Journal of Maps
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tjom20

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Robert Storrar [a] & Chris R. Stokes [b]
[a] Department of Geography , The University of Reading , Reading , RG6 6AB , UK.
[b] Department of Geography , The University of Durham , Science Site, South Road, Durham , DH1 3LE , UK E-mail:
Published online: 23 Jan 2012.

Journal of Maps, 2007, 191-210

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ROBERT STORRAR[1] and CHRIS R. STOKES[2]

[1]Department of Geography, The University of Reading, Reading, RG6 6AB, UK.

[2]Department of Geography, The University of Durham, Science Site, South Road, Durham, DH1 3LE, UK; c.r.stokes@durham.ac.uk

(Received 8th December 2006; Accepted 18th March 2007)

Abstract: Victoria Island lies at the north-western extremity of the region covered by the vast North American Laurentide Ice Sheet (LIS) in the Canadian Arctic Archipelago. This area is significant because it linked the interior of the LIS to the Arctic Ocean, probably via a number of ice streams. Victoria Island, however, exhibits a remarkably complex glacial landscape, with several successive generations of ice flow indicators superimposed on top of each other and often at abrupt (90°) angles. This complexity represents a major challenge to those attempting to produce a detailed reconstruction of the glacial history of the region. This paper presents a map of the glacial geomorphology of Victoria Island. The map is based on analysis of Landsat Enhanced Thematic Plus (ETM+) satellite imagery and contains over 58,000 individual glacial features which include: glacial lineations, moraines (terminal, lateral, subglacial shear margin), hummocky moraine, ribbed moraine, eskers, glaciofluvial deposits, large meltwater channels, and raised shorelines. The glacial features reveal marked changes in ice flow direction and vigour over time. Moreover, the glacial geomorphology indicates a non-steady withdrawal of ice during deglaciation, with rapidly flowing ice streams focussed into the inter-island troughs and several successively younger flow patterns superimposed on older ones. It is hoped that detailed analysis of this map will lead to an improved reconstruction of the glacial history of this area which will provide other important insights, for example, with respect to the interactions between ice streaming, deglaciation and Arctic Ocean meltwater events.

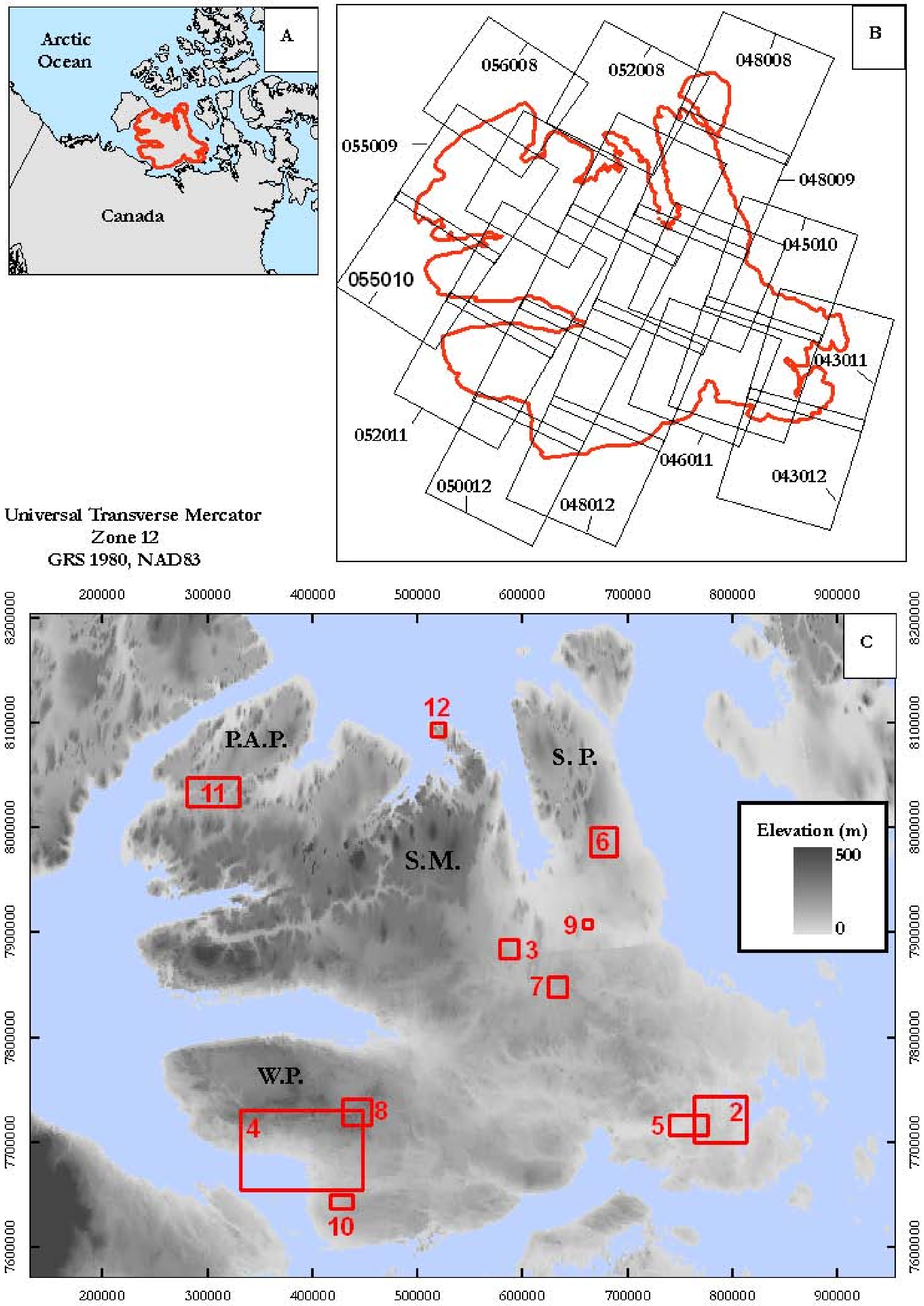
ISSN 1744-5647
http://www.journalofmaps.com

1. Introduction

Victoria Island constitutes a landmass of around 225,000 km^2 (only slightly smaller than the United Kingdom) and spans the border between Nunavut Territory and Northwest Territories in the Canadian Arctic Archipelago, separated from the Canadian mainland by a shallow strait that is only 20 km wide at its narrowest point. Much of the island is underlain by gently dipping to flat-lying dolomite and minor limestones, sandstone and shale of early Palaeozoic age. The most prominent Precambrian strata form a broad syncline trending northeast across Victoria Island from Amundsen Gulf to Hadley Bay and comprise sandstone, siltstone, shale, limestone, dolomite, and gypsum, overlain by basaltic lava and agglomerate (Fyles, 1963). This north-east trending belt of Precambrian rocks forms a series of bedrock ridges and plateaux that comprise the Shaler Mountains in north-central Victoria Island, where summits typically reach 350-430 m a.m.s.l., but are locally in excess of 500 m (Fyles, 1963), see Figure 1. Occasional glacial landforms are found in this bedrock-dominated region (e.g. eskers) but the area is generally devoid of glacial features compared to the low-lying palaeozoic rocks. These low-lying areas are generally within 175 m of sea level but locally reach up to 350 m a.m.s.l. Here, glacial lineations dominate the landscape and numerous lakes and rivers commonly follow irregular patterns dictated by the glacial geomorphology.

