

DIGITAL ELEVATION MODELS FROM SHUTTLE RADAR TOPOGRAPHY MISSION DATA – NEW INSIGHTS INTO THE QUATERNARY HISTORY OF NEWFOUNDLAND

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ABSTRACT

Shuttle radar topography data are used to construct a digital elevation model for the Island of Newfoundland. The model provides a new means of visualizing the landscape of the Island, and allows many large-scale glacial features to be identified. Use of these images in interpreting surficial geology is demonstrated using examples from the Northern Peninsula, St. George's Bay, northeast Newfoundland and the Avalon Peninsula. The model is particularly useful for identifying large-scale oriented landforms such as flutings, drumlins and crag-and-tail features. Preliminary mapping of these features offers insights into the ice-flow patterns and glacial history of Newfoundland.

INTRODUCTION

Remote sensing methods are invaluable in mapping Quaternary and surficial geology, and each technological advance has provided a new means of visualizing the landscape, and thus providing insight into geological history. In Canada, the first major breakthrough came with near-complete aerial photographic coverage following the Second World War, allowing remote areas to be easily examined, and preliminary interpretations of surficial geology to be made. When satellite data first became available, it allowed examination of large-scale patterns and trends, but interpretation was limited by image resolution. Remote sensing using radar became available in the 1980s and 1990s, and proved to be particularly useful in areas of tree-cover, due to its ability to penetrate vegetation (Graham and Grant, 1991), and to image shadowed areas (Simms and Bell, 1998).

Recently, data from the Shuttle Radar Topography Mission (SRTM) were made freely available, with almost global coverage. Digital elevation models can be made from these detailed elevation data. The model produced for Newfoundland allows identification and mapping of large-scale glacial features, some previously unidentified, as well as improved delineation of known features.

WHAT IS SRTM?

The Shuttle Radar Topography Mission (SRTM) was flown by the space shuttle "Endeavor" in February of 2000,

a joint project of the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA). The objective of the mission was to map the surface topography of the Earth using synthetic aperture radar. This method compares radar images of the surface from two slightly separated vantage points to obtain elevation data with an absolute accuracy of 16 m. Relative differences in elevation are measured to a much greater degree of accuracy, allowing more subtle topographic features to be seen. The data point spacing was approximately 30 m, and the entire area between 60°N and 56°S was covered. The dataset was processed over a period of two years, and now is available free of charge via the Internet.

SRTM data increasingly is used for interpreting glacial history and geomorphology in Canada. Campbell (2005) observed numerous previously unrecognized large-scale, ice-flow features in Saskatchewan. Lowell and Fisher (2005) attempted large-scale reconstruction of the southern Laurentide Ice-Sheet using SRTM data and Matile *et al.* (2003) used SRTM interpretation in mapping surficial deposits of southern Manitoba. Mei *et al.* (2005) integrate RADARSAT-1, Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM), Landsat and Indian Remote-Sensing Satellite (IRS) images to support surficial mapping.

METHODS

The data for Newfoundland and Labrador were downloaded, and examined using "Global Mapper" software

(<http://www.globalmapper.com/>). It was found that this specialized product produced much better results than modules integrated into general GIS packages. It allows various means of visualization, including easy manipulation of illumination angles, application of varying vertical exaggeration and overlaying of other images. The standard image used in this paper uses false shaded relief, illuminated from various directions at an altitude of 45°, and with a vertical exaggeration of 2.5. Images produced in Global Mapper were imported into ArcMap for examination and mapping.

INTERPRETATION

The Island-wide image shows a clear influence of bedrock on topography, as might be expected, but also numerous glacial features (Figures 1 and 2). Areas of thick glacial sediment are easily identified on the image as being areas of relatively subdued topography. Small-scale glacial features generally are not visible, and eskers but large-scale streamlined features, and larger moraines show clearly. Two false-shaded relief images were used in interpretation of features, one illuminated from the northwest, the other from the northeast. False-shaded relief emphasizes features perpendicular to the direction of illumination, and use of only one illumination angle results in features elongate parallel to the direction of illumination being poorly portrayed.

As with all methods of remote sensing, interpretation of these images involves a degree of uncertainty. The topography of Newfoundland is influenced by bedrock properties, and by the affects of glaciation. In interpretation, particularly when examining linear features, it may be difficult to determine if a feature was formed by glacial activity, or reflects bedrock structure. These problems are faced in aerial photograph interpretation also, but the higher resolution in aerial photographs often gives a greater degree of certainty. When examining the SRTM mapping, preliminary interpretations were checked in some cases against existing mapping, and by examination of aerial photographs.

Subtle features such as low-relief, ribbed moraine appear to be better shown on the SRTM image than on aerial photographs in some areas. This is perhaps due to the ability of radar to penetrate vegetation that masks these features on aerial photographs.

EXAMPLES

RIBBED AND ROGEN MORaine

Large moraines and moraine fields are readily recognizable on the SRTM image, including various scales of features aligned generally perpendicular to ice-flow. Relief is

variable and areas previously mapped as Rogen or ribbed moraine are identifiable on the image.

The classic form of Rogen moraine is that of a set of evenly spaced ridges oriented transverse to glacial flow. Individual moraine ridges are sinuous, rarely anastomosing and branching, concave down-ice and asymmetrical with steeper distal slopes. The moraines range from 10 to 30 m high, 50 to 450 m wide, 300 to 2500 m long, and are spaced 100 to 300 m apart (Lundqvist, 1964; Knight and McCabe, 1997; Hättestrand, 1997; Dunlop, 2004). Rogen moraine (Hoppe, 1959; Lundqvist, 1969, 1981) is part of a continuum of subglacial landforms that include flutes and drumlins. Where this transition does not occur, or has not been demonstrated, other terminology has been proposed, including ribbed moraine (Hughes, 1964; Carl, 1978; Dunlop, 2004), washboard moraine and cross-valley moraine.

The largest field of Rogen moraine in Newfoundland, covering more than 1000 km², is located on the central part of the Avalon Peninsula (Figure 3). The moraines are oriented perpendicular to regional northward-flowing ice, and were variously interpreted as being recessional features (Henderson, 1972), produced by subglacial deposition immediately prior to regional stagnation (Rogerson and Tucker, 1972), and formed by subglacial floods (Fisher and Shaw, 1992). Marich *et al.* (2005) combined morphological and sedimentological analyses of the moraines to propose that they formed subglacially during regional deglaciation and were preserved by final stagnation of the Avalon ice cap. An attempt to resolve the subglacial mechanism for ridge formation was inconclusive.

