

LATE WISCONSINAN ICE-FLOW HISTORY ON THE TIP OF THE NORTHERN PENINSULA, NORTHWESTERN NEWFOUNDLAND

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ABSTRACT

This paper presents a re-evaluation of late Wisconsinan ice-flow history on the tip of the Northern Peninsula, in light of new field data and an improved understanding of the regional ice dynamics. Striation and clast-provenance data form the basis of a proposed four-stage ice-flow model between the Last Glacial Maximum and the late glacial Younger Dryas cooling event. During its maximum configuration, Labrador ice flowed southeast, across the Strait of Belle Isle onto the tip of the Northern Peninsula, and coalesced with ice from the Long Range Mountains, deflecting it southwestward into the eastern Gulf of St. Lawrence. During deglaciation, the thinning Labrador ice was channelled toward calving margins at either end of the Strait of Belle Isle. This facilitated the expansion and formation of local upland ice divides on the Northern Peninsula, in some cases reversing the ice-flow direction. The rapid retreat of tidewater ice margins above the marine limit was followed by a re-advance, linked to Younger Dryas climatic cooling.

INTRODUCTION

During the late Wisconsinan, most of North America was covered by the Laurentide Ice Sheet (LIS; Wright, 1894; Dyke and Prest, 1987). In peripheral parts of the continent, such as the Island of Newfoundland, smaller ice complexes formed independent of, but merged with, the LIS (Grant, 1989). The zone of contact between the LIS and the Newfoundland ice complex was mostly seaward of the modern coastline, except on the northern tip of the Great Northern Peninsula (hereafter called the Northern Peninsula; Figure 1; Grant, 1992). This region, therefore, provides a unique opportunity to study the terrestrial geological evidence of the interaction of the two ice masses.

Despite the significance of the region for Newfoundland's glacial history, few field studies have followed up on Grant's initial work in the 1970s that proposed the zone of Labrador ice inundation (Grant, 1969, 1970, 1986). Since then, new roads have been built, permitting access to previously inaccessible forested areas. Also, advances in technology, such as cosmogenic dating (*e.g.*, Gosse *et al.*, 1995) and seabed mapping (*e.g.*, Piper *et al.*, 1994; Shaw *et al.*, 2009), have improved our understanding of the extent and dynamics of the southeastern LIS during the last glaciation. It is now widely accepted that ice extended almost to the edge of the continental shelf at the Last Glacial Maximum (LGM) and covered coastal uplands with non-erosive cold-based ice

(Hughes, 1998; Piper and McDonald, 2001; Clark and Mix, 2002; Gosse *et al.*, 2006; Shaw *et al.*, 2006). It is timely, therefore, to re-examine the published records of late Wisconsinan ice dynamics on the tip of the Northern Peninsula in light of new field data and current models of regional glaciation.

The purpose of this study is to i) compare published models, both conceptual and field-based, of the ice-flow history for the region, ii) report new field data, and iii) propose a modified ice-flow model that best fits all the available evidence.

PREVIOUS WORK AND APPROACH

In a synthesis of field studies conducted primarily in the 1970s, Grant (1992) proposed that ice from Labrador flowed southeast across the tip of the Northern Peninsula at the LGM. During deglaciation, ice flow shifted to southwestward, particularly along the west side of the Peninsula (Grant, 1992; Figure 2). Additionally, he described a late deglacial re-advance from the Long Range Mountains, called the Ten Mile Lake re-advance, which extended into the southern part of the study area and terminated at a well-defined end moraine complex (Grant, 1969, 1970, 1992; Liverman *et al.*, 2006). Grant's reconstructions were based primarily on striations, flow-parallel landforms, clast-provenance data and radiocarbon dates.

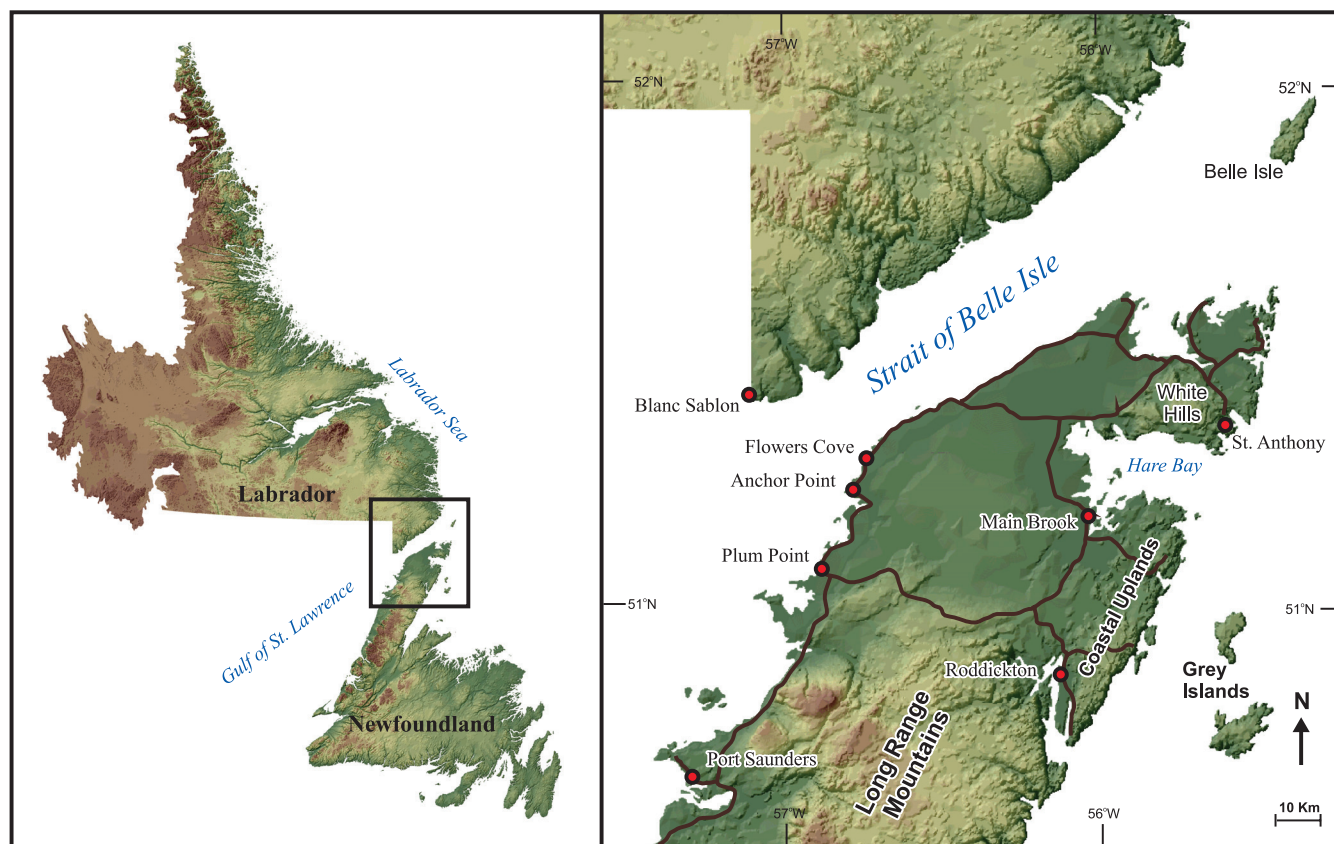


Figure 1. Location map featuring major roads and communities in the study area overlain on a digital elevation model.