It has long been recognised that Victoria Island possesses an exceptionally well-preserved glacial landscape which contains an abundant array of glacial features that betray an extremely complex glacial history (Washburn, 1947; Fyles, 1963). Much of the island is dominated by highly convergent and divergent patterns of glacial lineations (and associated moraines and meltwater features), many of which lie superimposed on each other and often at abrupt angles (Fyles, 1963; Sharpe, 1988; Hodgson, 1994; Stokes et al., 2006).

Figure 1 Location map of Victoria Island in the Canadian Arctic Archipelago (A) and coverage of the Landsat ETM+ satellite images that were employed during the mapping (B). A digital elevation model of Victoria Island is shown in ‘C’, which also shows the approximate location of the figures used in this paper. S.P. = Storkerson Peninsula; W.P. = Wollaston Peninsula; S.M. = Shaler Mountains; P.A.P. = Prince Albert Peninsula.


Arctic Ocean
A
Canada
B
056008
052008
048008
055009
048009
045010
055010
043011
052011
046011
043012
050012
048012
Universal Transverse Mercator
Zone 12
GRS 1980, NAD83
C
P.A.P.
S.P.
S.M.
W.P.
Elevation (m)
500
0
1
2
3
4
5
6
7
8
9
10
11
12

Unlike the more uniform flow patterns on the mainland immediately to the south (cf. Prest et al., 1967), the complex glacial geomorphology of Victoria Island presents numerous challenges for those seeking to reconstruct its glacial history. During the last two decades, for example, there have been several debates with regard to the maximum extent of the Late Wisconsinan ice sheet/ice shelf in this region (Dyke, 1987); the location of ice divides and the timing of ice streams (Hodgson, 1994; Clark and Stokes, 2001); the role of subglacial meltwater floods in landform generation (cf. Sharpe, 1988); the palaeoclimatic significance of end/hummocky moraine complexes (Dyke and Savelle, 2000); the evidence of a grounded Arctic ice shelf during the Late Pleistocene (cf. Jakobsson et al., 2005); and the possibility of large meltwater/iceberg fluxes into the Arctic Ocean which may have triggered abrupt climate change (Darby et al., 2002; Tarasov and Peltier, 2005; Stokes et al., 2005).

Resolving these issues will be helped by a detailed knowledge of the glacial features on Victoria Island and in this paper, we present a map of the glacial geomorphology, created from analysis of Landsat Enhanced Thematic Mapper Plus (ETM+) satellite imagery.

2. A Brief Note on Previous Mapping

The first detailed descriptions of the glacial geomorphology on Victoria Island were presented in Washburn (1947) and Fyles (1963) and many of the features described by these authors were subsequently generalised on the Glacial Map of Canada (Prest et al., 1967). On this map, the glacial geomorphology on Victoria Island stands out as unusually complex, with lineation patterns apparently 'be-headed' by other flow patterns at abrupt angles (up to 90°) and with eskers sometimes completely misaligned with the underlying lineation direction. It should be remembered, however, that the apparent complexity represented on the Glacial Map of Canada is actually an oversimplification. The cartographic limitations imposed by the small scale of the map (1:5,000,000) forced the authors to generalise the features and it was impossible to depict all of the flow patterns. Significantly, where one or more sets of glacial lineations were superimposed in the same location, only one set is depicted on the Glacial Map of Canada.

The Glacial Map of Canada has served as a superb reference work which has laid the foundation for more detailed mapping on Victoria Island. Much of this mapping has been conducted with great efficiency by the Geological Survey of Canada and there are several excellent reports and maps on the surficial geology of various parts of the island (e.g. Sharpe, 1992; Hodgson, 1993). These maps are largely unprecedented in terms of the detail but generally only cover a part of the island. In order to fill the 'scale gap' between the Glacial Map of Canada (1:5,000,000) and the detailed surficial geology mapping (usually 1:250,000 or less, e.g. Sharpe, 1992) we present a complete map of the glacial geomorphology of Victoria Island. This map is well suited for identifying individual ice flow events (i.e. 'flow-sets': see Clark, 1999), and regional deglaciation features (i.e. esker patterns and moraines), both of which are essential prerequisites for a detailed reconstruction of the glacial history.

3. Methods

The map was created from digital mapping of glacial landforms on Landsat Enhanced Thematic Mapper Plus (ETM+) satellite imagery. These images were obtained from the Natural Resources of Canada GeoGratis website (http://geogratis.cgdi.gc.ca/) and imported into ERDAS Imagine 8.7 software as orthorectified images (Universal Transverse Mercator projection zones 11 to 13; spheroid: GRS 1980; Datum: NAD83). A total of 21 overlapping ETM+ images provided complete coverage of the island and Figure 1 shows their location and some corresponding path and row numbers.

Various band combinations were explored to increase the detection of landforms and a 7, 5, 2 (R, G, B) false colour composite generally proved most useful. The false colour composites had a resolution (pixel size) of 30 m and the higher spatial resolution (15 m) of the panchromatic band (band 8) was found to be helpful for mapping complex areas and subtle landforms. Landforms were identified and mapped at several different scales to avoid any scale-bias in their detection. Where available, previous maps and reports provided a useful cross-reference and check of our mapping (see reference list for examples).

The digital elevation model used as a background in the map was extracted from the GTOPO30 database (http://edcdaacuusgs.gov/gtopo30/gtopo30.asp) and has an approximate spatial resolution of 1 km (Figure 1). Note that adjacent islands and the mainland were not mapped.

4. Results: description of glacial geomorphology

Glacial lineations (including drumlins and mega-scale glacial lineations) are streamlined landforms whose long-axis is aligned with ice flow direction. They are abundant in the low-lying areas of Victoria Island, predominantly in the east, south, and southwest (see map). A total of 54,365 lineations were identified and these are symbolised as a black line which extends along the a-axis of each individual lineation. Glacial lineations on Victoria Island exhibit a range of shapes and sizes. Their most common form is the classic elliptical drumlin shape: 1-5 km long, 100-500 km wide, and 10-30 m high (cf. Sharpe, 1984). In places, however, the lineations are much longer (>10 km) and exhibit much higher elongation ratios (>10:1). An example of these features, which might be better described as mega-scale glacial lineations (cf. Clark, 1993), are shown in Figure 2, alongside some more typically-sized smaller drumlins. In places, successively younger generations of lineations can be seen overprinted on one another, often at abrupt angles (Figure 2).

Moraines are also conspicuous features on Victoria Island and occur in a variety of settings. Easily recognisable are small individual moraine ridges that appear in a nested sequence overprinted on glacial lineations and which mark successive ice margin positions during deglaciation. These ridges are often a few kilometres long and a few 10s-100s metres wide and a typical example is shown in Figure 3. In contrast, some moraine ridges appear as huge complexes that can be traced for several tens of kilometres. These moraines are most commonly developed near the coastline of south-western Victoria Island, where they mark the terrestrial limit of low-gradient ice lobes/ice streams which occupied the shallow straits adjacent to the island (cf. Sharpe; 1988; Stokes et al., 2006). The largest such moraine is the Colville Moraine, shown in Figure 4 (see also Sharpe, 1992). In addition to moraines which form at the terminal and lateral margins of the ice, we also identified moraine ridges which likely formed subglacially in the shear zone between ice which was flowing at different speeds (e.g. at the border between cold- and warm-based ice). These moraines are termed 'lateral shear margin moraines' (cf. Dyke et al., 1992) and a good example is shown in Figure 5. Where these subglacial shear moraines clearly mark the border of an ice stream, they might be more appropriately referred to as 'ice stream shear margin moraines' (see also Stokes and Clark, 2002). A good example of an ice stream shear margin moraine is shown in Figure 6.