Examination of the Rogen moraine field on the Avalon Peninsula using the SRTM images allows a better visualization of its topographic setting, and clearly shows the association with hummocky moraine and flutes. It appears to be formed in a broad topographic depression, with hummocky terrain occurring locally within the field at slightly higher elevations. Flutes are well developed on the western flank of the moraine field.

An extensive area of ribbed moraine is found in the Kitty's Brook – Chain Lakes area, southwest of Sheffield Lake in central Newfoundland (Figure 4). Individual ridges in this area are up to several kilometres long and lie within and transverse to valleys. MacClintock and Twenhofel (1940) considered these moraines to be recessional features from Topsails-centred ice, whereas Tucker (1974) thought that the ridges were too large to be typical of ribbed moraine, and proposed that they formed through a combination of recession and ablation, with large ice blocks stagnating between ridges.

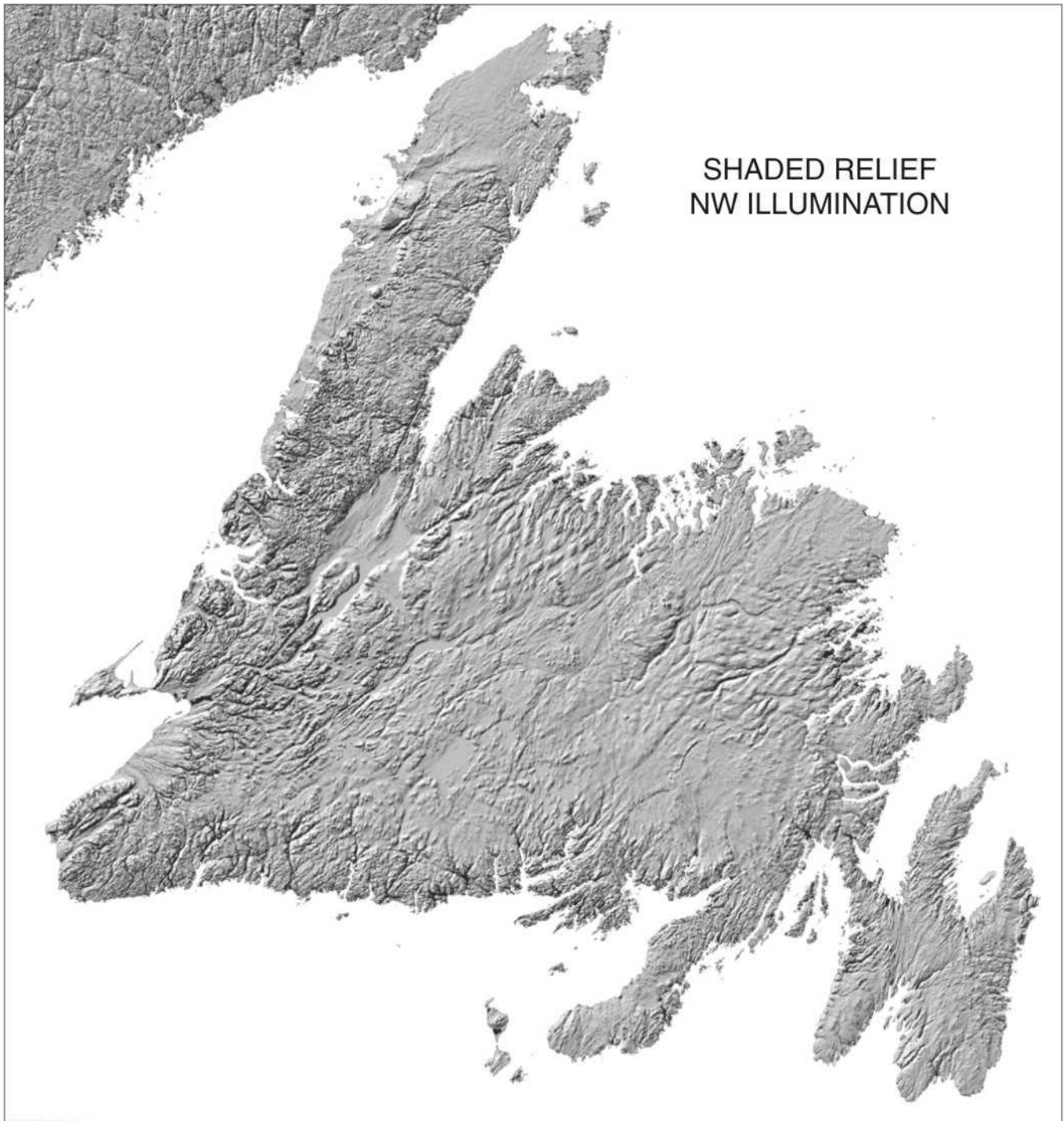


Figure 1. False-shaded digital elevation models of Newfoundland from SRTM data. Illumination from the northwest at an azimuth of 45° . Illumination from the northwest emphasizes bedrock features, as Newfoundland is dominated by a northeast-southwest structural trend, perpendicular to the angle of illumination.

Ribbed moraines are seen elsewhere on Figure 4 but are less clear, due to lower relief, and their visibility is dependent on the illumination angle chosen. They sometimes occur in areas previously mapped as hummocky moraine (Liverman and Taylor, 1990).

TEN MILE LAKE MORAINE

The Ten Mile Lake moraine was first mapped by Grant (1992) as a long ridge, 10 to 30 m high, traceable over, at least, 20 km, and semi-circular in shape. The southern end

