areas are underlain by Cambro-Ordovician siliciclastic marine sedimentary rocks of the Gander Zone, inferred to have formed along the continental margin of the early Iapetus Ocean. Farther west, bedrock consists of marine siliclastic rocks (including sandstones, conglomerates, and siltstones) and island-arc volcanic and volcanoclastic rocks ranging in age from Cambrian to Silurian and comprising parts of the Dunnage Zone (Colman-Sadd and Crisby-Whittle, 2002). After the closing of the Iapetus Ocean, these rocks, along with those of the Gander Zone, were intensely folded, imparting the northeast–southwest structural trend observed in the bedrock. This structural trend has the potential to complicate mapping of subglacial landforms in the area because the main ice-flow trend is also northeast. All rocks were crosscut during the Siluro-Devonian by gabbros and granites of the Mount Peyton and Hodges Hill Intrusive suites. These granitoids now form the local topographic highs in the study area (Mount Peyton – 487 m; Hodges Hill – 569 m).

The regional topography slopes gently coastward (Figure 2). Areas underlain by volcanic rocks tend to have higher elevation, likely reflecting their greater resistance to weathering and erosion compared to the adjacent sedimentary rocks. The coastline is composed of headlands separating numerous smaller bays and inlets. Several major rivers, including the Exploits River, Great Rattling Brook, Gander River and Northwest Gander River, occupy valleys that typically follow the softer siliclastic bedrock of the Dunnage Zone.

Table 1. Locations and descriptions of published glacial mapping projects in Canada utilizing SRTM data

Author	Location	Primary Use	Additional Comments
Matile <i>et al.</i> , 2003 Matile and Keller, 2007	Manitoba	Reconnaissance mapping to produce 1:250 000- and 1:1 000 000-scale surficial geology maps	Limited ground truthing
Campbell, 2005	Saskatchewan	Identification of previously unmapped large-scale landforms, for regional ice-flow mapping	Identified potential ice streams based on mapping of large-scale glacial lineations
Mei <i>et al.</i> , 2005	Northern Alberta	Surficial mapping of inaccessible areas	SRTM used in conjunction with RADARSAT-1, Landsat and Indian Remote Sensing Satellite images
Lowell and Fisher, 2005	Southern Canada and northern USA	Interpretations of large-scale landforms	SRTM DEMs used to reconstruct a deglacial history of the southern Laurentide Ice Sheet
Liverman <i>et al.</i> , 2006	Newfoundland	Interpretations of surficial geology, particularly glacial landforms	SRTM DEMs used for interpreting large-scale oriented landforms such as flutes, drumlins and crag-and-tail hills
Ross and Parent, 2007	Canadian prairies	Identification of obscured streamlined terrain	In conjunction with borehole data SRTM DEM led to the identification of large-scale tributary flow within the southwestern Laurentide Ice Sheet
Batterson and Taylor, 2007	Newfoundland	Mapping geomorphic features to aid in ice-flow reconstructions	Used to supplement ice-flow mapping from aerial photographs and striations
Hickin and Levson, 2008	Northeastern British Columbia and northwestern Alberta	Mapping of large-scale streamlined landforms of the former Cordilleran and Laurentide ice sheets	Used in conjunction with LiDAR DEMs

SURFICIAL GEOLOGY AND GLACIAL HISTORY

The surficial geology is dominated by varying thicknesses of sediment. Concealed and exposed bedrock dominates coastal areas whereas till cover increases inland, ranging from till veneer to thick till blanket in central and southern regions (Liverman and Taylor, 1990). Topographic highs, such as Hodges Hill and Mount Peyton, are characterized by thin and discontinuous sediment cover, although the presence of erratics indicates that the area was once ice covered. Typically the slopes of topographic highs are mantled with sediment, with the up-ice (southwest) side having

thicker till deposits than the down-ice side. The southern margin of the study area is dominated by extensive fields of hummocky till terrain (Liverman and Taylor, 1990). Low-lying areas along the coast generally contain either glaciofluvial or glaciomarine sediments. Marine limit for the area is placed at 58 m above sea level based on the elevation of a raised delta surface at Laurenceton, near Botwood (MacKenzie and Catto, 1993). Large river valleys, such as the Exploits and those of its tributaries, contain extensive glaciofluvial sand and gravel deposits. Major meltwater channels and esker complexes are commonly aligned with these large valleys. Regional glacial histories have been