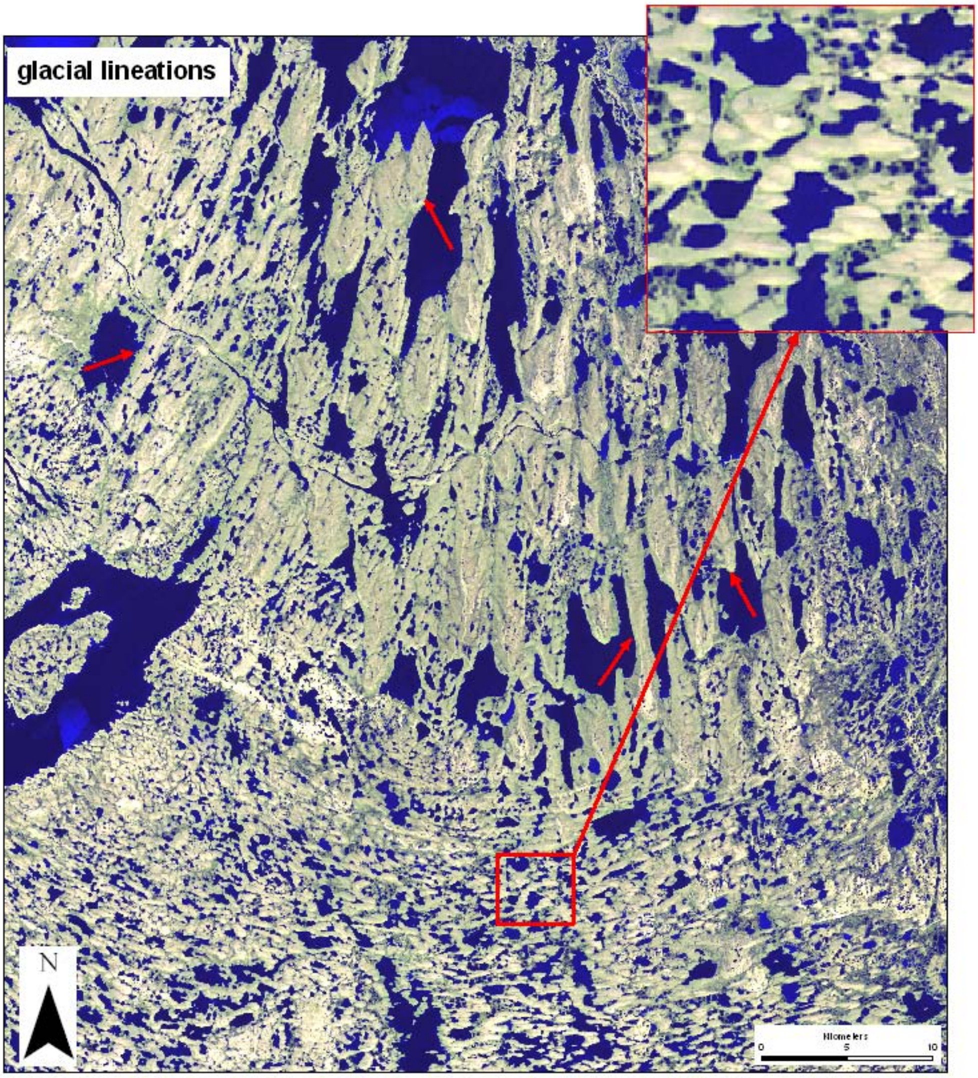


Figure 2 Landsat ETM+ satellite image (R,G,B: 7,5,2) of glacial lineations in south-eastern Victoria Island. The top half of the image shows large mega-scale glacial lineations (MSGL) indicating flow from south to north (individual landforms highlighted with red arrows). The bottom half of the image shows smaller glacial lineations (drumlins) superimposed on the MSGL and indicating a younger ice flow from east to west (see inset). See Figure 1 for location.

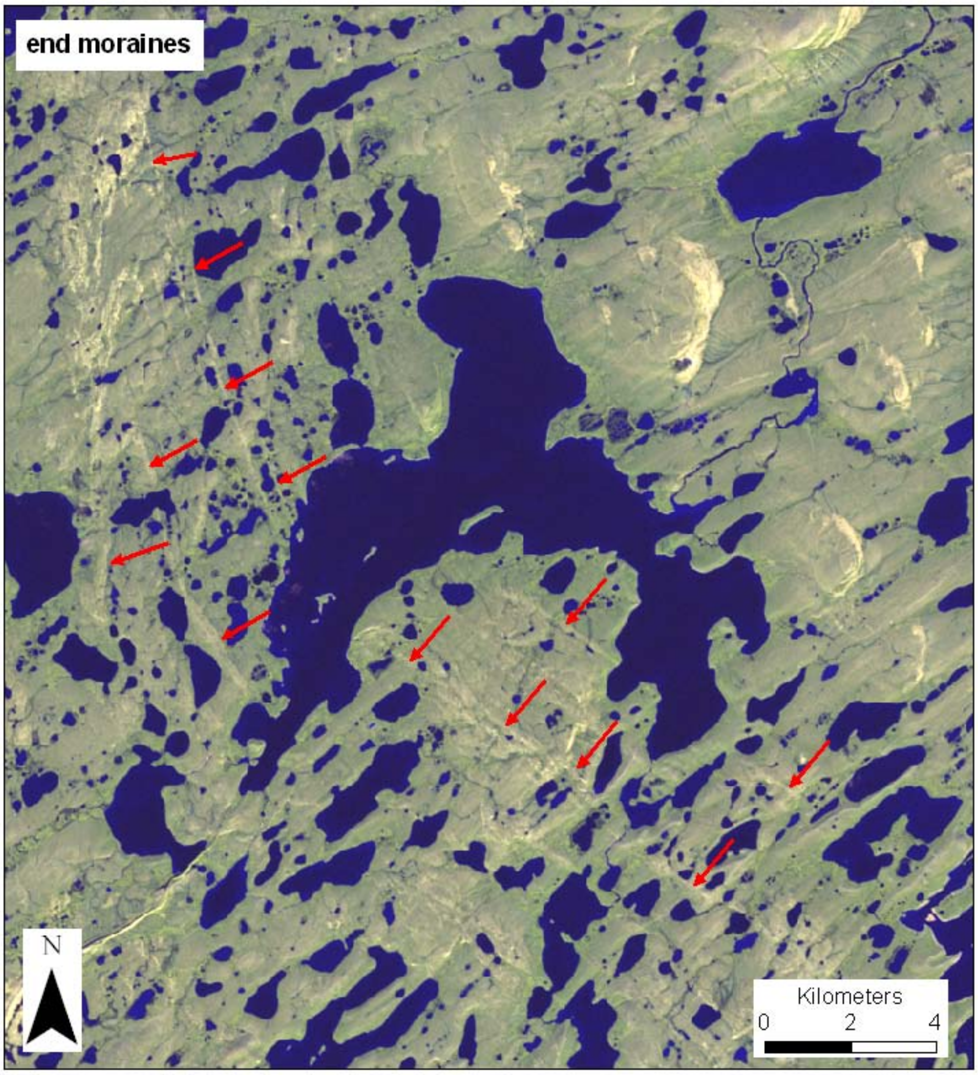


Figure 3 Landsat ETM+ satellite image (R,G,B: 7,5,2) of a series of end moraine ridges (red arrows) on central Victoria Island. The ice flow that formed these ridges flowed from the north-east to south-west. Also note the esker in the bottom left hand corner of the image. See Figure 1 for location.