In the last decade or so, two conceptual models of glaciation, one continental in scale, and the other regional in focus, proposed ice flow histories for northwestern Newfoundland that appeared to contradict Grant's field evidence. In his LGM model of the LIS, Hughes (1998) proposed that an ice stream flowed northeastward through the Strait of Belle Isle, fed by ice sources from southern Labrador and northwestern Newfoundland (Figure 2). More recently, Shaw *et al.* (2006) proposed a conceptual model of deglaciation in Atlantic Canada that stressed the importance of ice streaming. Their model was primarily constrained by geomorphic and geological evidence from the continental shelf. They proposed a LGM ice divide along the central axis of the Northern Peninsula that curved across the Strait of Belle Isle and onto southern Labrador. The divide persisted during deglaciation. In the Strait of Belle Isle, it separated southwestward ice flow that drained into the Laurentian Channel ice stream from northwestward ice flow to the Labrador Sea (Figure 2).

The Shaw *et al.* (2006) and Grant (1992) models both show a strong southwestward flow pattern along the west side of the Northern Peninsula and a roughly southeastward flow along the east side of the Peninsula, south of Hare Bay (Figure 2). The areas where these two models differ are the

northeastern part of the Peninsula, north of Hare Bay (zone 1, Figure 2), the area west of Hare Bay including the northwest coast of the Peninsula (zone 2, Figure 2), and the north side of the Strait of Belle Isle along the southern Labrador–Québec coast (zone 3, Figure 2). Hughes' (1998) model does not share any ice-flow patterns with the other two models (Figure 2).

Fieldwork in 2003 and 2009 focused on ice-flow mapping on the tip of the Northern Peninsula with a particular emphasis on recording new data in zones 1 and 2, where field evidence might resolve the conflicting ice-flow histories. Ice-flow data from McCuaig (2002) on the Labrador side of the Strait of Belle Isle (zone 3) were available for this analysis through the Geological Survey of Newfoundland and Labrador Striation Database (hereafter called the striation database; Taylor, 2001); equivalent data on the southeastern Québec shore were published by Dionne and Richard (2006). Landform data were digitized from Grant's Quaternary geology map of the region (Grant, 1986).

STUDY AREA

The study area incorporates NTS 1:250 000-scale map sheets 2/M, 12/P, and the northern edge of 12/I on the North-

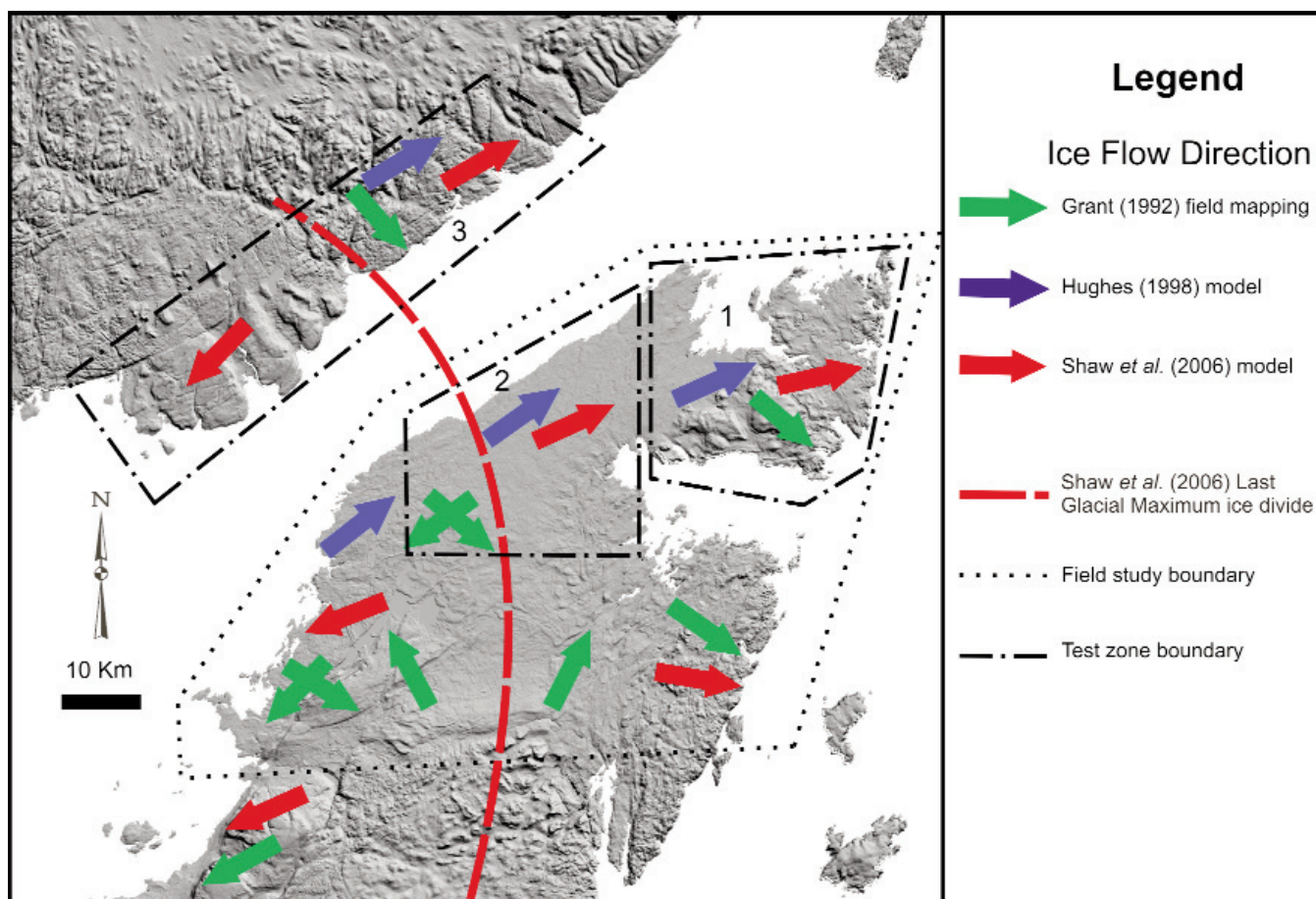


Figure 2. Predicted ice-flow patterns based on published models of deglaciation. Also shown are key zones where the models conflict, as discussed in the text. Digital elevation model was produced by the Newfoundland and Labrador Department of Natural Resources using data from the Shuttle Radar Topography Mission.