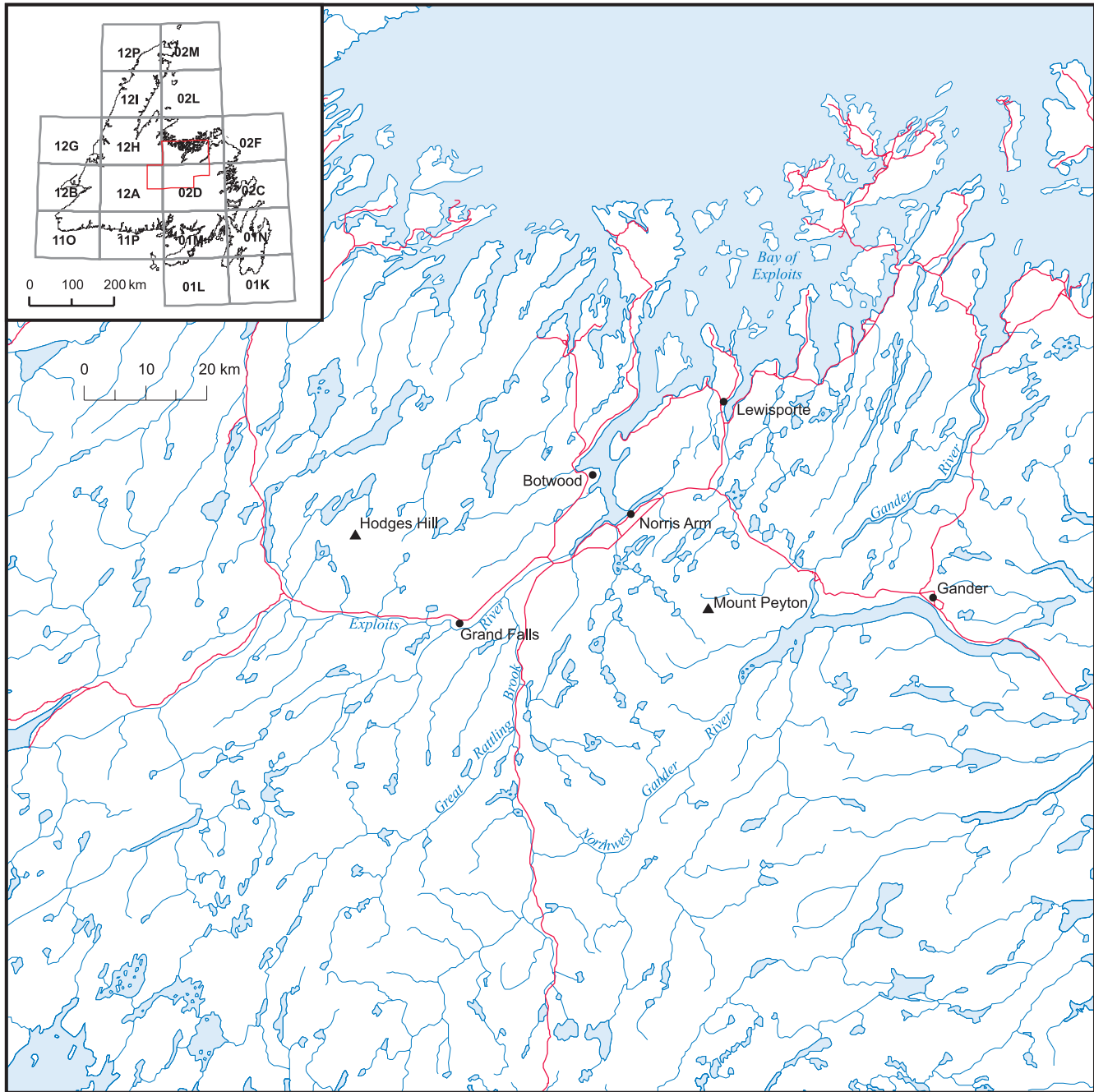


Figure 1. Map of study area.

compiled by a number of previous workers including Rogerson (1982), Grant (1974, 1989), St. Croix and Taylor (1991) and Batterson and Taylor (1998). A three-phase sequence of glacial events has been proposed (St. Croix and Taylor, 1991; Batterson and Taylor, 1998). The earliest flow was an eastward ice advance, evidence for which was observed across much of northeastern Newfoundland (St. Croix and Taylor, 1991; Scott, 1994; Batterson and Taylor, 1998) and with a likely source in The Gaff Topsails. The second flow, which is repeatedly described as the dominant ice flow, was

to the northeast from an ice divide arching across south-central Newfoundland from Middle Ridge to Meelpaeg Lake (Grant, 1974; Rogerson, 1982). St. Croix and Taylor (1991) subdivided this flow into an earlier northeastward flow followed by a later more northward flow into the Bay of Exploits. The third flow is described as a localized eastward flow, most likely representing re-advance of a remnant ice cap west of Grand Falls during Younger Dryas cooling (St. Croix and Taylor, 1991).

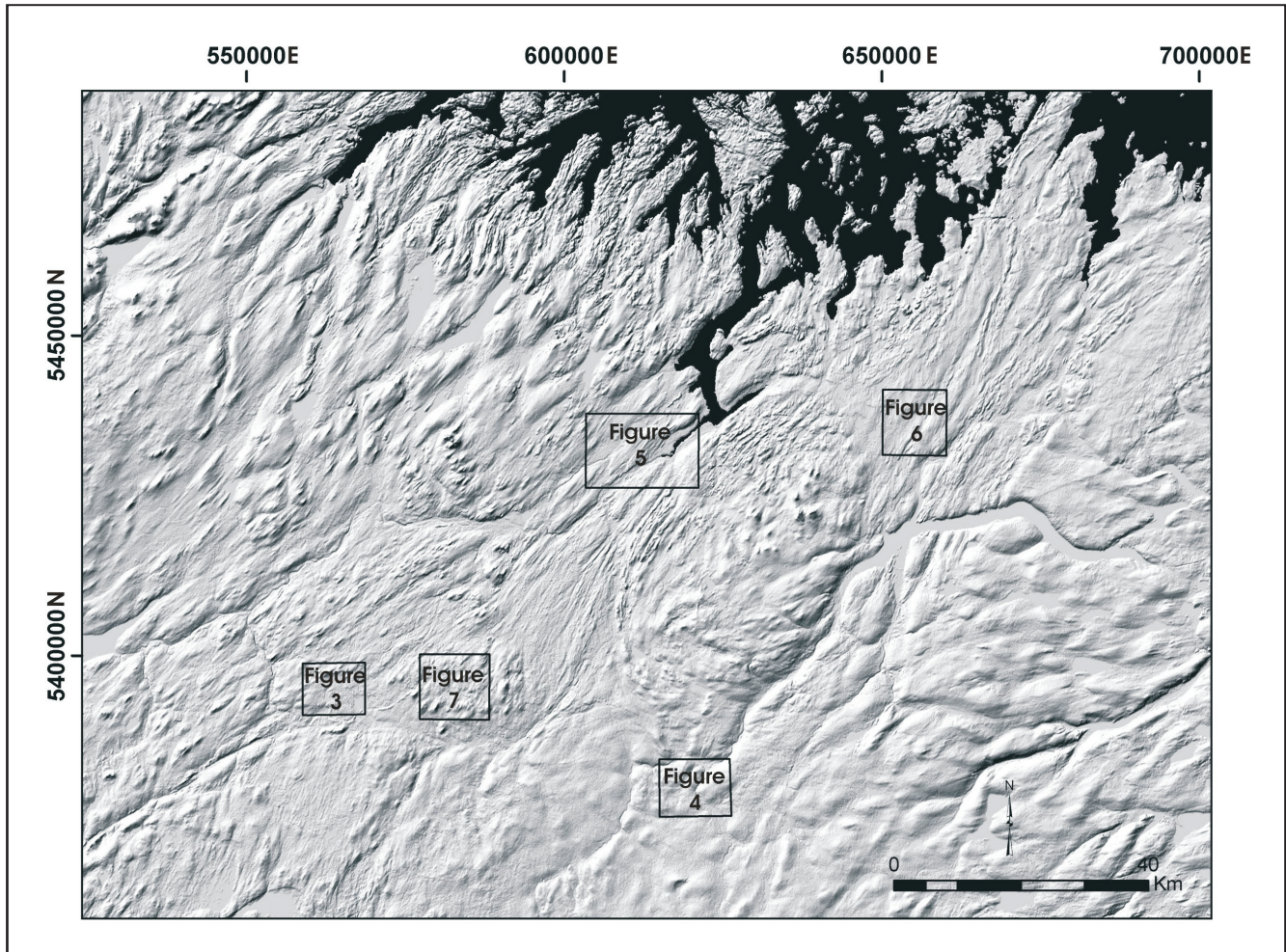


Figure 2. False-shaded SRTM image of study area with locations of subsequent figures outlined by boxes. Image is illuminated from the northwest.