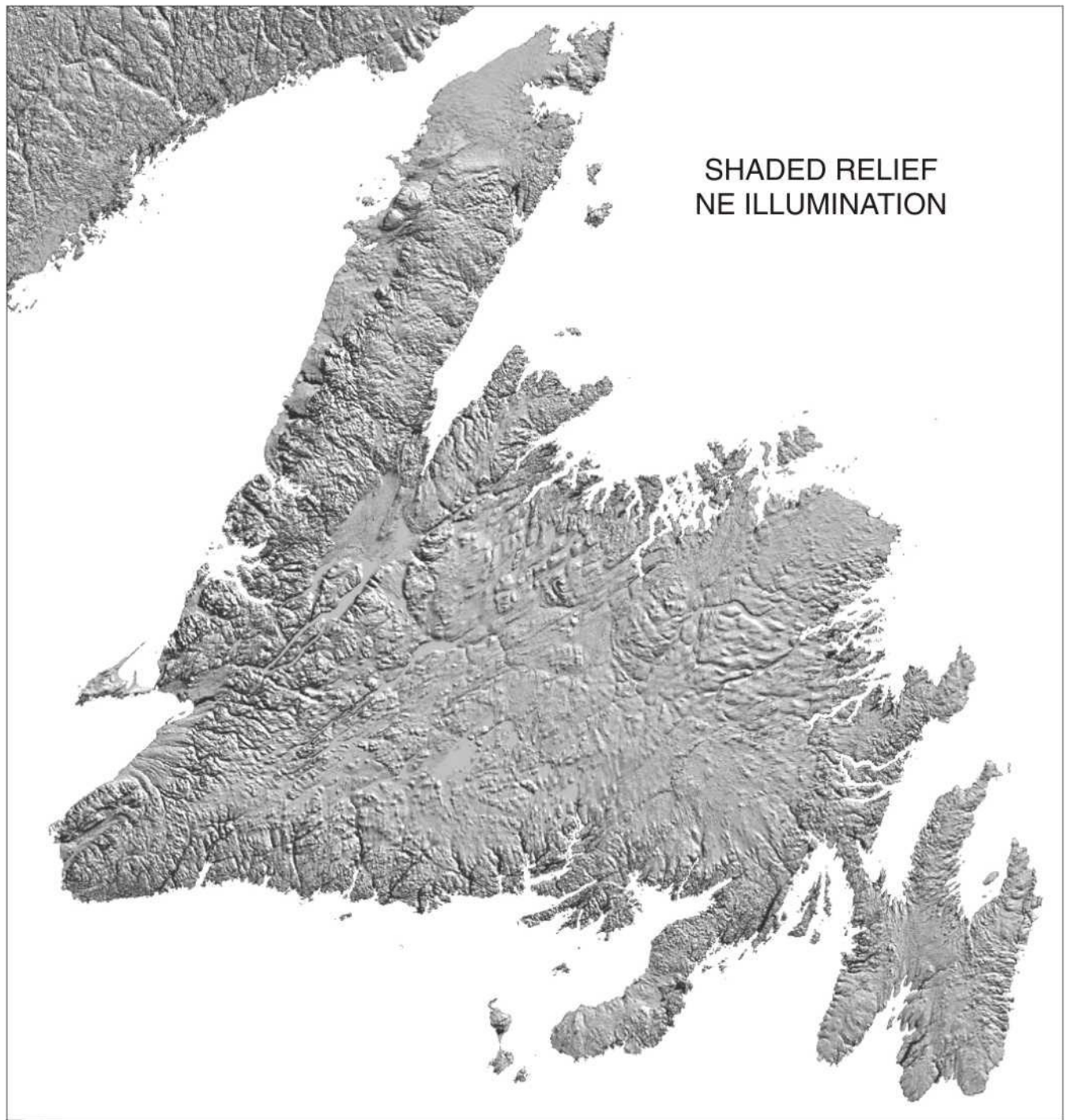


Figure 2. False-shaded digital elevation models of Newfoundland from SRTM data. Illumination from the northeast at an azimuth of 45° .

of the moraine splits into two segments, that further divides into several ridges. The main part of the moraine consists of a single ridge, that truncates DeGeer moraines, and terminates in the east, in an area of hummocky moraine. Where the ridge intersects Ten Mile Lake, cutbanks show it to be composed of a silty diamicton, containing marine fossils

including blocks of barnacles, dated at $11\,000 \pm 160\text{BP}$ (GSC-1634). Grant (*op. cit.*) interpreted the moraine as showing a late-glacial re-advance of the Long Range Ice Cap, ploughing up marine sediment deposited after initial deglaciation.