ern Peninsula (Figure 1). To the south are the Long Range Mountains and to the east are the coastal uplands, which reach a maximum elevation of ~300 m in the White Hills. Most of the remaining field area is below 100 m elevation and was inundated by the Goldthwait Sea during the early postglacial period (Grant, 1992). The study area is, for the most part, underlain by Cambrian to Ordovician carbonate rocks (Figure 3; Bostock *et al.*, 1983). Along the east side of the Peninsula is the Middle Ordovician St. Anthony Slice Assemblage, an ophiolite suite that includes highly deformed and meta-sedimentary rocks, ocean-floor basalt, gabbro, and peridotite (Bostock *et al.*, 1983). To the south of the study area, in the Long Range Mountains, and to the north of the study area in southern Labrador, are highly metamorphosed Precambrian rocks from the Canadian Shield (Bostock *et al.*, 1983). These are predominantly granites, syenites and granitoid gneisses. Gabbros, anorthosites and norites outcrop in southern Labrador but are not present in the northern Long Range Mountains (Figure 3).

FIELD METHODS

To address the goals of this study, two types of ice-flow data were collected: striations and indicator clast lithology. At each outcrop, seven parallel to subparallel striations were measured and the median orientation recorded. Where possible, directions were inferred using stoss-and-lee forms on the bedrock surface and concentric chatter marks (Hubbard and Glasser, 2005). In the event of multiple striation orientations at a single site, age relationships were inferred using crosscutting relationships and lee-side preservation, if present. The level of confidence associated with each striation and its direction and age relationship was recorded as high, medium or low.

The absence of bedrock exposure (zone 2) or the widespread occurrence of weathered bedrock (zone 1) restricted striation data in some areas. Only striations classified as high confidence and directions and age relationships deter-

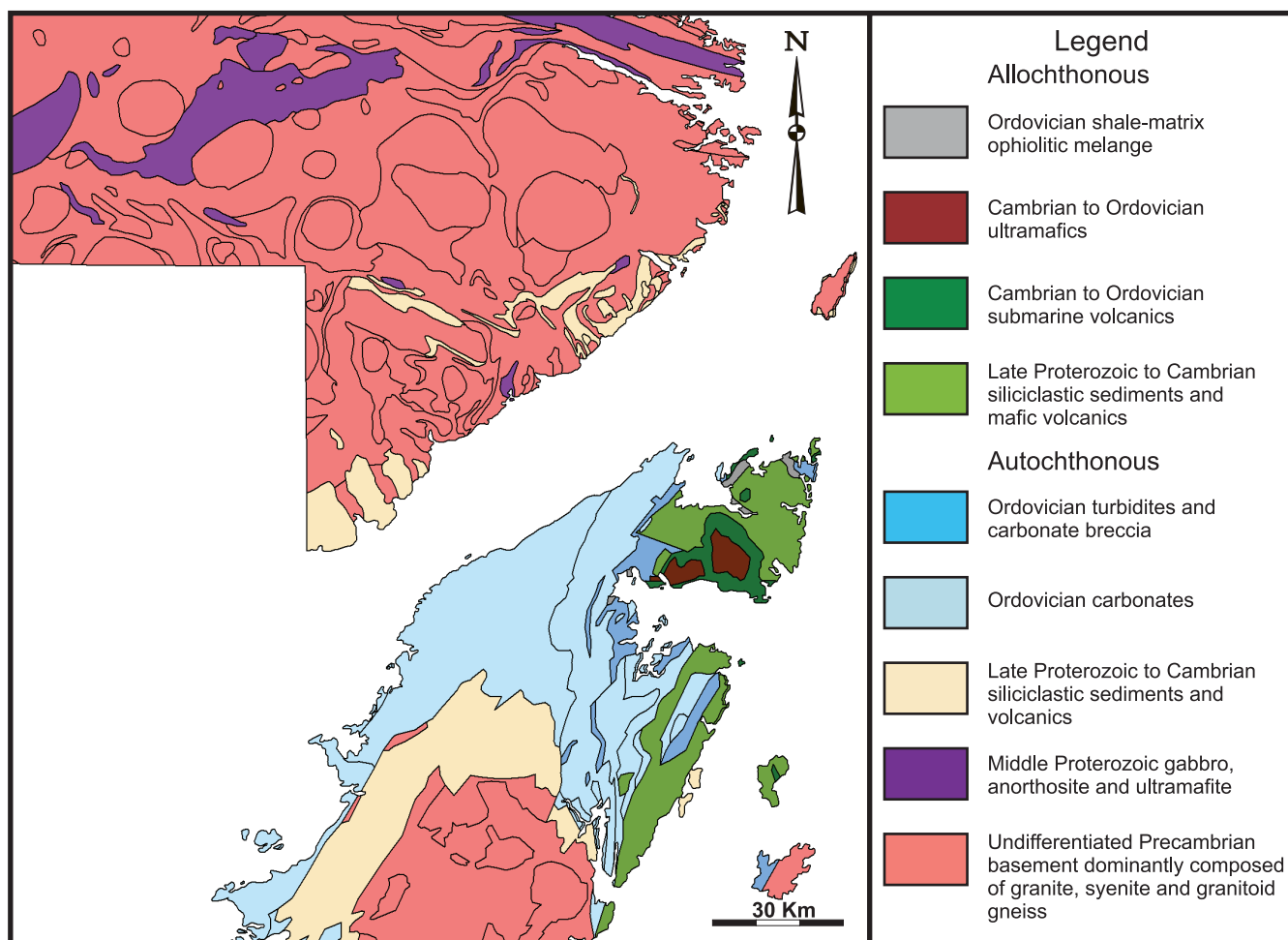


Figure 3. Generalized bedrock-geology map. Rock types used for clast-provenance studies include anorthosite and peridotite (Colman-Sadd *et al.*, 1990; Wardle *et al.*, 1997; Geoscience Resource Atlas, 2010).

mined with a high degree of confidence, were used for mapping. These data supplemented those collected in previous studies (Figure 4).