Figure 4 Landsat ETM+ satellite image (R,G,B: 7,5,2) of the 'Colville' moraine on Wollaston Peninsula, south-western Victoria Island. The Colville moraine can be traced almost continuously for around 280 km and was produced by a low-gradient ice stream/lobe in Dolphin and Union Strait (cf. Sharpe, 1988; Stokes et al., 2006). This ice stream produced glacial lineations which can be seen in the lower half of the image, south of the moraine (indicating ice flow from east to west), whereas large areas of hummocky moraine characterise the upland area to the north of the moraine, alongside isolated zones of lineations (e.g. top right of the image). See Figure 1 for location.

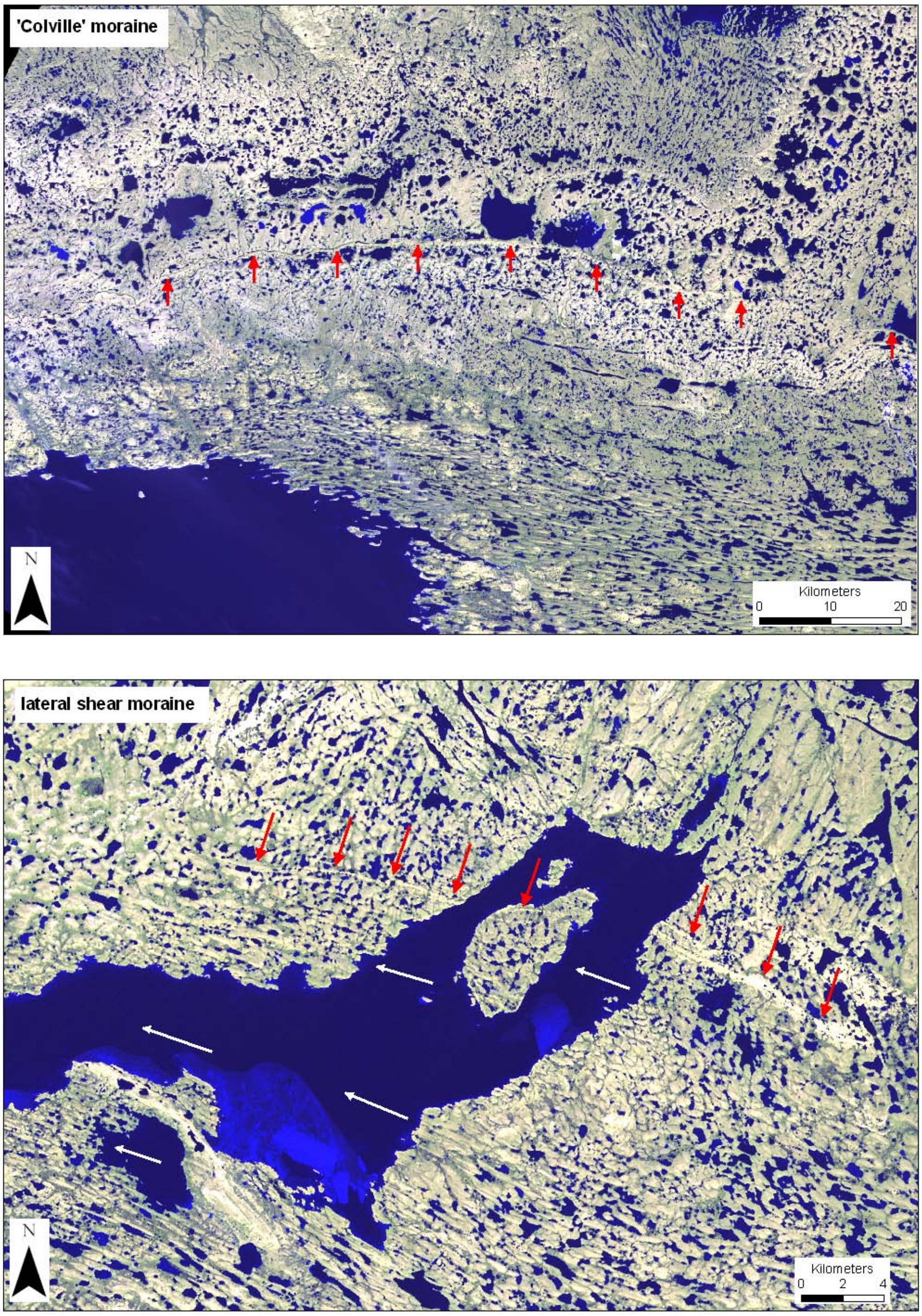


Figure 5 Landsat ETM+ satellite image (R,G,B: 7,5,2) of a lateral shear moraine (red arrows) bordering a drumlin field on south-eastern Victoria Island. The drumlin field in the lower half of the image records ice flow from the south-east to the north-west (white arrows). See Figure 1 for location.