DATA AND METHODS

GLACIAL LANDFORMS

A range of subglacial landforms were mapped for this study. Subglacial landforms are defined as longitudinal or transverse accumulations of sediment formed below active ice (Rose, 1987; Benn and Evans, 1998). Longitudinal subglacial landforms are features that are aligned parallel to flow and include flutes, drumlins and megaflutes (Plate 1), with divisions being defined based on differences in length and elongation ratio (Table 2). Rose (1987) suggested that flutes, drumlins and megaflutes form a continuum of bedforms. In an effort to simplify classification, all longitudinal subglacial bedforms in this study are classified as flutes. Ribbed moraine occurs as fields of coalescent crescentic ridges of sediment lying transverse to former ice flow (Benn and Evans, 1998; Plate 2). These ridges have lengths rang-

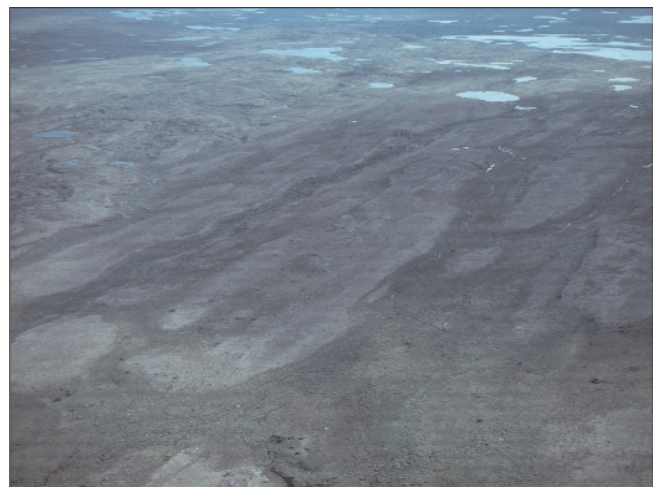


Plate 1. Oblique aerial photograph of low relief flutes. Ice flow was from bottom left to top right.

Table 2. Classification of flow-parallel landforms by dimensions (m) according to Rose (1987). Elongation ratio is defined as length (l) divided by width (w)

Landform	Typical Length	Typical Height	Elongation Ratio
Flute	< 100	< 3	> 4
Drumlin	> 200	> 5	< 4
Megaflute	>100	< 5	> 4



Plate 2. Oblique aerial photograph of ribbed moraine in the central Avalon Peninsula, Newfoundland.

ing from 45 to 16 000 m (mean = 688 m), widths from 17 to 1100 m (mean = 278 m) and heights ranging from 1 to 64 m (mean = 17 m; Benn and Evans, 1998; Dunlop and Clark, 2006). An additional class of elongate bedforms has been mapped – crag-and-tail hills. These are generally either erosional or depositional features consisting of a resistant bedrock crag at the up-ice end and a tail of less resistant bedrock or sediment down-ice (Benn and Evans, 1998; Plate 3).

STUDY APPROACH

The standard desk-top approach to landform and surficial geology mapping involves stereoscopic viewing and interpretation of stereo-pairs of aerial photographs ranging in scale from 1:50 000 to 1:12 500 or larger. Landform mapping using a digital DEM, however, requires visualization of the data using various illumination angles, shaded-relief effects and vertical stretching. In this study, it is hypothesized that the aerial photograph interpretation will produce the most complete landform dataset because of the characteristics of aerial photographs that aid in the interpretation of landforms (*e.g.*, tone, texture). In contrast, the SRTM DEM mapping is likely to include more large-scale landforms because of the coarser resolution and more basic topographic characteristics (*e.g.*, elevation, slope angle and aspect).



Plate 3. Photo of crag-and-tail hill. Ice flow was from right to left. Note presence of prominent up-ice bedrock 'crag' and tapered down-ice 'tail'.

DATA SOURCES AND ANALYSIS

The landform database derived from stereoscopic viewing and interpretation of stereo-pairs of 1:50 000-scale black and white aerial photographs, here named AERIAL, was generated by the lead author. To ensure completeness of mapping, many areas were re-examined after initial interpretation. The landform database generated from SRTM data interpretation, named SRTM, was compiled by D. Liverman (unpublished data, 2008). It was originally designed to provide island-wide landform mapping at a reconnaissance level. A second SRTM based dataset, known as SRT-MAerial, was compiled by the lead author to test whether a combination of aerial photograph and SRTM DEM interpretation would generate a more complete landform database than SRTM data alone.

Seamless SRTM elevation data were downloaded and imported into *Global Mapper* software from which two DEMs were produced with false-shaded illumination from the northeast and the northwest. Landform height in all three datasets was measured using the SRTM elevation data. The landform width was either measured from aerial photographs or SRTM DEMs, and landform length was generated in *ArcMap*. Mapping was supplemented by 1:50 000-scale topographic, surficial geology (Liverman and Taylor, 1990) and bedrock geology (Colman-Sadd and Crisby-Whittle, 2002) maps, and consultations with geologists who have extensive knowledge of the study area.

Qualitative visual inspection of mapping accuracy was supplemented by analysis based on spatial distribution of landform type and surficial geology. Surficial units identified by Liverman and Taylor (1990) were reclassified as follows: 1) thick till, including till blanket, hummocky terrain

and areas of ridged till; 2) thin till or till veneer; 3) concealed bedrock; 4) exposed bedrock and; 5) other, including alluvium, colluvium, glaciofluvial sand and gravel, and marine sediments. Where individual landforms crossed multiple surficial units, they have been counted more than once, resulting in landform counts by unit totalling more than 100%.