An important line of evidence used by Grant (1992) in his ice-flow reconstruction was the dispersal of erratics from Labrador onto the Northern Peninsula. Grant (1992) proposed that all highly metamorphosed Precambrian rocks from the Canadian Shield, found in till on the tip of the Northern Peninsula, were sourced from southern Labrador. An examination of geology maps for the study area (Colman-Sadd *et al.*, 1990; Wardle *et al.*, 1997) shows that many of the Precambrian units outcropping in southern Labrador also outcrop in the northern Long Range Mountains (Figure 3); only outcroppings of anorthosite and norite are unique to southern Labrador. On the tip of the Northern Peninsula, peridotite only outcrops in the White Hills and its dispersal may be a useful indicator of local ice flow (Figure 3).

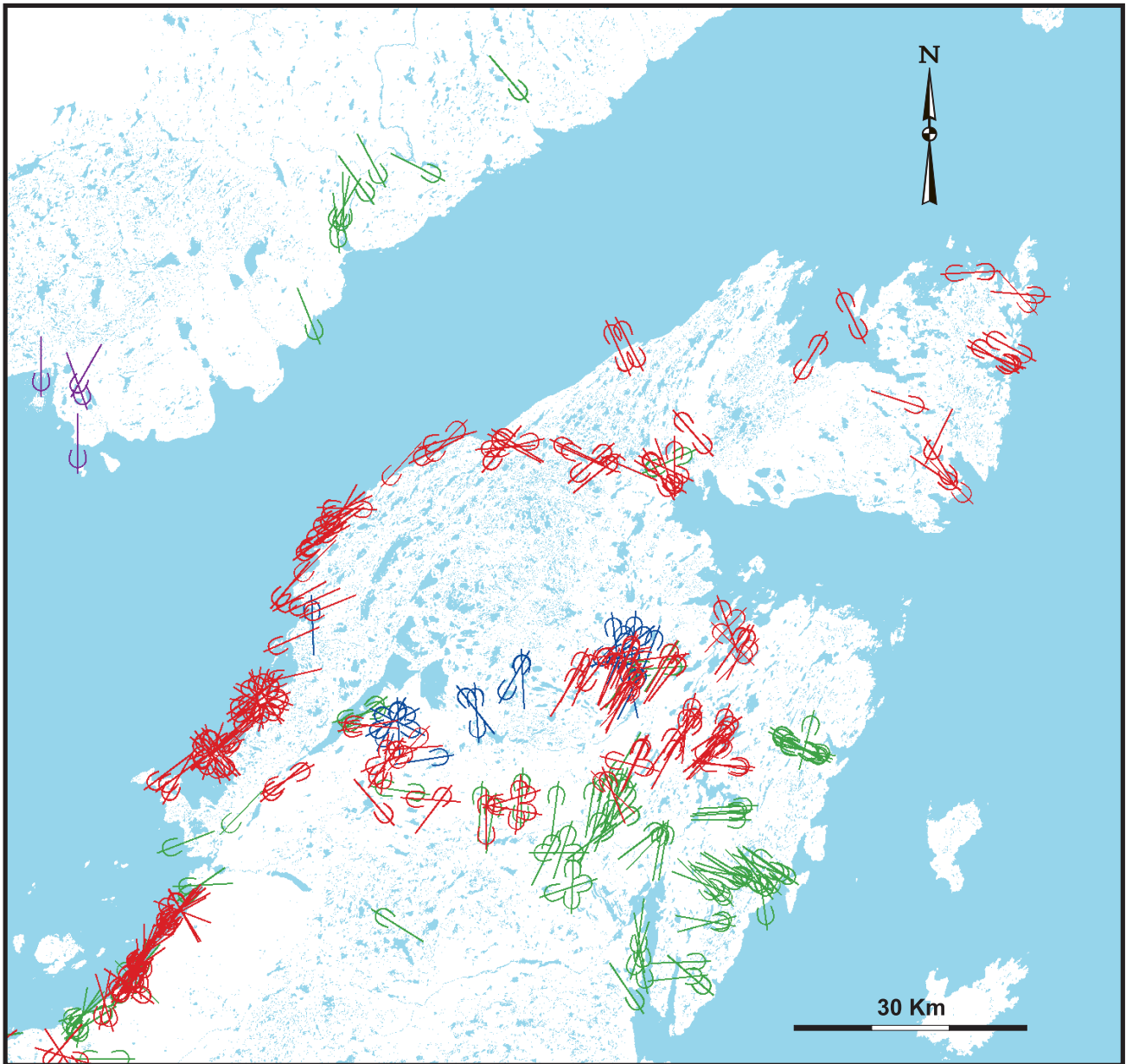
Anorthosite and peridotite are both easily identifiable in hand sample and have a restricted bedrock source, thus they

are ideal for clast-provenance studies. During fieldwork, these rock types were searched for in boulder fields, at any sites visited for striation mapping and in sediment exposures.

RESULTS

STRIATIONS

Newly acquired striation data exhibit several strong ice-flow patterns. In zone 1, striations mainly exhibit an eastward to southeastward flow direction ranging from 087° to 148° (Figure 5). The only exceptions are two striations, both with an ice-flow orientation of 030 – 210° . In zone 2, data were collected along the sides of Route 430 only (Figure 5). Along the western portion of the road, striations exhibited both southwest ($\sim 230^{\circ}$) and northwest trends (293° to 302° ; Figure 5). At one site, a striation with a sense of 257 – 077° was crosscut by another with a sense of 302 – 122° , indicating that the southwest–northeast trend was the older of the two. On the north coast near Big Brook, a few striations



Striation Sources

2009 field season		Newfoundland and Labrador striation database	
	Direction known		Direction known
	Direction unknown		Direction unknown
2003 field season		Dionne and Richard (2006)	
	Direction known		Direction known
	Direction unknown		Direction unknown

Figure 4. Map showing all available striation data in and adjacent to the field area. Different colours represent various data sources.