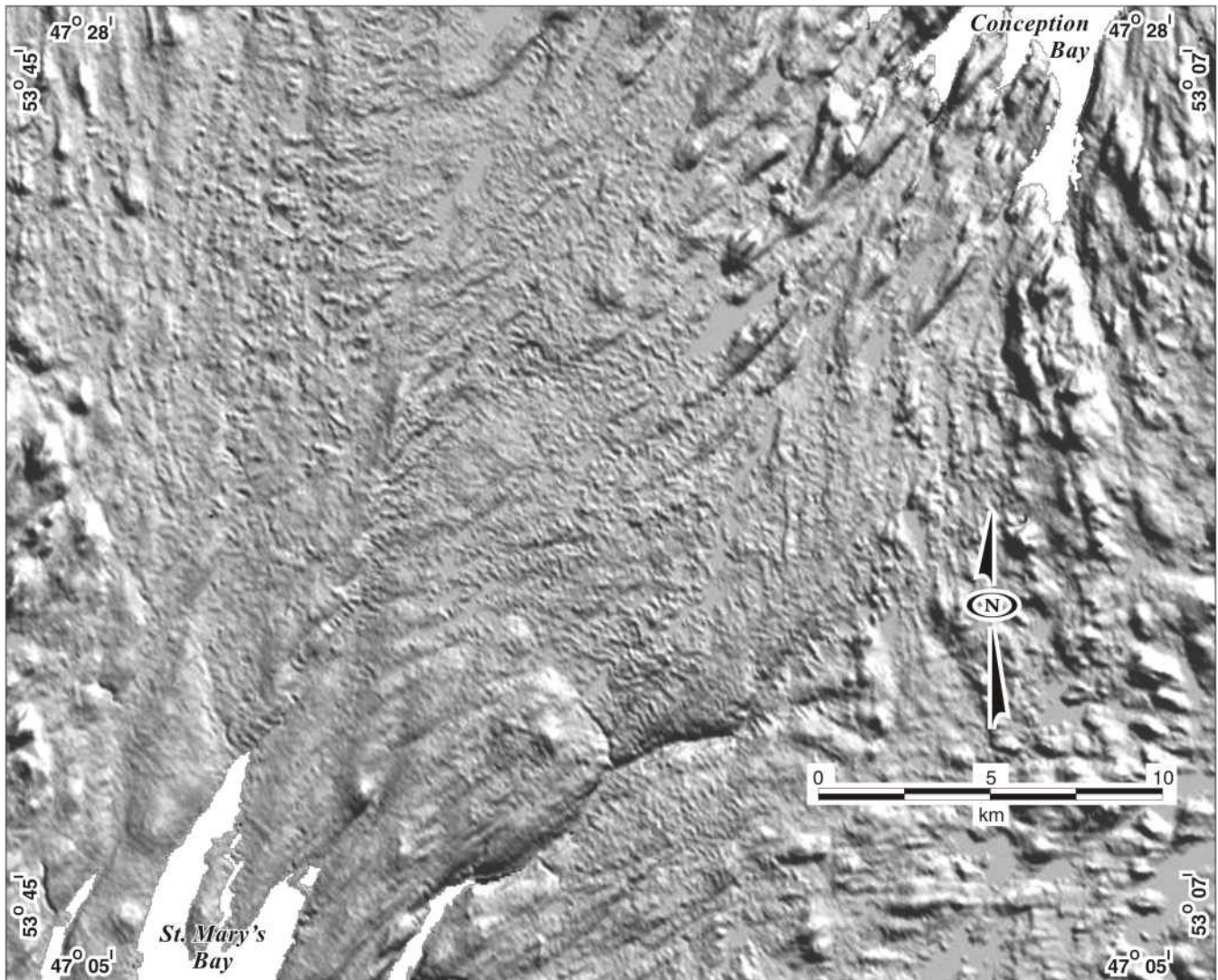


Figure 3. Rögen moraine field, central Avalon Peninsula. Numerous oriented ridges are clear on the image, reflecting ice-flow from an ice dome centred in St. Mary's Bay. On the upper part of the image, streamlined landforms (flutings, crag-and-tails) show ice flowing into Conception Bay.

The SRTM data (Figure 5) shows the moraine as a larger, perhaps more complex feature than that described by Grant (1992). The basic morphology is as described by Grant (*op. cit.*) in the western part, with four distinct ridges intersecting Ten Mile Lake converging to the north to form a single ridge. This ridge varies in elevation, but forms a clear semi-circular pattern. However, at the eastern end it seems that rather than dying out in an area of hummocky moraine, the ridge system re-appears in the form of multiple, parallel to sub-parallel ridges (at least 7 to 10), three of which are quite prominent, varying in width from 0.1 to 1 km and extending northwest–southeast for 10 km or more. The moraines converge to the southeast and appear to be truncated by a single ridge oriented northeast–southwest, possibly indicating re-advances along sections of the ice

margin. The relief on this ridge is accentuated on the SRTM image by a steep channel eroded into its eastern flank. The channel was most likely formed by proglacial meltwater routed toward Hare Bay during deglaciation. To the south of the moraine complex, a zone of drumlinized till is clearly seen on the SRTM image, indicating that ice flowed out of the Long Range Mountains to build the Ten Mile Lake moraine complex.

It seems likely that this broad morainal complex is part of the same system identified by Grant (1992) as the Ten Mile Lake moraine, and is likely of similar age. Whereas the ridges are well-defined with high relief in the west near Ten Mile Lake, farther east they are more subdued and appear to record the progressive southward retreat of a curvilinear ice

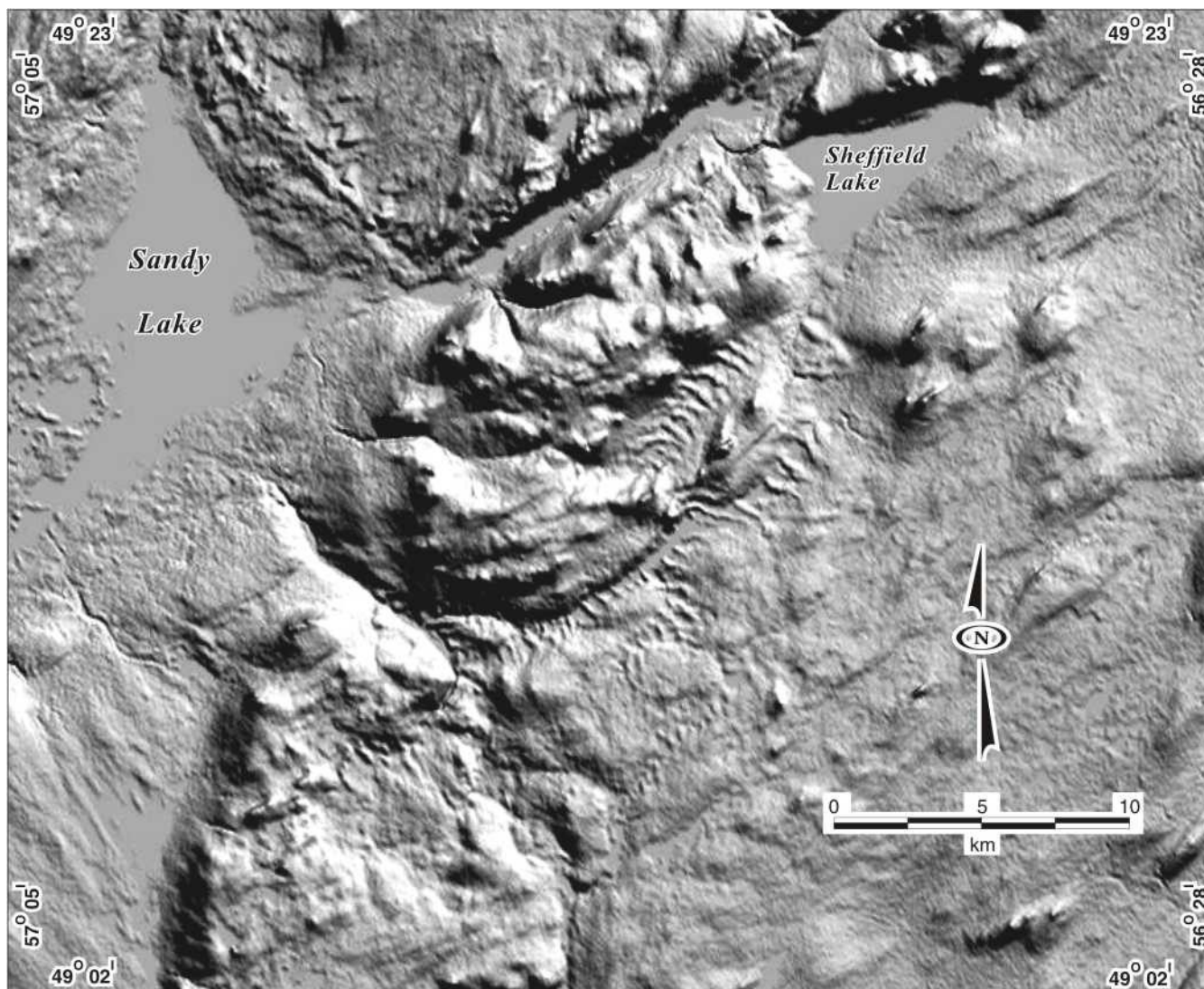


Figure 4. Ribbed moraine in the Kitty's Brook area. Large scale high-relief ribbed moraine is clearly shown, but in addition more subtle ribbed moraine features are visible close to Sheffield Lake and elsewhere. Streamlined landforms indicating northwest flow are seen in the lower left of the image, whereas similar landforms indicating northeast flow are seen on the upper right.