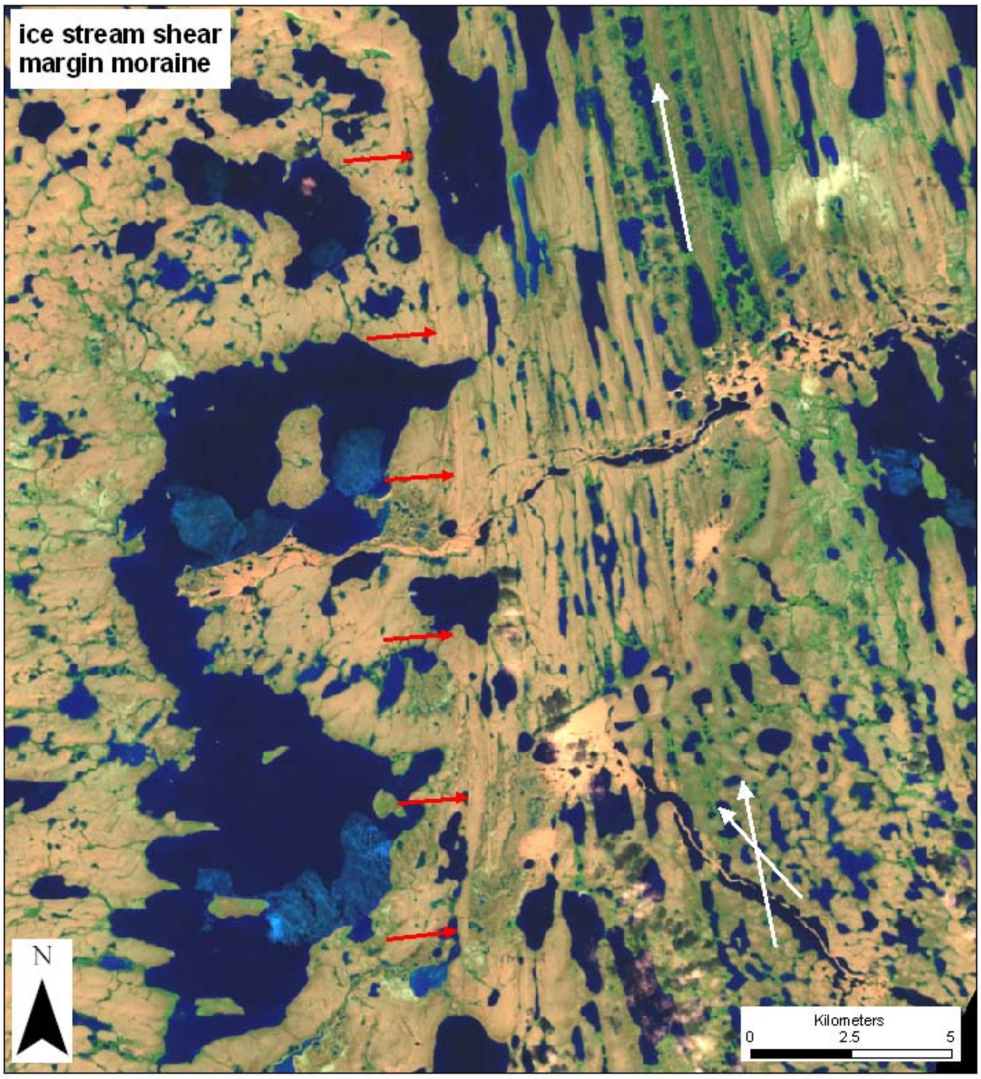


Figure 6 Landsat ETM+ satellite image (R,G,B: 7,4,2) of an ice stream shear margin moraine (red arrows) on Storkerson Peninsula, north-eastern Victoria Island. This type of moraine forms subglacially at the lateral margin of a rapidly-flowing ice stream (Stokes and Clark, 2002) and can be seen here bordering a south to north flowing ice stream (the M'Clintock Channel Ice Stream: Hodgson, 1994; Clark and Stokes, 2001), recorded by mega-scale glacial lineations. The long esker that runs east to west across the centre of the image dissects the moraine and the age control from Hodgson (1994) indicates that slow-flowing ice must have been present adjacent to the ice stream (i.e. this is not a lateral moraine). The orientation of this esker and another in the bottom right hand corner, indicate that ice flow direction had radically changed by the time of deglaciation. Smaller lineations in the bottom right corner are superimposed on the MSGL indicating a younger ice flow event from the south-east, also recorded by the aligned esker direction (white arrows). Also note the glaciofluvial deposits (outwash fan) at the terminus of the southern-most esker. See Figure 1 for location.

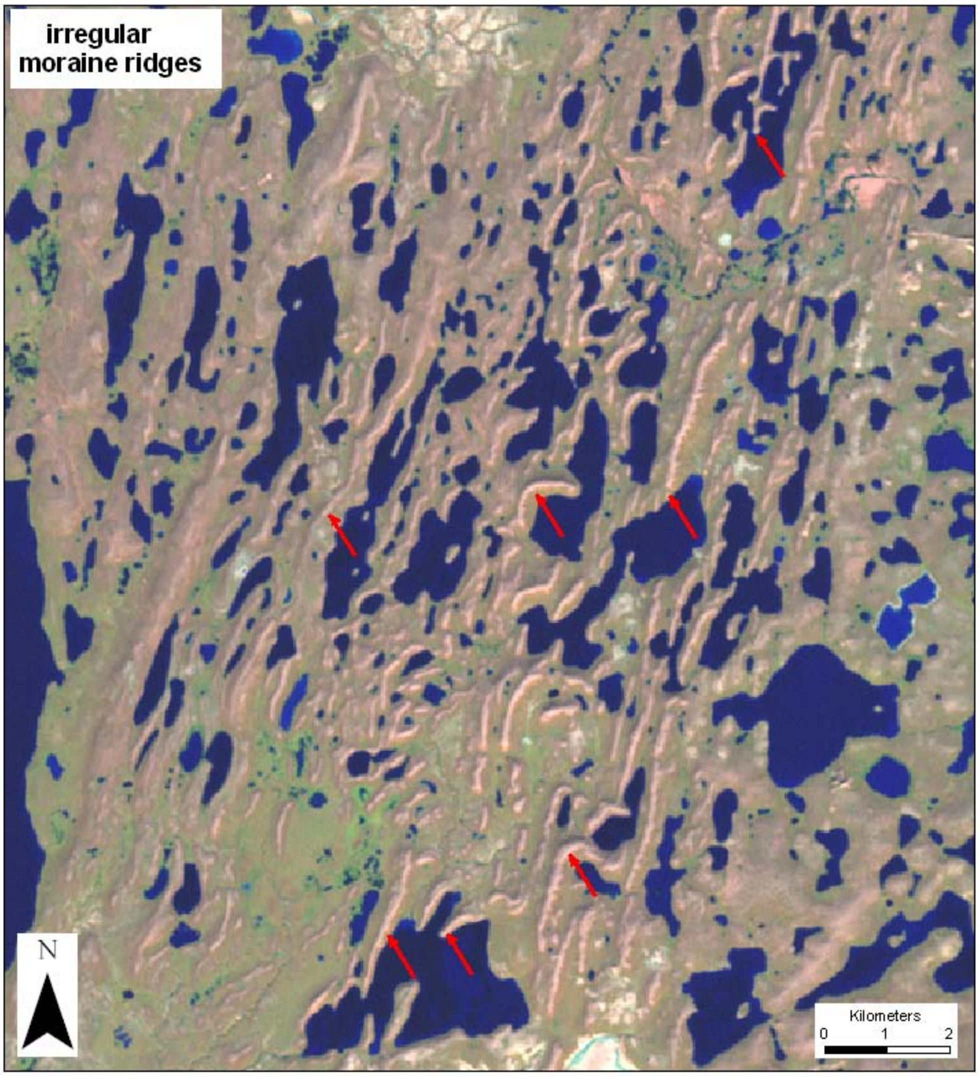


Figure 7 Landsat ETM+ satellite image (R,G,B: 7,4,2) of a series of irregular moraine ridges (red arrows) in central Victoria Island. They have not been widely reported from other areas of the Laurentide Ice Sheet bed. See Figure 1 for location.