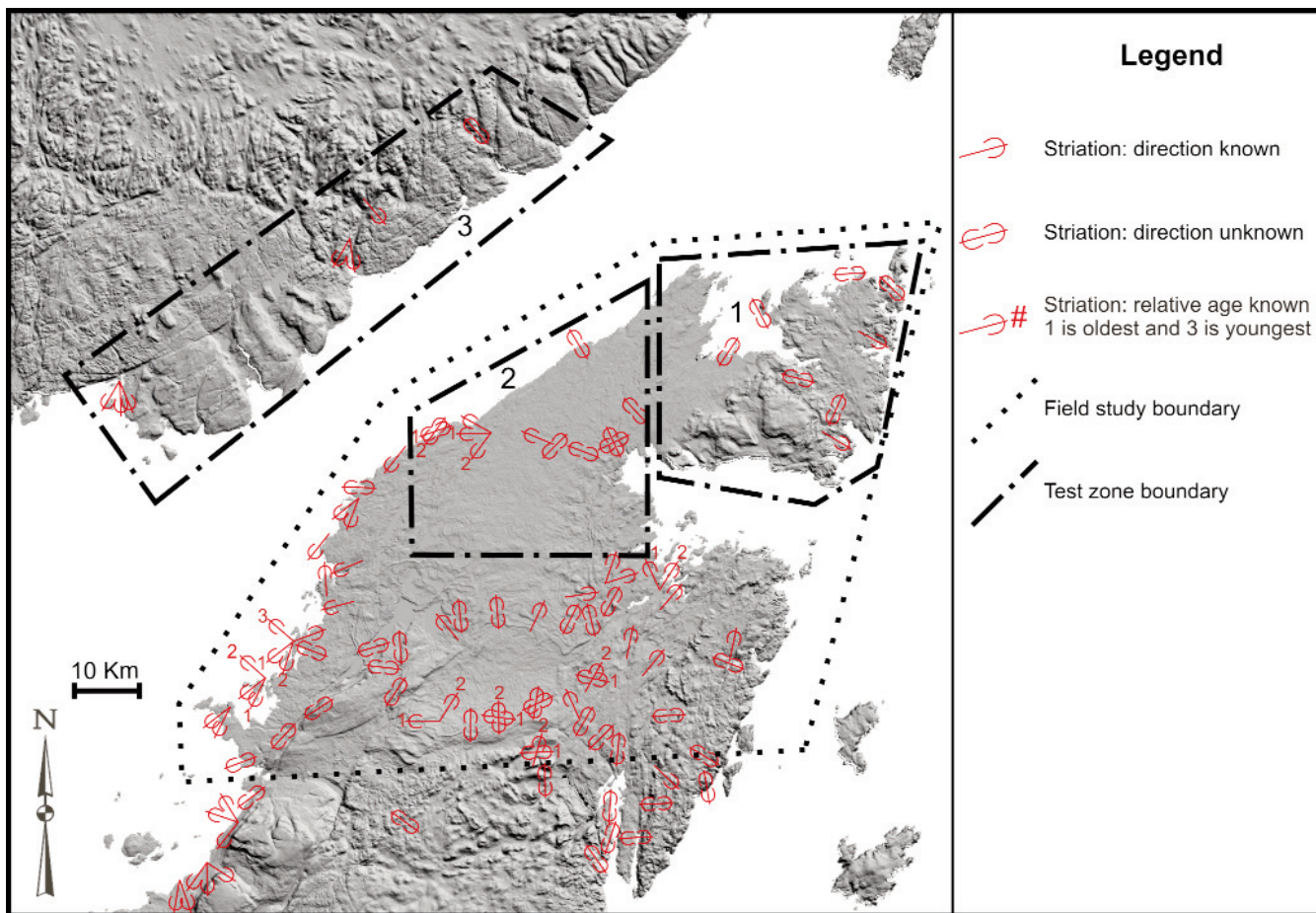


Figure 5. Summarized striation data in and adjacent to the study area. Data were filtered for quality and clarity. Digital elevation model was produced by the Newfoundland and Labrador Department of Natural Resources using data from the Shuttle Radar Topography Mission.

were measured with a sense of $\sim 150\text{--}330^\circ$ ($\pm 10^\circ$; Figure 5). Flow direction could not be determined for any of these striations. Zone 3 striations displayed both south and southeast flow directions with a few exhibiting a southwest flow (McCuaig, 2002; Figure 5).

Outside of the key zones, a strong southwest flow was identified along the west side of the Peninsula (Figure 5). These striations range from west (272°) to south-southwest (200°). At the few sites where age relationships could be interpreted, the westward flow was the oldest. Several coastal sites north of Plum Point have striations that trend in a wide range of directions (Figure 5).

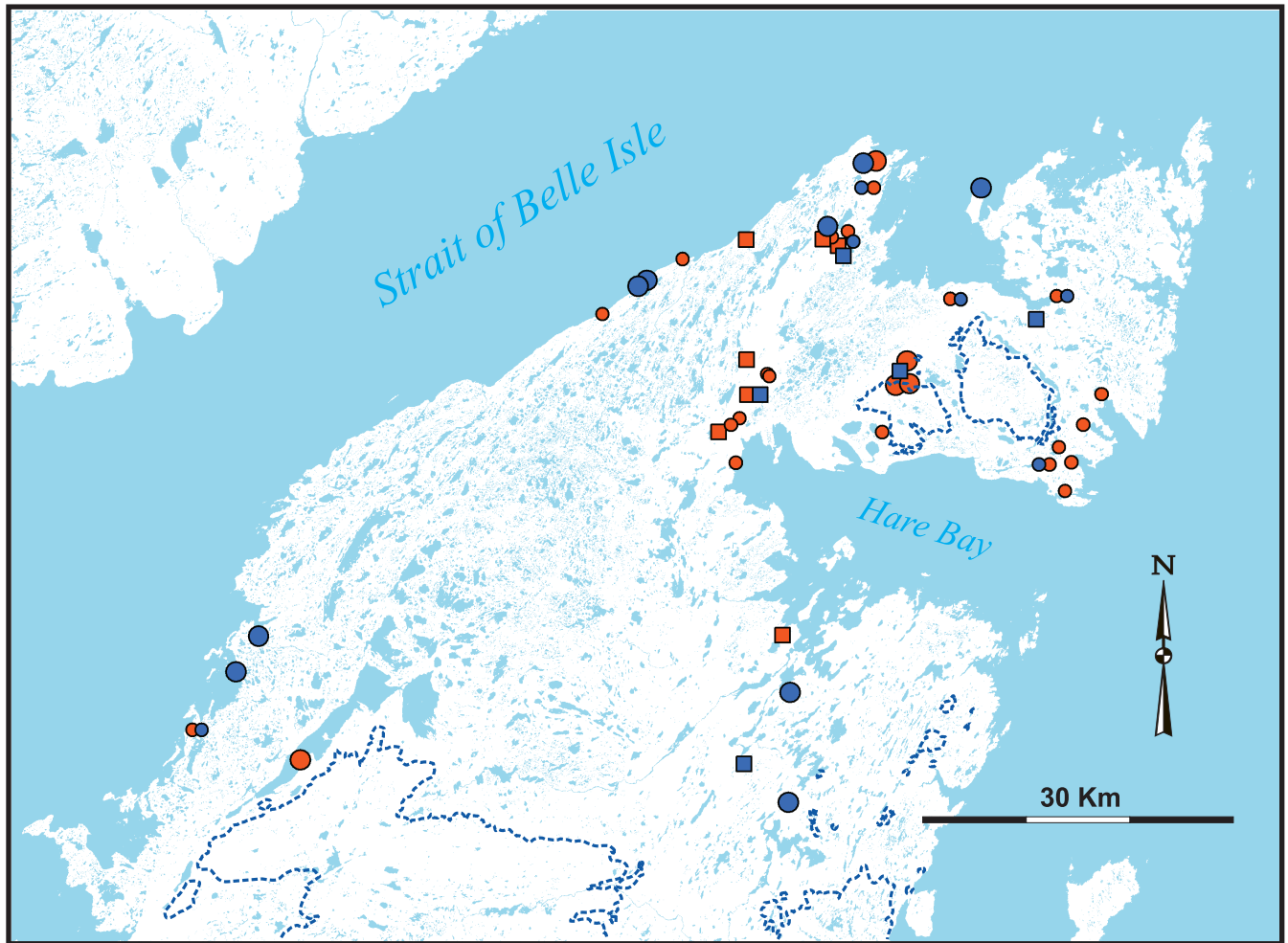
In the southern part of the study area, striations mainly exhibited a northward flow pattern ($358\text{--}016^\circ$) in the centre of the Peninsula and a northeastward flow pattern ($012\text{--}043^\circ$) toward the east coast (Figure 5). An east–west trend ($\sim 085\text{--}265^\circ$) was also found at many sites, five of which demonstrated that it is the oldest ice flow in the area. Along the east coast there was a marked southeast flow with