margin. Deglaciation may have been interrupted by readvances, which would not be unexpected where the margin was likely in contact with the sea (e.g., Hare Bay). The view of the Ten Mile Lake moraine system on the SRTM image provides an opportunity to see individual features, that are mappable at the scale of aerial photographs, in the context of the larger system and superimposed on the regional topography and geology. Planned field mapping has been revised on the basis of the details observed on the SRTM image.

ST. GEORGE'S BAY

The Quaternary geology of St. George's Bay was discussed by Liverman and Bell (1996), Liverman *et al.*

(1999), Sheppard *et al.* (2000) and Bell *et al.* (2001). The broad, low relief coastal plain fronting the Long Range Mountains generally has a thick cover of Quaternary sediments cut by major river valleys, and few small-scale ice-flow indicators in the form of striations. The SRTM DEM shows clear indications of streamlined landforms suggesting ice flow to the northwest, and no clear evidence of the coast parallel flow suggested by Liverman *et al.* (1999) (Figure 6). As this area has few areas of exposed bedrock, and virtually no striations are preserved, these large-scale landforms provide useful evidence of ice flow, not clearly seen on aerial photographs. The large ridges marking Robinsons Head and Highlands are clearly visible on the DEM, and can be delineated using oblique views. The topography of the

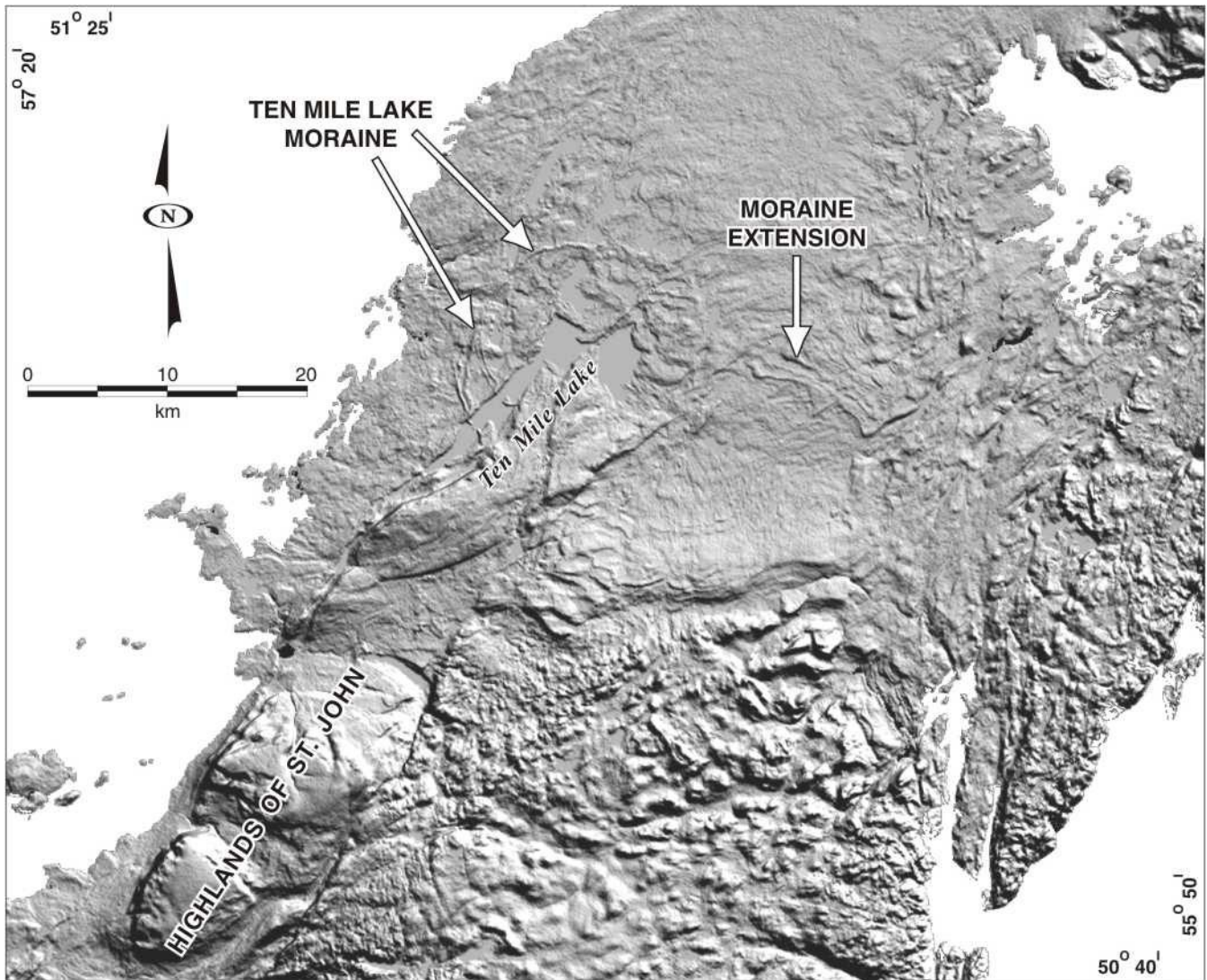


Figure 5. Ten Mile Lake moraine, and extension. Ten-Mile Lake moraine, Great Northern Peninsula. The moraine is clearly evident as an arcuate ridge north of Ten Mile Lake. Prominent ridges mark a possible eastward extension of the moraine system, not previously identified. The Highlands of St. John are also prominent in the bottom left of the image. The Highlands of St. John are prominent in the lower left of the image. Prominent ridges mark a possible extension to the moraine system not previously identified.