RESULTS

Data trends are presented first for the study area as a whole and then by individual landform type. In each of the three datasets, ribbed moraine was the most common landform type, constituting more than 75% of all delineated landforms (Table 3). Flutes were the next most common, representing 14% of all landforms mapped in AERIAL and between 7 and 9% in SRTM and SRTMAerial. Crag-and-tail hills were least common and represented less than 8% of all landforms. AERIAL typically had higher total landform counts than both SRTM and SRTMAerial (Table 3).

Table 3. Individual and total landform counts for each database

Landform	AERIAL	SRTM	SRTMAerial
Ribbed Moraine	2848	2645	2599
Flute	500	221	258
Crag-and-Tail	288	180	264
Total	3636	3046	3121

RIBBED MORaine

The AERIAL dataset had the highest number of ribbed moraine ($n = 2848$) followed by SRTM ($n = 2645$) and SRTMAerial ($n = 2599$; Table 3). In each dataset, more than 85% of the ribbed moraine was identified in areas of thick till, and at most only 20% was identified in areas of till veneer. SRTM and SRTMAerial generally produced slightly higher percentages of ribbed moraine than AERIAL within terrain classified as concealed bedrock or 'other'.

Although the counts for ribbed moraine are consistent across each of the three datasets, visual inspection suggests that there was significant variation in the scale of landform classified as ribbed moraine, with those mapped from SRTM generally being larger (Table 4). For example, mean length and width was 550 m and 225 m, respectively, for SRTM, in contrast to 355 m and 196 m for AERIAL. Height measurements were similar for all datasets (mean = 2.9 m). Larger scale ribbed moraine was readily identified on all datasets (Figure 3).

Mapping of ribbed moraine from AERIAL and SRTM does not reproduce the same spatial pattern (Figure 4). It

Table 4. Variation in landform length and width between datasets; mean value in parentheses

Landform	AERIAL	SRTM	SRTMAerial
Ribbed Moraine			
Length (m)	90–2700 (355)	200–2200 (550)	200–2300 (620)
Width (m)	125–300 (195)	150–350 (225)	150–375 (220)
Flute			
Length (m)	500–5000 (1560)	315–3150 (1265)	600–6000 (1700)
Width (m)	120–640 (306)	150–380 (326)	150–450 (310)
Crag-and-Tail Hill			
Length (m)	300–3000 (1300)	370–2000 (1100)	500–3250 (1400)
Width (m)	96–650 (310)	250–700 (420)	250–600 (430)

generally has a wider spatial distribution on SRTM compared with aerial photograph interpretation alone and typically occurs in areas classified as hummocky moraine by Liverman and Taylor (1990), such as in the southern margin of the study area. A similar association was also noted by Liverman *et al.* (2006). Ribbed moraine was most easily identified on SRTM when false illumination was from the northeast (Figure 5).

FLUTES

Flute counts from AERIAL ($n = 500$) are substantially higher than those from SRTM ($n = 221$) or SRTMAerial ($n = 258$; Table 3). The large discrepancy suggests that flutes are likely under-represented in SRTM-based mapping (Figures 5 and 6). For instance, an additional 43 flutes, or 20%, were identified on the SRTM DEM when combined with aerial photograph interpretation.

Flutes are most commonly mapped in areas of thick till (65–94%), and only 10% in areas of till veneer. Twice as many flutes were mapped on concealed bedrock from SRTM and SRTMAerial compared to AERIAL; however, they represented a minor percentage (20%) of the overall count.

The mean length of mapped flutes varied from one database to another with the longest ones in SRTMAerial (1700 m) and shortest ones in SRTM (1266 m; Table 4). Mean width and height measurements for flutes varied much less among databases, ranging between 306 and 326 m and 4.8 and 5.6 m, respectively.