a range of $104\text{--}150^\circ$ (Figure 5). Four sites south of Hare Bay indicate a northwest flow ranging from 311° to 343° .

CLAST PROVENANCE

Peridotite clasts were observed either on the surface or in raised beach deposits. They show a subradial distribution approximately 30 km out from White Hills (zone 1, Figure 6). The only exceptions were two sites in the southwest corner of the study area (Figure 6). Anorthosite clasts were mainly clustered in zone 1 in the northeast corner of the study area, with a few sites in the southeast and southwest (Figure 6). A single anorthosite clast was found in a till exposure in zone 1; all others were found on the surface or in raised beach deposits.

All samples of peridotite and anorthosite were found below marine limit. Those that were located in section were either in till or raised beach deposits, whereas those on the surface were typically in boulder fields or on till and raised marine surfaces. The source of raised beach deposits and



Anorthosite

- Boulder on surface
- Cobble/pebble on surface
- Cobble/pebble in section

Peridotite

- Boulder on surface
- Cobble/pebble on surface
- Cobble/pebble in section

----- Marine Limit

Figure 6. Distribution of clast-provenance data by lithology.

boulder fields in the study area is typically local till reworked by wave action during postglacial marine regression. Isolated erratics may have been rafted by icebergs during a phase of tidewater ice-marginal retreat in the Strait of Belle Isle (*see below*); however, this phase was most likely brief (<500 years according to the deglacial chronology of Shaw *et al.*, 2006) and sedimentary evidence of ice-rafted debris was absent in exposures in the field area (*e.g.*, dropstones, deformed bedding; *cf.*, Benn and Evans, 1998). It is assumed, therefore, that all anorthosite and peridotite erratics were transported by glacier ice to the study area.

LANDFORMS INDICATIVE OF ICE FLOW

Grant (1986) mapped several fields of flow-parallel drumlins, *rôches moutonnées* and small, flow-perpendicular ice-marginal moraines within the study area (Figure 7). These moraines were interpreted by Grant (1992) to be DeGeer moraines deposited at a tidewater glacier margin retreating inland toward the centre of the Peninsula. Three major trends can be determined from these data: a southeast and eastward flow in zone 1; a southwest flow in zone 2 along the west coast; and a northeast flow in the east, radi-

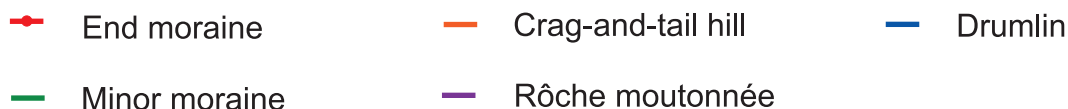
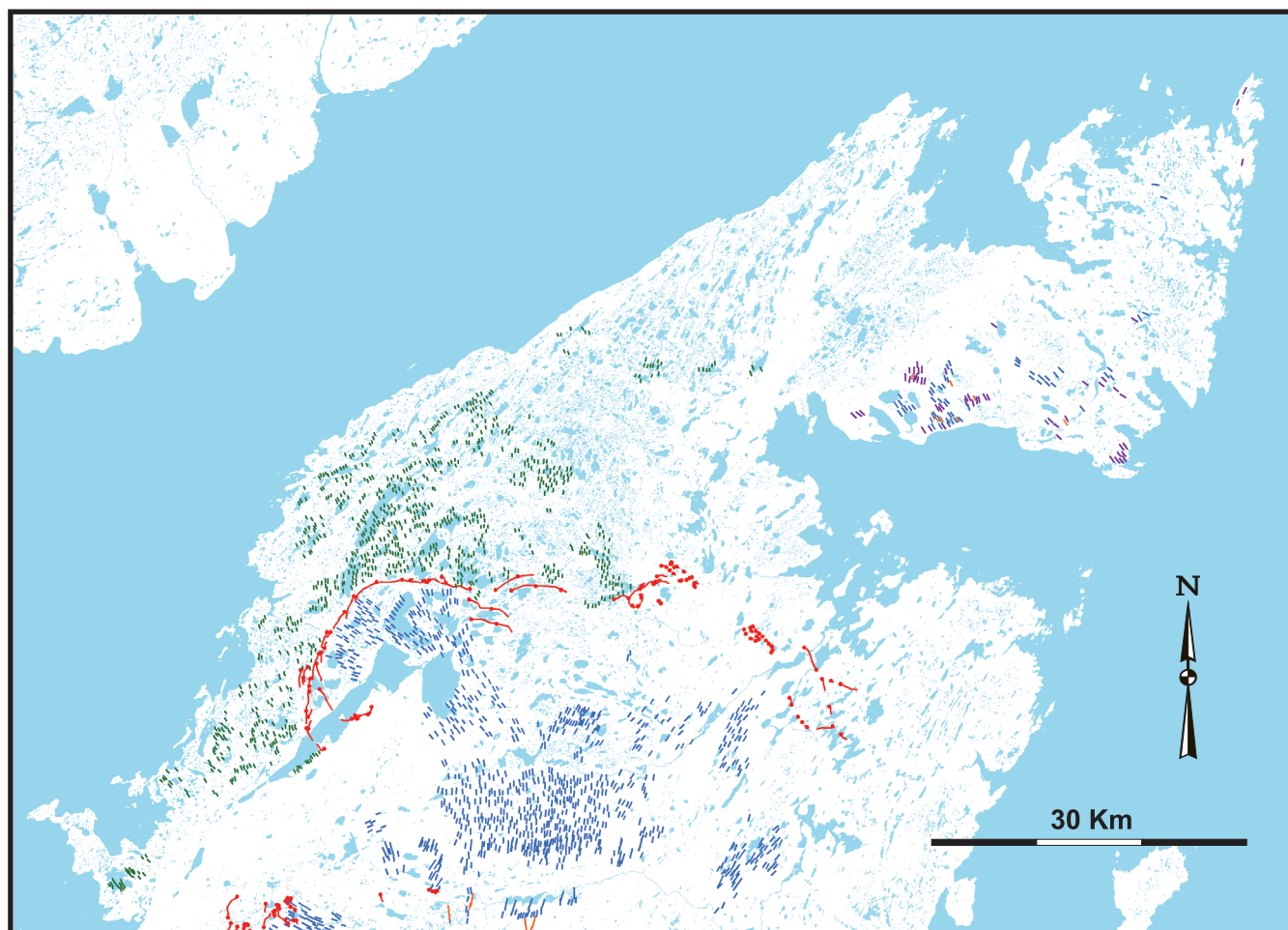