Robinsons Head ridge is particularly well shown, even though it is close to the limit of DEM resolution. It forms a sinuous ridge splaying out near the coast, with apparently large kettles. This fits well the model of Bell *et al.* (2001) that describes subglacial feed of sediment to a fan-delta at the former ice margin near the present coast.

To the north of the bay, the single esker mapped by previous workers (Liverman, 1999; Batterson, 2001) is clearly shown to be part of a broad glaciofluvial complex extending from the Long Range Mountains to the coast.

LARGE-SCALE ICE-FLOW FEATURES

The most effective use of the SRTM data is in delineation of large-scale streamlined features. These features range from less than one kilometre to over 15 km long, and can be over a kilometre wide. Such large-scale features may not be recognized on aerial photographs because of their size; some features identified here have not been mapped previously.

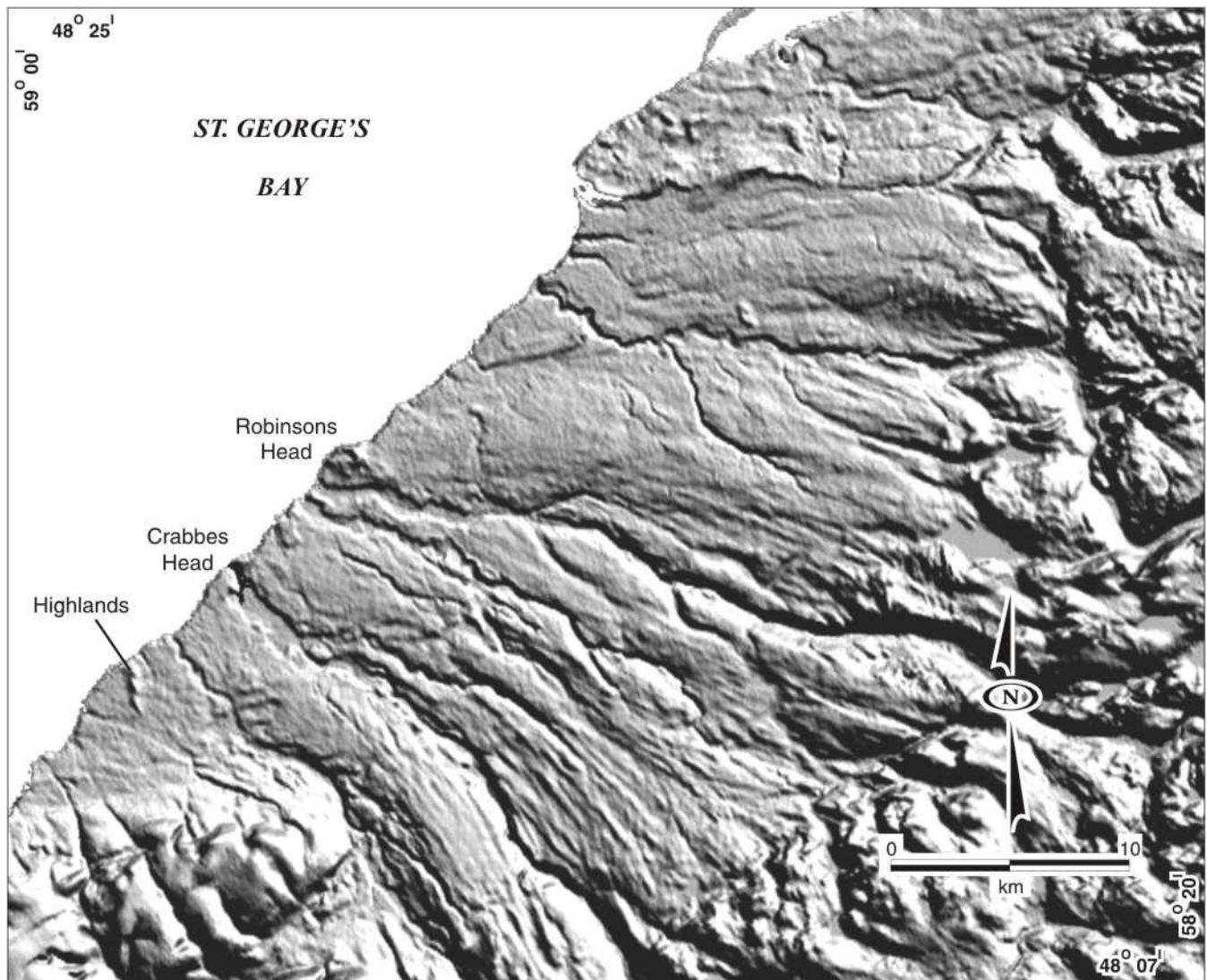


Figure 6. *St. George's Bay.* Ridges at Highlands, Crabbes Head and Robinsons Head form topographic highs. A distinct pattern of streamlined landforms shows ice emerging from the Long Range Mountains across the broad coastal plain.

Glacial landforms vary in morphology from almost linear elongate shapes to drumlin-like forms. Giant crag-and-tail features are also seen. They are clear in most areas that are not dominated by bedrock topography, particularly in the southeastern part of the Province. Although likely influenced by underlying bedrock characteristics, in many places they crosscut bedrock trends, and thus likely relate to glacial effects. However, they tend to be best developed when paralleling structural trends in the bedrock. These landforms are commonly associated with ribbed moraine, oriented perpendicular to their long axis.

The large-scale patterns established can clearly be seen on Figure 7, with a continuum of streamlined landforms flowing due east onto the Bonavista Peninsula, with little influence from the topographic lows of Trinity and Bonav-

ista bays. This suggests that the pattern may reflect the glacial maximum, when the thickness of the ice sheet overwhelmed the local effects of topography.