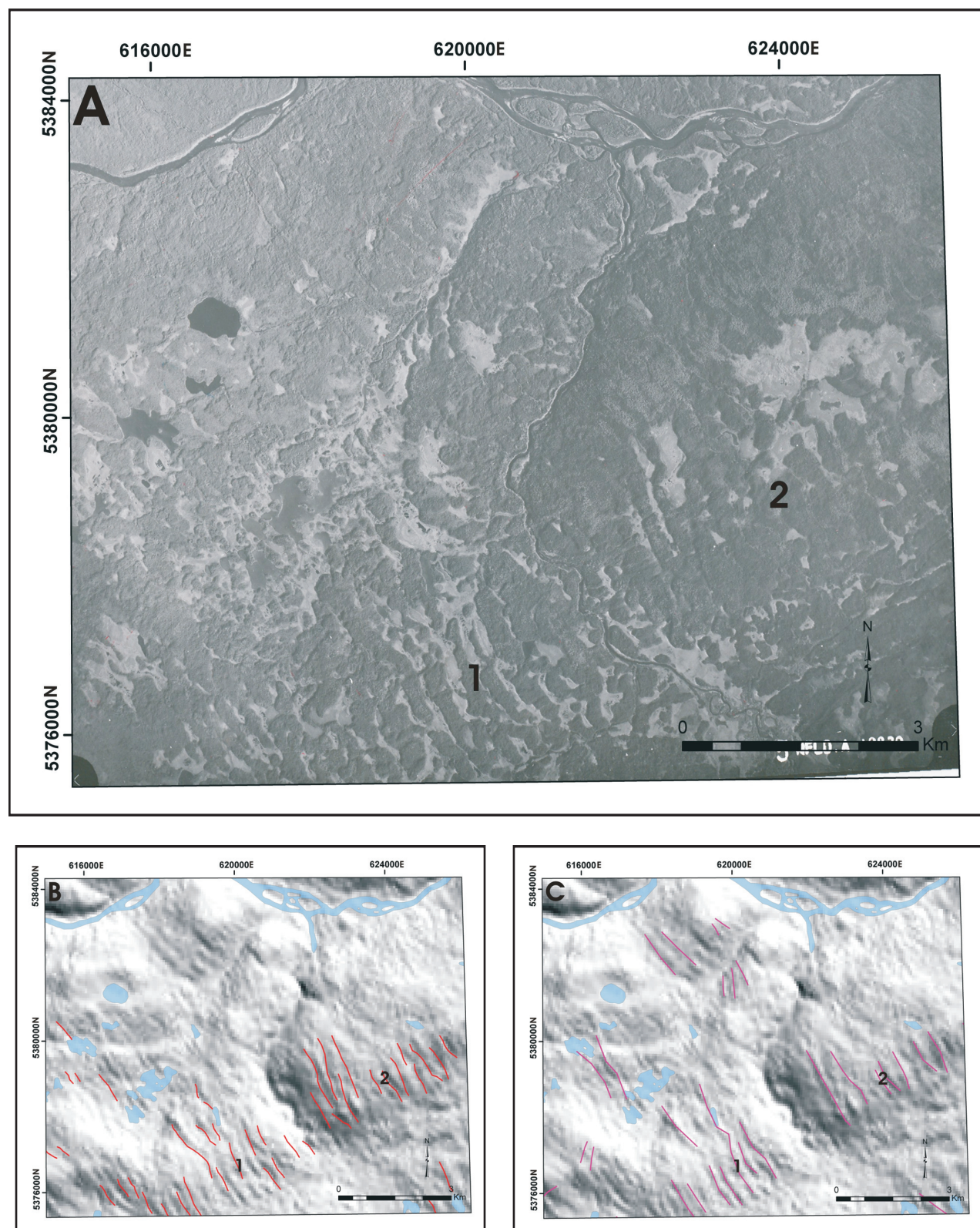


Figure 3. A) Aerial photograph of large ribbed moraine aligned with long axis northwest–southeast. 1 and 2 indicate locations where large ribbed moraine were mapped from both aerial photographs and SRTM DEMs. B) SRTM image illuminated from northeast showing ribbed moraine mapped from aerial photos (red lines). C) SRTM image illuminated from northeast showing ribbed moraine mapped from SRTM DEMs (pink lines).

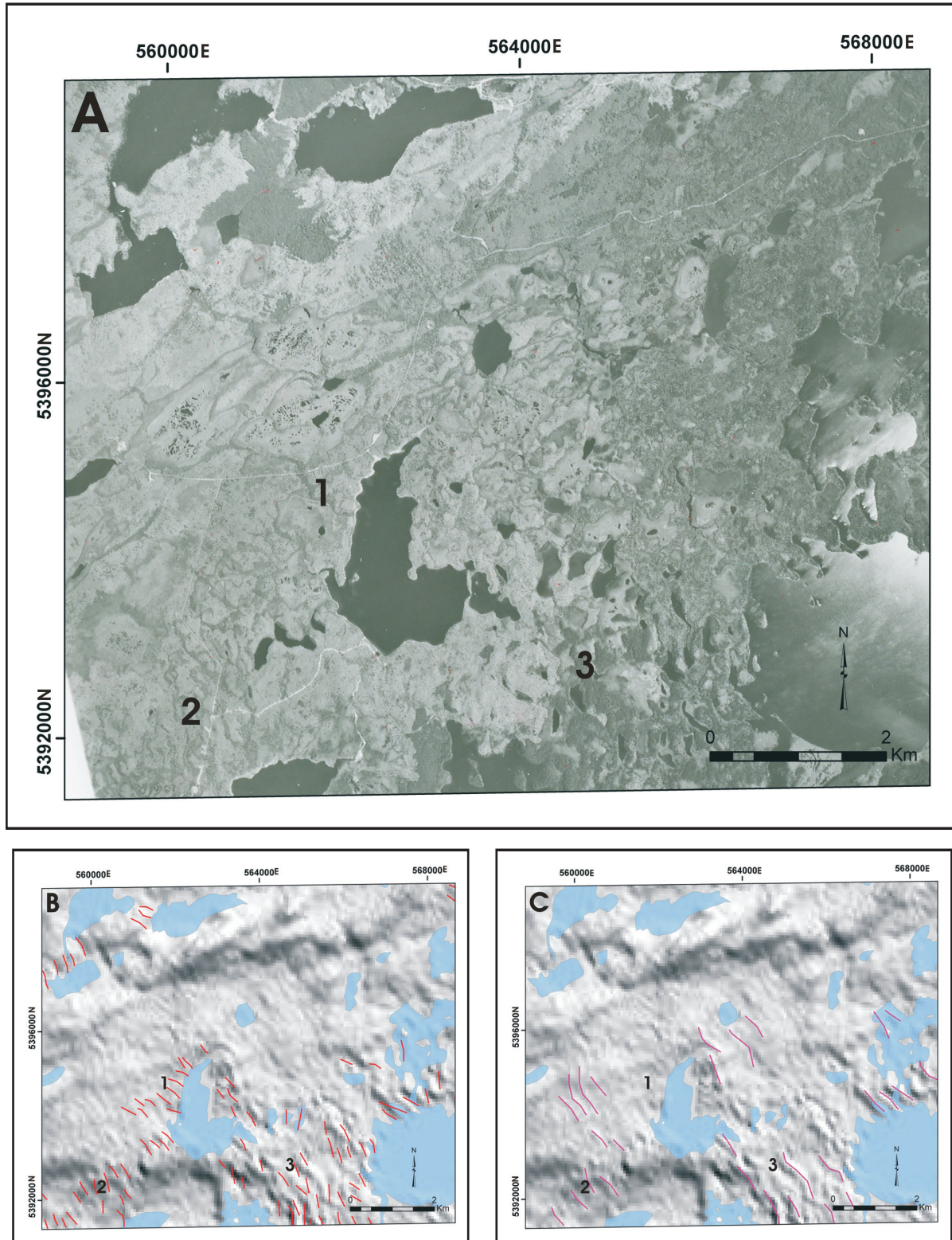


Figure 4. A) Aerial photograph of ribbed moraine field aligned with long axis northwest–southeast. 1 indicates location of subtle ribbed moraine mapped from aerial photographs but not SRTM DEMs. 2 and 3 indicate locations where ribbed moraine mapped from SRTM DEMs were larger than those mapped from aerial photographs. B) SRTM image illuminated from the northeast. Red lines represent ribbed moraine mapped from aerial photographs. C) SRTM image illuminated from northeast. Pink lines represent ribbed moraine mapped from SRTM.