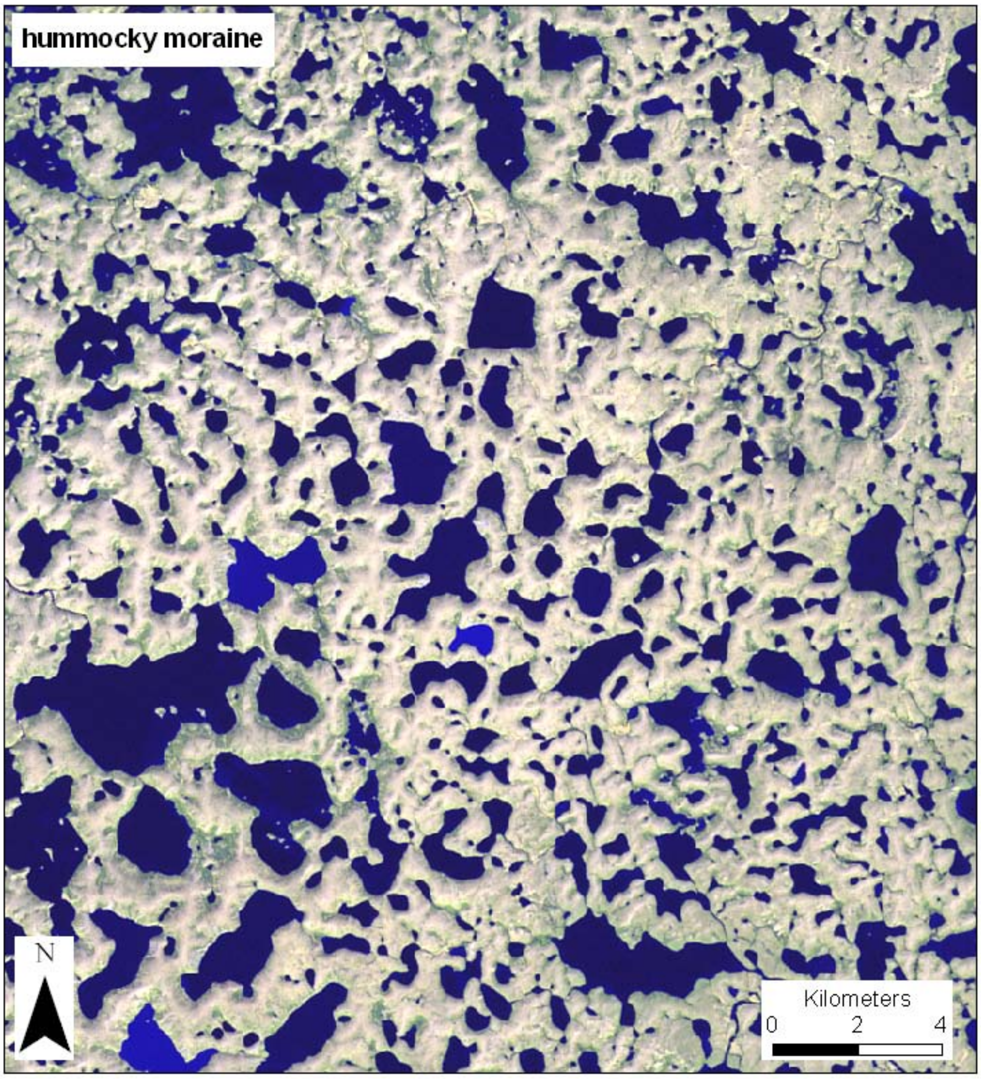


Figure 8 Landsat ETM+ satellite image (R,G,B: 7,5,2) of a region of hummocky moraine on central Wollaston Peninsula, south-western Victoria Island. See Figure 1 for location.

In addition to the moraine ridges detailed above, we also map a series of irregular moraine ridges in central and south-eastern Victoria Island. Individual ridges are a few 10s of metres high, a few 100s of metres wide and several kilometres long (Fyles, 1963). According to Fyles (1963), they are similar in composition, size and orientation to the drumlins to the west and north but differ from the drumlins in being curbed or irregular in trend. An example of these irregular moraine ridges is shown in Figure 7. Note that it is sometimes very difficult to decipher between these various types of moraines (Figure's 3-7) and for this reason, they are grouped together as one feature on the map.

In contrast to the curvilinear moraines described above, hummocky moraine is represented by numerous peaks and depressions and individual moraine ridges are very difficult to identify, see Figure 8. *Hummocky moraine* characterise extensive areas of Victoria Island, particularly on the plateaus of the peninsulas in the south-west and north-east. The origin of hummocky moraine is debated. On Wollaston Peninsula (Figure 4 and 8), for example, some workers argue that it forms from the regional stagnation and down-wasting of ice (e.g. Sharpe, 1992) whereas others suggest that it represents a complex series of individual moraine ridges that formed along active ice margins during steady retreat (e.g. Dyke and Savelle, 2000).

Our mapping also revealed some minor moraine ridges that resemble *ribbed moraines* (cf. Dunlop and Clark, 2006). Fyles (1963) also noted these features, describing them as short irregular ridges of stony till a few metres to a few tens of metres high, several hundred metres wide and trending roughly at right angles to nearby drumlins. Figure 9 shows a Landsat image of these ridges, which seem to fit the characteristics of ribbed moraines described in Dunlop and Clark (2006). If they are, indeed, ribbed moraine, they are unusual in that they occur in such a small location, and almost in isolation.

Eskers are numerous and conspicuous across most of Victoria Island, but especially within the low-lying eastern and southern parts of the island. They exhibit a range of lengths from <1 km to >70 km in length and some are fed by tributary eskers, see Figure 10. Like the glacial lineation patterns, the distribution and orientation of eskers is varied, and reveals a non-uniform pattern of deglaciation. On the mainland to the south of Victoria Island, eskers and lineations line up in a sub-parallel pattern across several hundred kilometres (see Prest et al., 1967) and indicate a uniform retreat direction from the north-west. On Victoria Island, however, eskers do not show a predominant orientation and in many places, do not necessarily line up with the glacial lineations underneath. In some locations, the eskers terminate in areas with significant *glaciofluvial deposits* such as outwash plains and deltas (Figure 6). These features are also mapped and, in conjunction with end moraines, indicate major ice margin positions.