The origin of such large-scale features is not clear. A number of researchers (Brennand *et al.*, 1996; Shaw and Kvill, 1984; Shaw *et al.*, 1986) suggested that both large- and smaller-scale streamlined landforms relate to huge volumes of meltwater at the base of the ice. Others propose that the features relate to the direct effects of ice without major intervention from meltwater. One of the difficulties with postulating meltwater erosion for these features in Newfoundland relates to the volume of water required. If these features are caused by meltwater then a large reservoir of water must have built up in the centre of the Newfoundland Ice Cap. It may be that melting from the Newfoundland Ice

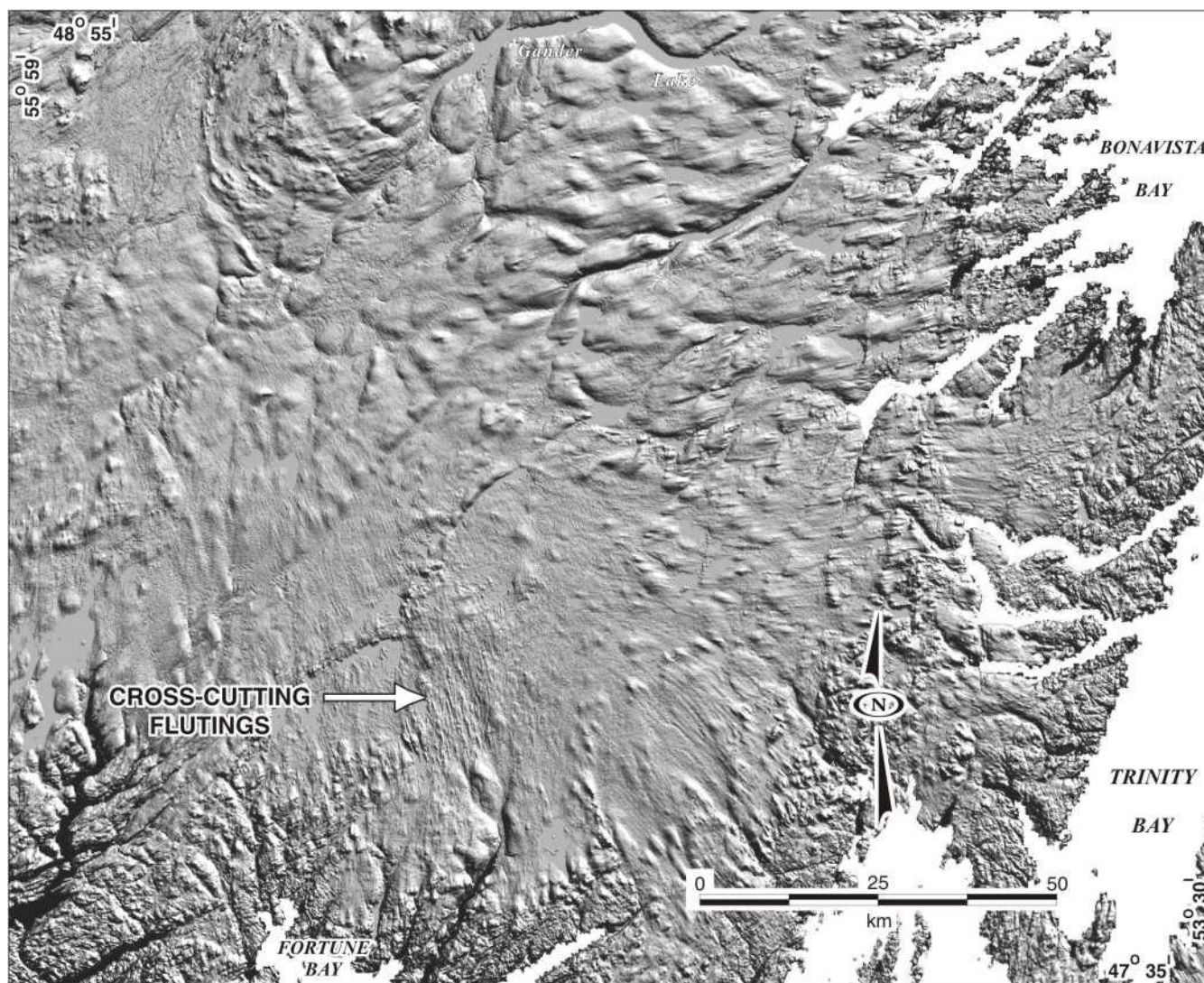


Figure 7. Streamlined landforms in eastern Newfoundland. A radial distribution of oriented landforms is apparent, as well as a variety of shapes, ranging from elongate flutes to crag-and-tails and broad drumlin like forms.

Cap alone cannot have supplied sufficient water to establish flow over such a wide area. Unless there was a hydrological connection between this area and the Laurentide Ice sheet, there may be insufficient water volumes to allow an origin by subglacial meltwater.

Extensive striation mapping has revealed a complex record of ice flow in Newfoundland. Several ice centres are postulated for the Island of Newfoundland, with the three primary ones being located on the Northern Peninsula, in central Newfoundland and over the Avalon Peninsula. Smaller subsidiary ice centres developed as the main ice caps retreated and broke up (Grant, 1974). The ice-flow patterns revealed by these large-scale features apparently formed close to the maximum extent of glacial ice during the last glaciation (Figure 8). There is no evidence of deflec-

tion by local topography, or drawdown into major valleys, and they do not seem to be related to flow from deglacial ice centres.

Spatially coherent areas of flow patterns (“flow-sets” using the terminology of Boulton and Clark, 1990) may be formed simultaneously in a single land-forming event, or progressively, as ice retreats. If formed simultaneously, then the alignment of the features mark paleo flowlines in the ice at the time of formation. If time transgressive, then only the orientation of individual features can be related to flow (Clark, 1997). Time transgressive lineaments can be identified by crosscutting relationships, changes in morphology, and a lesser degree of parallelism. The flow sets seen in the SRTM image mostly do not appear to be time transgressive based on these criteria.