Figure 7. Location and type of landforms associated with ice-flow history as mapped by Grant (1992).

ating to the northwest in the west along the southern edge of the study area.

DISCUSSION

Although the distribution of indicator rock types largely reflects the sampling effort along roads in the study area, it shows two interesting patterns: i) extensive dispersal of anorthosite from Labrador that suggests a strong southeast ice flow across the northern half of the study area and overlap of the western coastline of the Peninsula by southwestward-flowing ice; and ii) a distribution of peridotite that strongly suggests a radial ice flow from its source in the White Hills. Of particular note, is the northern dispersal of peridotite, which required a subsequent/later reversal in ice-flow direction in zone 1 from southeastward to northwestward ice flow.

The striation patterns support these primary ice flows and provide additional details on ice dynamics and flow chronology. Specifically, four major ice-flow patterns can be deduced from the data. First, there is a strong east to southeast striation pattern in zones 1 and 2 in the northernmost part of the study area, in the northern part of zone 3 in southern Labrador and also along the east coast south of Hare Bay. Although many of the striation sites in zones 1 and 2 provide orientations only, the clustering of anorthosite erratics originating from southern Labrador in this area supports the view that Labrador ice flowed across the Strait onto the tip of the Northern Peninsula. Second, striation evidence confirms a south to southeastward ice flow from the southern half of zone 3 in Labrador that appears to be deflected southwestward along the west coast of the Northern Peninsula. This deflection was likely due to ice flow from the Long Range Mountains into the Gulf of St. Lawrence. The

earliest flow pattern on the coast is westward, perpendicular to the Long Range ice divide, followed by a southwestward flow, which likely reflects the coalescence of Labrador and Long Range ice in the Gulf. Third, in zones 1 and 2 there are striation sets that either oppose the southeastward-dominant flow pattern or are perpendicular to it (Figure 4). These striations are consistent with a north to northwestward ice-flow pattern from the White Hills as suggested by the dispersal pattern of peridotite erratics. There are no relative age determinations on the two sets of striations; however, it is assumed here that the pervasive southeastward flow from Labrador is the oldest and the more restricted White Hills flow pattern was superimposed on it later. Fourth, there is a strong radial pattern of northeast-to-northwest ice flow at the northern end of the Long Range Mountains that cross-cuts an earlier east to southeastward flow. The latter is interpreted to represent the movement of Labrador ice across the Peninsula (*see above*), whereas the former is consistent with a northward dispersal of Long Range ice onto the lowlands. The formation of a drumlin field is also associated with this northward dispersal (Figure 6; Grant, 1992).

The ice-flow patterns proposed above require modifications of the Grant (1992) and Shaw *et al.* (2006) models and rejection of the Hughes (1998) model. None of the ice-flow patterns required by the Hughes (*op. cit.*) model were observed in the study area. Grant's original assertion that Labrador ice advanced across the northern tip of the Northern Peninsula is largely confirmed by the new ice-flow data; however, there is no evidence that the southeastward flow occurred along the west coast of the Peninsula south of the Strait of Belle Isle. Instead, the evidence here suggests a coalescence of Labrador and Long Range ice to form a southwestward flow largely parallel to the coast. The Shaw *et al.* (2006) model requires divergent flow on either side of an ice divide that straddles the Strait of Belle Isle during the LGM. Such an ice divide would not generate ice flow to disperse anorthosite erratics from Labrador onto the Northern Peninsula and there is no evidence for northeastward-trending ice flow in zones 2 and 3, which would be expected from such an ice divide. The relocation of the Shaw *et al.* (2006) ice divide farther east onto the Northern Peninsula during deglaciation is more consistent with the ice-flow evidence (*see below*). The radial ice flow at the northern end of the Long Range Mountains is consistent with Grant's (1992) proposed Ten Mile Lake re-advance during a late stage of deglaciation on the Northern Peninsula.

On the basis of the field evidence presented in Figures 4–7 the following ice flow history is proposed for the study area (Figure 8):

1. At the LGM, Labrador ice flowed southeast across the Strait of Belle Isle and the northernmost tip of

the Northern Peninsula onto the adjacent continental shelf (Figure 8A). Farther south, it coalesced with ice from the Long Range Mountains and was deflected southwestward into the eastern Gulf of St. Lawrence. Prior to coalescence, Long Range ice advanced unhindered across the coastline into the Gulf. North and north-eastward flow of Long Range ice was deflected southeastward into the Labrador Sea by Labrador ice.

2. During deglaciation, as Labrador ice thinned and retreated toward the northwest, ice flow became topographically influenced and a new ice divide developed over coastal uplands and the White Hills (Figure 8B). This ice divide is simply shown in Figure 8B as an extension of the Long Range Mountains ice divide; however, it may have had a more complex configuration, made up of local ice divides in upland areas. The re-orientation of ice flow at this stage of deglaciation was likely facilitated by the migration of calving bays at either end of the Strait of Belle Isle. Both Grant (1992) and Shaw *et al.* (2006) proposed such a calving bay in the eastern Gulf of St. Lawrence and Grant (1992) attributed a series of DeGeer moraines on the coastal lowlands (Figure 7) to the migration of this tidewater ice margin across the present-day coast during the Goldthwait Sea highstand. It is proposed here that a similar tidewater ice margin would have developed in the northeastern end of the Strait of Belle Isle as the ice cover thinned and ice flow from Labrador was topographically channelled by the marine embayment. Drawdown of Northern Peninsula ice into these calving bays dispersed peridotite erratics from the White Hills in a fan-shaped pattern from north to southwest on the western flank of the ice divide (Figure 6). DeGeer moraines in zone 2 (Figure 7) would have formed during eastward retreat of White Hills ice across the coastal lowlands. The eastern flank of the ice divide would have generated eastward-flowing ice toward an offshore tidewater ice margin. The timing of Deglacial Stage 1 is roughly placed at 13 ka BP, consistent with the radiocarbon chronology of ice retreat proposed by Grant (1992).
3. The ice margins portrayed in Deglacial Stage 2 (Figure 8C) are speculative and intended to show the persistence of upland ice caps and divides in the study area and the retreat of Labrador ice to moraine systems inland of the Strait of Belle Isle coast (*cf.*, Bell and McCuaig, 2004). The timing of Deglacial Stage 2 is approximately 12 ka BP and reflects the rapid retreat of tidewater glacier mar-