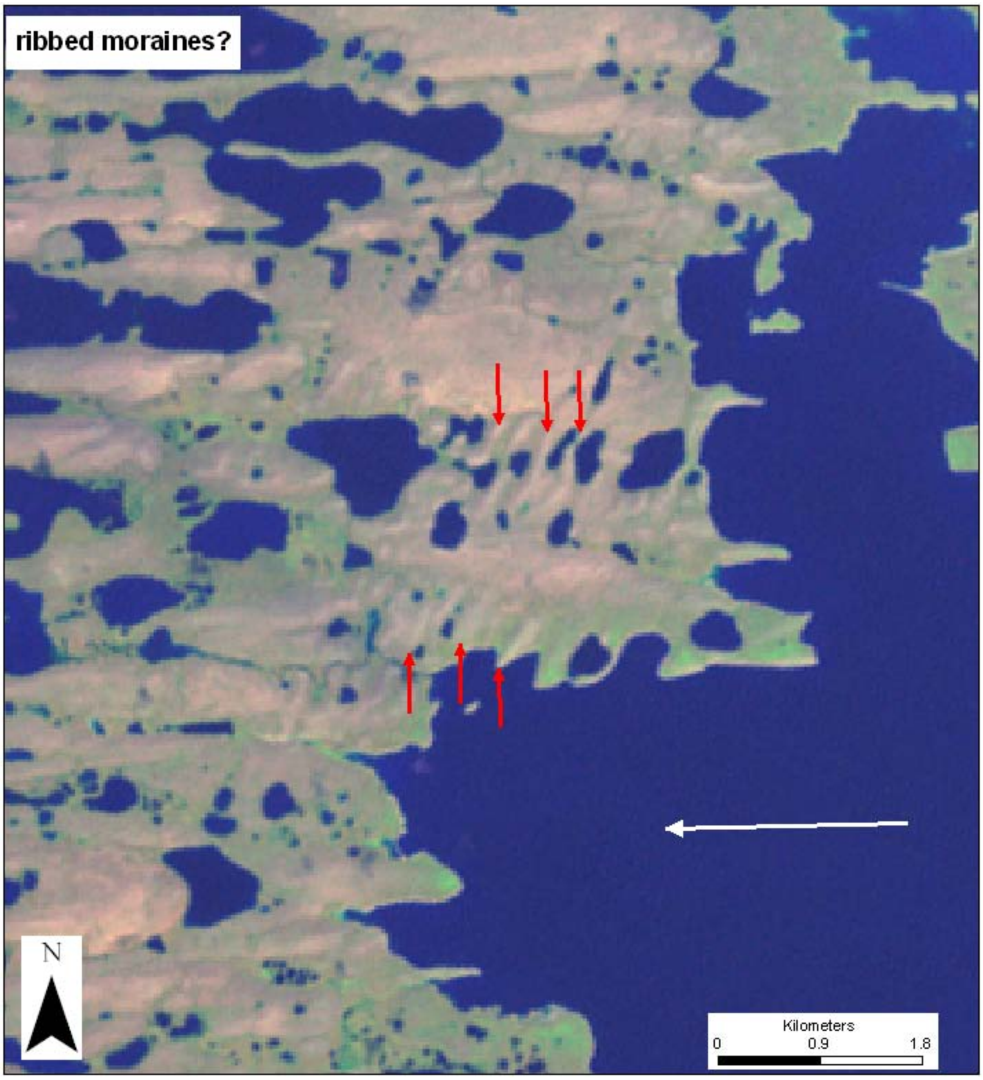


Figure 9 Landsat ETM+ satellite image (R,G,B: 7,4,2) of possible ribbed moraines in central Victoria Island. This isolated patch of transverse ridges (red arrows) is superimposed on lineations indicating ice flow from east to west (white arrow). They resemble the characteristics of ribbed moraines but are unusual in that there are only a handful of ridges and they occur in complete isolation. An alternative hypothesis is that they represent end moraines, but there isolated appearance and small sinuous form suggests this is unlikely. See Figure 1 for location.

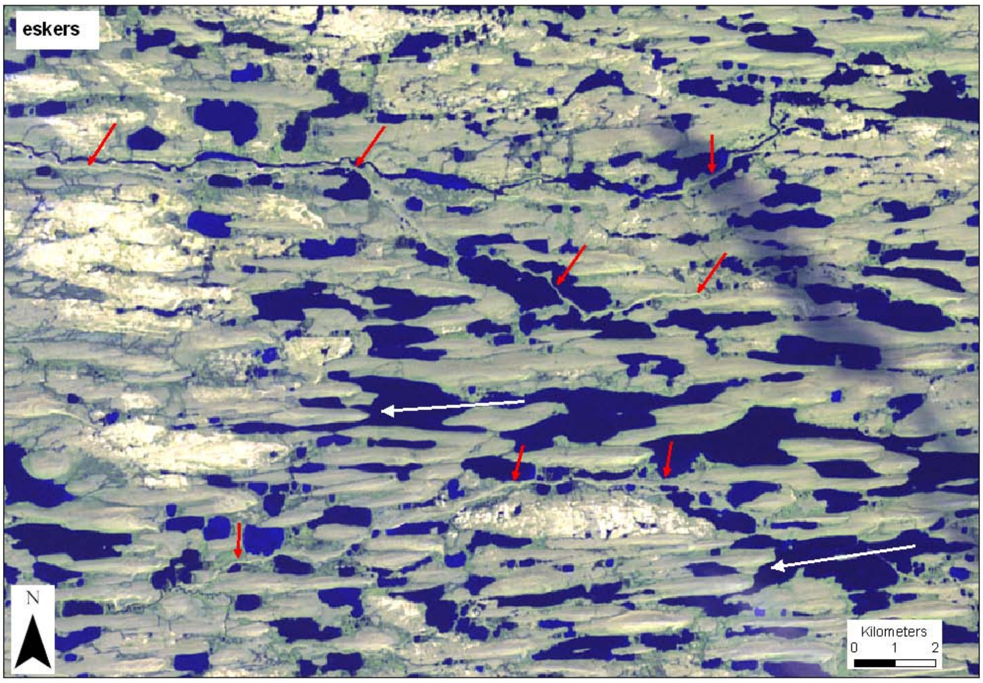


Figure 10 Landsat ETM+ satellite image (R,G,B: 7,4,2) of eskers (red arrows) on Wollaston Peninsula, south-western Victoria Island. See Figure 1 for location. Note that the eskers are aligned approximately with the direction of ice flow indicated by the underlying glacial lineations (white arrows) but that this is not always the case on Victoria Island. For example, one of the eskers in Figure 6 lies at 90° to the lineation direction underneath.

Also conspicuous on Victoria Island, particularly in the north-western regions, are large abandoned river channels cut by streams that are larger that the present ones. These *large meltwater channels* carried glacial meltwater alongside, within or away from the ice sheet on Victoria Island. Undoubtedly, smaller meltwater channels also exist on Victoria Island, but we restricted our mapping to the large channels, several 10s of metres wide. A large meltwater channel on Prince Albert Peninsula in north-western Victoria Island is shown in Figure 11.

Finally, isostatic rebound of Victoria Island has created prominent *raised shorelines*, which occur as nested sequences of wave-cut benches and beaches up to a few kilometres inland from the present day coastline, see Figure 12.