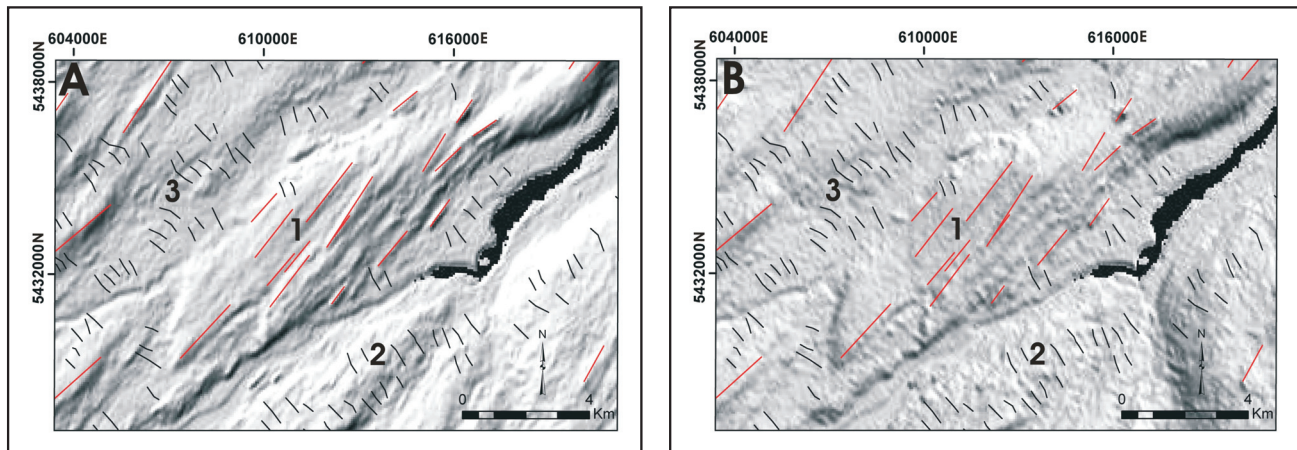


Figure 5. A) SRTM image illuminated from the northwest. 1 indicates where flutes mapped from SRTM (red lines) are preferentially highlighted when the illumination angle is perpendicular (northwest) to their long axis (northeast). B) SRTM image illuminated from the northeast. 2 and 3 indicate locations where ribbed moraine (black lines) are best viewed when the illumination is perpendicular to long axis of the landform (northwest).

CRAG-AND-TAIL HILLS

AERIAL ($n = 288$) and SRTMAerial ($n = 264$) had significantly more mapped crag-and-tail hills than SRTM ($n = 180$; Table 3.). Landform counts for crag-and-tail hills identified in areas of thick till ranged from 34 to 83%, whereas only 30% were mapped in till veneer. As anticipated, there were many more crag-and-tail hills (40%) identified on concealed bedrock compared to the other landform types.

Crag-and-tail hills were on average 200-300 m longer and 100 m or so narrower on both Aerial and SRTMAerial compared to SRTM alone (Table 4). Crag-and-tail hills were more readily visible on SRTM imagery than flutes and ribbed moraine (Figure 7) and their mean height (17 m) across all databases was significantly greater (2.9 m and 5.2 m for ribbed moraine and flutes, respectively).

DISCUSSION

This study indicates that mapping from aerial photographs facilitates the identification of a greater number of landforms than mapping solely from SRTM DEMs. Use of the SRTMAerial dataset (*i.e.*, some aerial photograph interpretation included) however, increased the number of mapped flutes. Nonetheless, landforms were significantly under-represented in landform counts derived from SRTM-based mapping as compared to those derived from aerial photograph interpretations (Table 3).

The highest counts for all landforms were, with the exception of crag-and-tail hills, located over areas of thick till. Based on the accepted definition of subglacial landforms (*see above*), the results indicate that mapping undertaken using the three datasets identifies landforms in areas

where thick surficial sediment should allow for their development. A reduction in landform counts over thin till is consistent with this outcome. However, the observed increase in ribbed moraine and flute counts on concealed bedrock in the SRTM and SRTMAerial databases is contrary to what would be expected as sediment thickness and cover decreases. This suggests that flutes and ribbed moraine may be misinterpreted in some instances on SRTM data and the greater detail provided by aerial photograph interpretation may produce more accurate results in comparison with SRTM-based interpretations.

In contrast, crag-and-tail hills appear to be correctly interpreted based on their association with predicted surficial geology. Given their composition, crag-and-tail hills should be located in areas with significant near-surface bedrock. Our results showed that 70% of crag-and-tail hills were identified on areas mapped as either concealed bedrock or till veneer, whereas units mapped as exposed bedrock and 'other' had generally low (less than 5%) counts.

Landform dimensions varied significantly between datasets with AERIAL generally having smaller landforms than SRTM-based interpretations. Some of the features identified in AERIAL had dimensions that would not allow them to be interpreted on the SRTM DEM. For example, low profile flutes may not be visible on SRTM DEMs due to inadequate visualization of tonal differences produced by relief shading. This apparent size biasing was not as significant an issue for the identification of crag-and-tail hills, as they typically have dimensions that are readily detectable from shadows produced by false shading. These results are similar to those presented by Liverman *et al.* (2006), who suggested that SRTM DEMs are best suited for mapping large-scale oriented landforms. Though not directly tested,