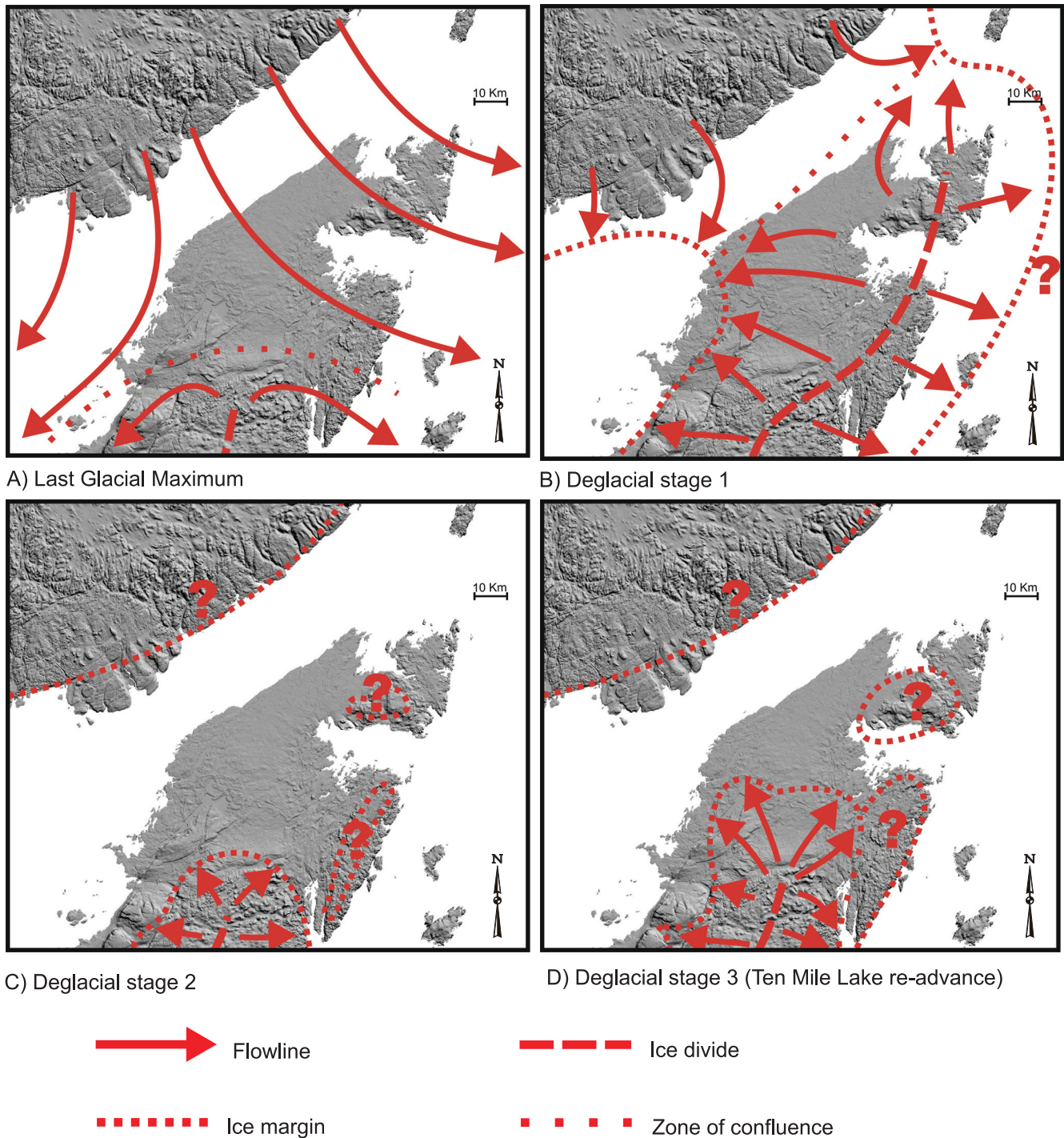


Figure 8. Proposed deglacial ice-flow history for the tip of the Northern Peninsula and southernmost Labrador. Digital elevation model was produced by the Newfoundland and Labrador Department of Natural Resources using data from the Shuttle Radar Topography Mission.

gins in the Strait of Belle Isle and the establishment of the Goldthwait Sea marine limit in the study area (Grant, 1992).

4. The final stage of ice-flow history presented here (Figure 8D) represents the Ten Mile Lake re-

advance documented by Grant (1992). This re-advance is recorded by striations, drumlins and the Ten Mile Lake moraine complex. Grant (1992) proposed that the re-advance was a glaciological response to regional cooling during the Younger Dryas and established local timing for the event at

~11.5 ka BP. It is assumed here that local ice caps on the White Hills and coastal uplands would have responded to climatic cooling in a similar manner to Long Range ice and are portrayed in Figure 8D as more extensive during Deglacial Stage 3; however, the ice marginal positions are speculative. Whether the southeastern margin of the Laurentide Ice Sheet in Labrador responded to Younger Dryas cooling is uncertain; two moraine systems - the Brador(e) and the Belles Amours - were built during inland retreat some time after 12.6 ka BP but more precise dating is required to establish a Younger Dryas re-advance in Labrador (Bell and McCuaig, 2004).

Further refinement of the proposed ice-flow history in the study area would greatly benefit from additional striation and clast-provenance mapping in the interior (*e.g.*, away from roads), above marine limit (*e.g.*, White Hills and coastal uplands) and on offshore islands (*e.g.*, Grey Islands, Belle Isle). These additional data could confirm the south-eastward movement of Labrador ice across the Northern Peninsula and into the Labrador Sea at LGM and the deglacial ice flow northeastward along the Strait of Belle Isle by coalescent Labrador and Newfoundland ice. Furthermore, the analysis of high resolution, swath multibeam sonar data from the seafloor of the Strait of Belle Isle may reveal ice-flow bedforms that can test the proposed model of deglaciation presented here (*cf.*, Brushett *et al.*, 2007).

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