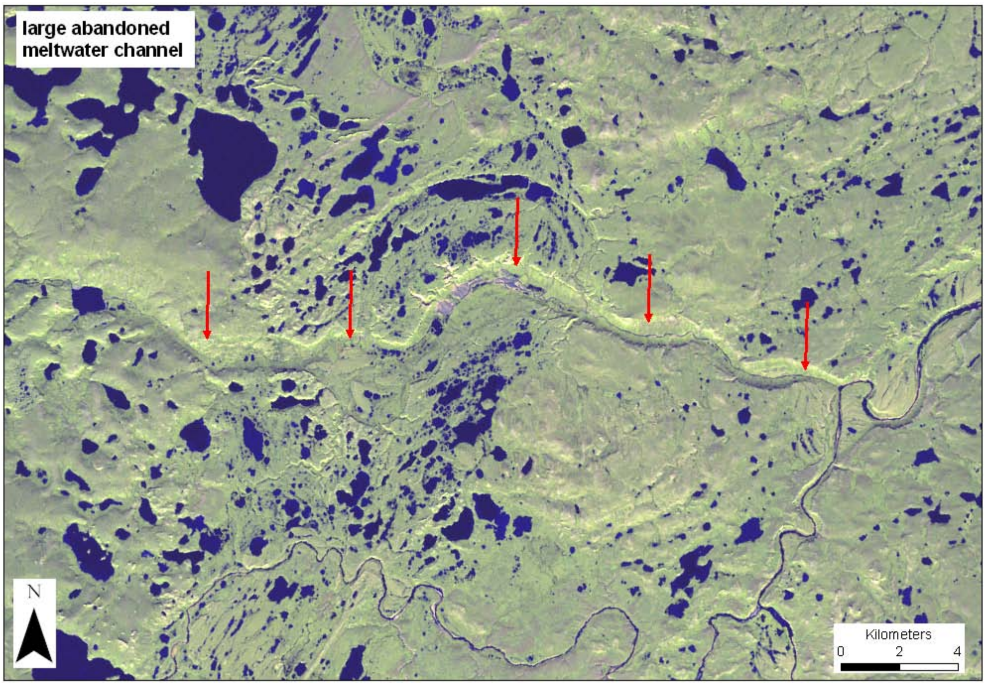


Figure 11 Landsat ETM+ satellite image (R,G,B: 7,4,2) of a large abandoned meltwater channel (red arrow) on Prince Albert Peninsula, north-western Victoria Island. See Figure 1 for location.

4. Conclusions & Implications

This paper presents a map of the glacial geomorphology of Victoria Island. Mapping from Landsat ETM+ imagery reveals a rich heritage of glacial landforms that betray a remarkably complex glacial history. The distribution and orientation of glacial lineations indicates marked changes in ice flow direction over time, with younger ice flows sometimes occurring at 90° angles to older flow patterns in the same location. The glacial lineations also display a wide range of sizes and if lineament elongation ratio is taken as a crude proxy for ice velocity (see Stokes and Clark, 2002), it would appear that several rapidly-flowing ice streams were focussed in the inter-island troughs (e.g. M'Clintock Channel, Dolphin and Union Strait, Prince Albert Sound) and infringed on the lowlands of Victoria Island (cf. Hodgson, 1994; Stokes et al., 2006). We note that the highest elevations of Victoria Island (around the Shaler Mts) are generally devoid of subglacial bedforms and therefore suggest that this area was characterised by cold-based ice for most of the Late Wisconsinan glaciation.

End moraines and eskers indicate that deglaciation occurred generally from the north-west to the south-east but that the pattern of retreat was not uniform across the island. Rather, it appears that ice was predominantly drained down into the inter-island troughs and that several re-advances occurred on eastern Victoria Island, successively overriding younger flow-sets, prior to final deglaciation.

It is anticipated that the map will be used to build a detailed reconstruction of the glacial history of Victoria Island which will, in turn, shed light on many issues in this important sector of the Laurentide Ice Sheet; such as ice streaming (Stokes et al., 2005), Arctic ocean meltwater events (e.g. Tarasov and Peltier, 2005) and the Arctic Ocean Ice Shelf hypothesis (Polyak et al., 2001).

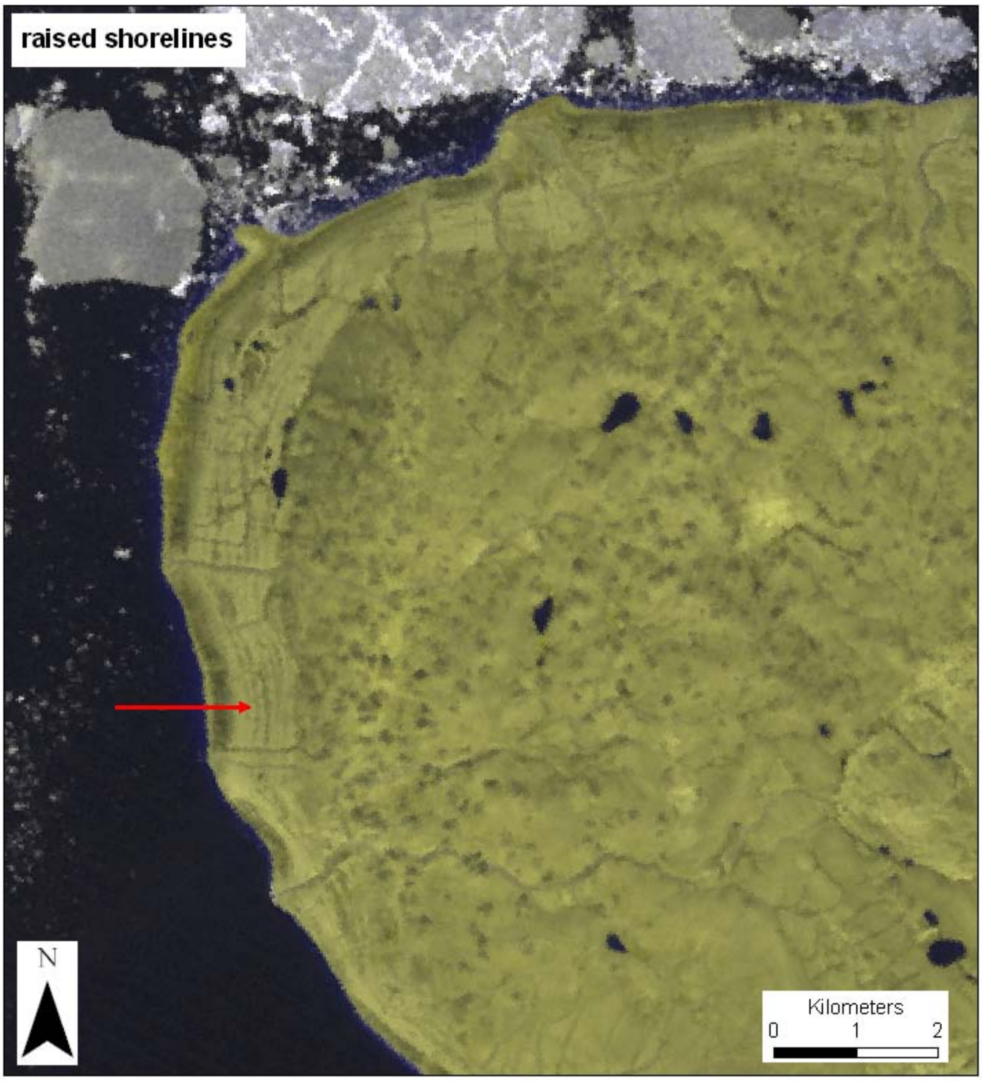


Figure 12 Landsat ETM+ satellite image (R,G,B: 4,4,2) of raised shorelines on Natkusiak Peninsula, northern Victoria Island. See Figure 1 for location.

Software

The Landsat ETM+ satellite images were manipulated in ERDAS Imagine 8.7 software. Separate Arc Coverages were created to represent each type of landform as either a line (e.g. glacial lineation, eskers) or polygon (e.g. large end moraine complexes, areas of Hummocky moraine). These coverages were then imported into ArcMap, where the final map was produced. The GTOPO 30 data was also processed in ERDAS Imagine 8.7 and imported to ArcMap to provide the background to the finished map.

Acknowledgements

This work was funded by a Nuffield Foundation Undergraduate Research Bursary (URB/32982). The authors are grateful for the constructive comments of Clas Hättestrand and Tim Fisher, which considerably improved this paper. We also thank an anonymous reviewer of the cartography.

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