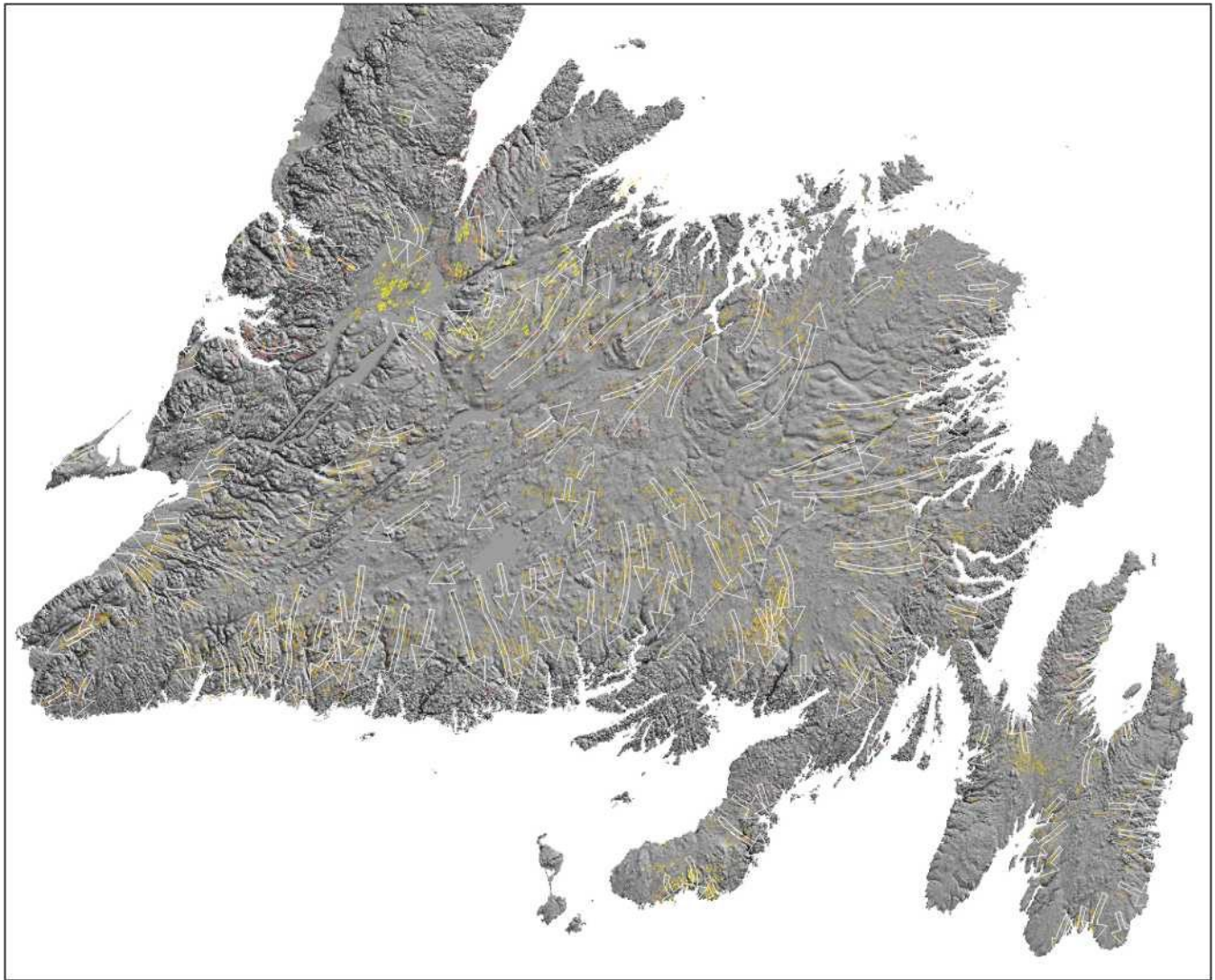


Figure 8. Streamlined features mapped from SRTM imagery combined with previous digital mapping. Arrows represent flowsets.

The pattern formed by compiling existing digital landform data combined with streamlined landforms mapped from SRTM imagery is interesting (Figure 8). The southeast part of the Island shows strong evidence for radial flow from an ice cap centred south of Gander Lake, but with a clear discontinuity between eastward flow in the Terra Nova area, and south-southeast flow in the Long Harbour–Bay du Nord area. This may reflect an ice divide in this area.

The south coast area shows fairly consistent southward flow from the Burin Peninsula as far west as Burgeo. This flow can be traced inland almost to Red Indian Lake. There is a discontinuity in the ice-flow pattern north of Red Indian Lake. There are numerous indications of northeast flow in the area covering the Bay of Exploits to Halls Bay, traceable up to Red Indian Lake. Another small but prominent area of

streamlined features shows northwest flow in the Hinds Lake area. There are numerous indicators of west to southwest flow in the area southwest of Red Indian Lake and east of the Long Range Mountains.

There are few crosscutting relationships apparent, and thus it cannot be determined if all these features formed simultaneously, or if more than one phase of ice flow is represented. However, the discontinuity between major ice-flow trends south of Red Indian Lake is sharp, suggesting at least two distinct phases of ice flow are represented by these large-scale features. The pattern south of this area suggests flow from a S-shaped ice divide that crossed Newfoundland from south of Gander to west of Red Indian Lake. Flow from this divide should be symmetrical, but there is no matching flow pattern to the north of the divide. This sug-

gests that the strong northeast flow seen from Red Indian Lake to the coast may represent a later event that has obliterated evidence of earlier flow. The effect of this flow is accentuated as, in many areas, it runs parallel to bedrock strike.

Clark *et al.* (2003) suggested that relatively elongate large-scale lineations reflect faster ice flow, often within ice streams. There is considerable morphological variation in the landforms observed but there is evidence of faster flow and perhaps ice-streaming in several areas of Newfoundland (Figure 8). The strong northeast flow identified above resulted in elongate landforms in the Grand Falls–Bay of Exploits area, and similar elongation is seen over the western Bonavista Peninsula, the Bay du Nord area, and north of Facheaux Bay (Figures 1 and 8).

CONCLUSIONS

Shuttle Radar Topography Mission (SRTM) data offers a new means of examining landscape and topography. This is best done through production of digital elevation models and false-shading. The data is limited in its resolution but is effective in delineating landscape features, particularly in heavily vegetated areas. The interpretations presented here are preliminary, but further work is planned using large-scale streamlined landforms identified in SRTM images in combination with other means of ice-flow mapping. This should yield a more detailed ice-flow history for the Newfoundland Ice Cap. Shuttle Radar Topography Mission imagery likely will be routinely used in surficial mapping in the future. It can provide a means of rapid interpretation of surficial geology and landforms prior to detailed examination through aerial photographs, and in the field. In addition, it allows for the identification of large landforms and landform patterns not readily apparent in aerial photographs.

Shuttle Radar Topography Mission imagery should prove to be an ideal means of examining the surficial geology of Labrador, where detailed mapping covers only small areas. Reconnaissance-level 1:250 000 maps of landforms could be produced for areas of interest relatively quickly using mainly SRTM supplemented by aerial photographs.

The use of SRTM imagery in bedrock mapping has not been explored in this preliminary study. Topography reflects bedrock composition and structure in many places, and SRTM may prove to be a valuable addition to existing mapping tools.

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