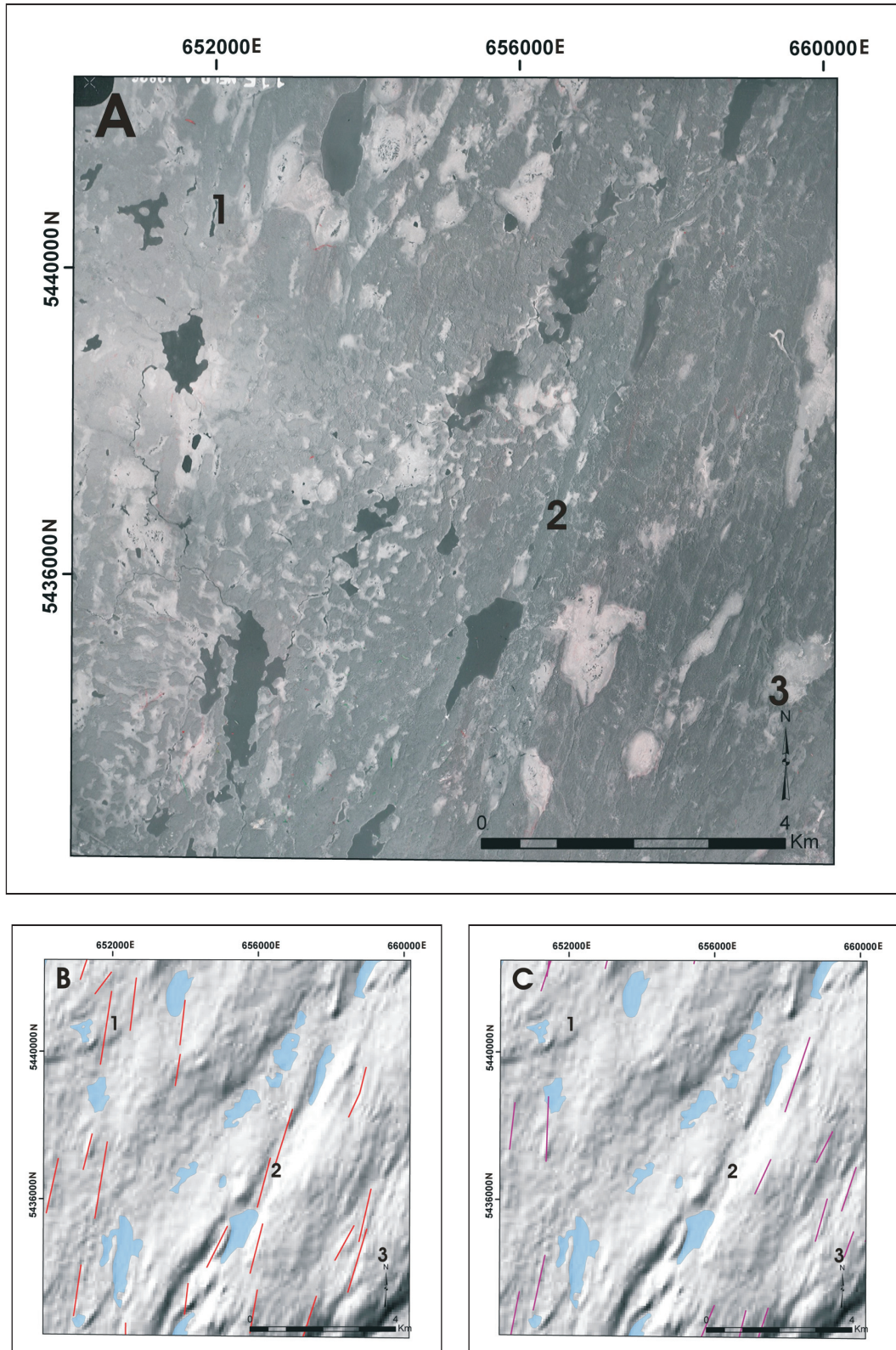


Figure 6. A) Aerial photograph of low-relief flutes trending to north-northeast. Areas with flutes identified in aerial photograph mapping but not from SRTM DEMs are indicated by 1, 2 and 3. B) SRTM image illuminated from the northeast with flutes mapped from airphotos (red lines). C) SRTM image illuminated from northeast with flutes mapped from SRTM (pink lines).

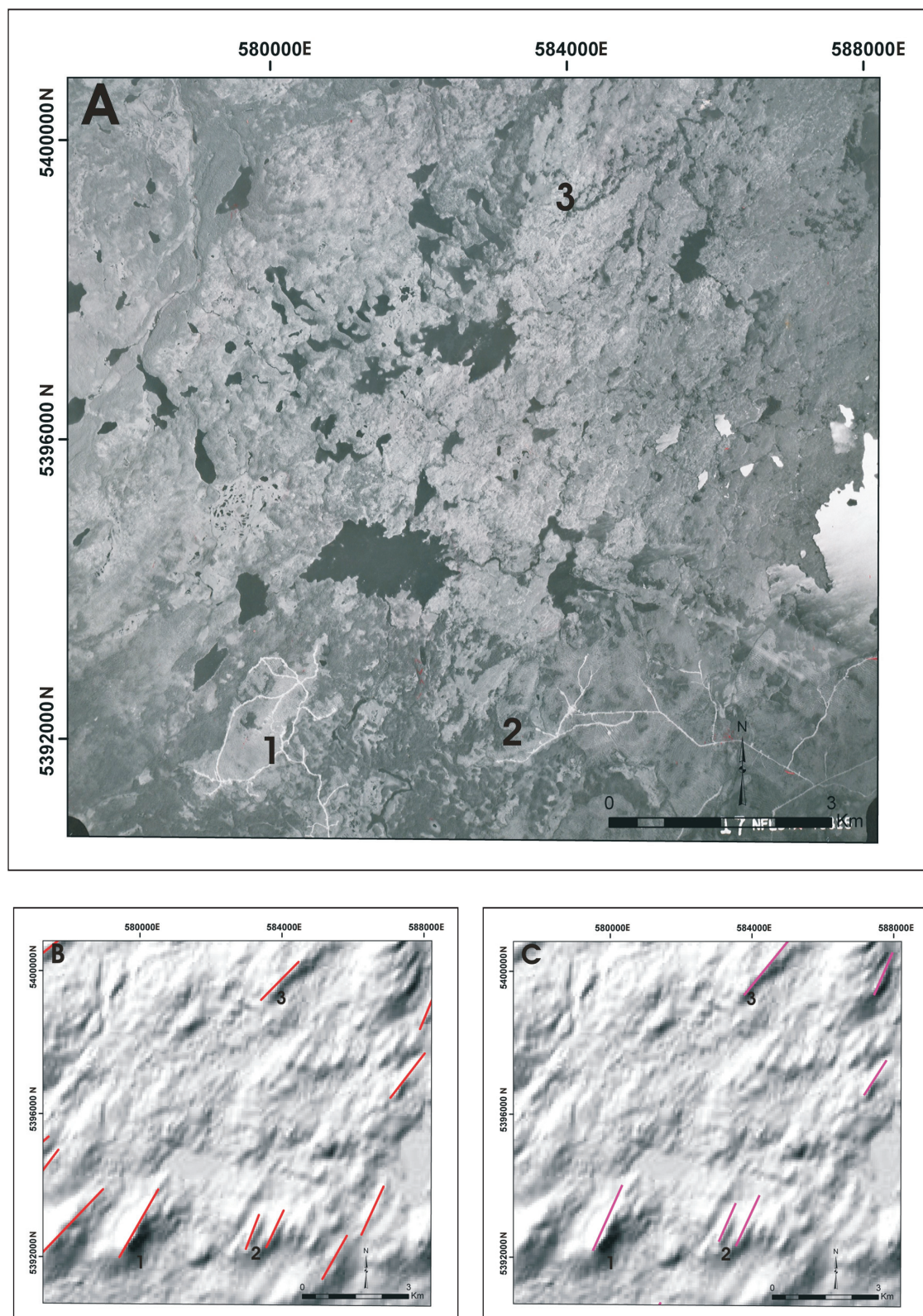


Figure 7. A) Aerial photograph of an area of crag-and-tail hills. Areas where similar landforms were mapped from both aerial photographs and SRTM DEMs are indicated by 1, 2 and 3. B) SRTM image illuminated from the northwest with crag-and-tail hills mapped from airphotos (red lines). C) SRTM image illuminated from northwest with crag-and-tail hills mapped from SRTM (pink lines).

this observation has implications for the mapping of subtle glacial landforms such as small eskers and meltwater channels, which would likely not be detectable on SRTM DEMs (*cf.*, subtle ribbed moraine and flutes).

The divergent results for ribbed moraine counts and sizes suggest that their identification in each of the three datasets has benefits and limitations. In many cases, ribbed moraine was mapped in similar areas, although individual ribs on aerial photographs were generally shorter, narrower and less widespread than those mapped from SRTM (Figure 4). For reasons similar to those identified for flutes (*i.e.*, low profiles which do not allow visualization on SRTM DEMs), it would seem that aerial photograph interpretation allows identification of moraines that are not readily detectable using SRTM. However, it also appears that mapping derived from SRTM is capable of identifying larger ribbed moraine, not observed on aerial photographs. The SRTM data may depict more widespread and larger moraine owing to the ability of radar to penetrate vegetation that might otherwise mask glacial landforms (Graham and Grant, 1991). Although ribbed moraine mapped from aerial photographs and SRTM DEMs had different dimension and distributions, they generally show similar directional trends. In all cases, ribbed moraine was within the dimensions described by Dunlop and Clark (2006).

It is critical to recognize the potential role of illumination angle and relief shading in introducing bias into landform mapping on SRTM DEMs. Elongate landforms such as flutes and crag-and-tail hills were best observed when illuminated from the northwest, as the dominant ice flow in this area was toward the northeast. When illumination was shifted to the northeast, few if any elongate landforms could be identified (Figure 5). As a result, much of the mapping of elongate landforms was undertaken using a northwest illumination, although a northeast illumination was used to check for landforms with alternate alignments. A similar result is observed in the mapping of ribbed moraine. As ribbed moraine is typically aligned transverse to the dominant ice-flow, in this case northeast, ridge crests were most easily mapped when highlighted from this same angle (Figure 5). Although illumination biases were recognized and accounted for in this study, in other areas where ice-flow histories are complex, the use of multiple view angles is critical to accurately identify all landforms produced from separate ice-flow events.

The regional bedrock structural trend in the study area is generally toward the northeast, similar to that of the dominant paleo-ice-flow direction. This may cause some misinterpretation of bedrock structure as elongate landforms. Where possible, it is recommended that supplemental surficial and bedrock geological data be used to help eliminate

mapping errors using SRTM. As expected, mapping of landforms from SRTM was significantly improved by knowledge generated through aerial photograph interpretation. Similarly, satellite imagery has been utilized by several authors (*e.g.*, Campbell, 2005; Mei *et al.*, 2005) to supplement mapping from SRTM. Although this methodology does not provide the same level of detail as aerial photograph interpretation, overlaying the high resolution satellite imagery on SRTM DEMs has the potential to eliminate some of the shortcomings in mapping from SRTM alone (*e.g.*, a lack of tonal and textural data).

Although mapping of each dataset produced variable results, the regional trends in landform patterns observed in aerial photographs are similar to those in SRTM DEMs, suggesting that for regional-scale landform-mapping, SRTM data are adequate. Additionally, SRTM mapping was accomplished in significantly less time than aerial photograph mapping, highlighting its value in reconnaissance level survey. Further, the regional approach provided by SRTM mapping, while perhaps not as detailed, allows for a better synthesis of glacial history over larger areas than that permitted through aerial photograph interpretation.

CONCLUSIONS

Recently released SRTM DEMs have the potential to revolutionize landform mapping, yet until now limited tests of the accuracy of maps derived from such data have been conducted. Results of this study indicate that:

- 1) Interpretation of SRTM DEMs leads to the identification of fewer landforms than interpretation from aerial photographs. This is because of the higher resolution, and the tonal and textural variations offered by aerial photographs, which allow visualization of subtle landforms that cannot be seen through relief-shading effects in SRTM DEMs.

- 2) Mapping from SRTM DEMs was slightly improved for elongate landforms, (flutes and crag-and-tail hills), by added knowledge derived from aerial photograph mapping.

- 3) The small scale of SRTM DEMs permits interpretation of larger landforms that might normally be missed in larger scale aerial photographs (*e.g.*, ribbed moraine) because of the coarser resolution and more basic topographic characteristics of SRTM DEMs (*e.g.*, elevation, slope angle and aspect).

- 4) Although landform counts varied between datasets, similar regional trends in landform type and associated surficial geological units are consistent with known results, indicating that SRTM mapping is capable of identifying regional landform distributions accurately.

- 5) Azimuth biasing effects introduced by false shading must be recognized and accounted for if mapping is to be considered accurate.

6) Depending on the application, each method has its particular advantages. Detailed landform mapping is better addressed by aerial photograph interpretation in which higher image resolution supports more detailed interpretation. The efficiency of SRTM mapping promotes its use in the production of preliminary, reconnaissance level ice-flow mapping of remote areas.

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