Using a GIS to Quantify Patterns of Glacial Erosion on Northwest Iceland: Implications for Independent Ice Sheets

Authors: Principato, Sarah M., and Johnson, Jeremiah S.

Source: Arctic, Antarctic, and Alpine Research, 41(1) : 128-137

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1523-0430-41.1.128

Arctic, Antarctic, and Alpine Research, Vol. 41, No. 1, 2009, pp. 128–137

Using a GIS to Quantify Patterns of Glacial Erosion on Northwest Iceland: Implications for Independent Ice Sheets

Sarah M. Principato† and*
*Jeremiah S. Johnson**

*Department of Environmental Studies,
Gettysburg College, 300 North
Washington Street, Campus Box 2455,
Gettysburg, Pennsylvania 17325, U.S.A.
†Corresponding author:
sprincip@gettysburg.edu

Abstract

Glacial erosion patterns on northwest Iceland are quantified using a Geographic Information System (GIS) in order to interpret subglacial characteristics of part of northwest Iceland affected by ice sheet glaciation. Ice scour lake density is used as a proxy for glacial erosion. Erosion classes are interpreted from variations in the density of lake basins. Lake density was calculated using two different methods: the first is sensitive to the total number of lakes in a specific area, and the second is sensitive to total lake area in a specific area. Both of these methods result in a value for lake density, and the results for lake density calculated using the two methods are similar. Areas with the highest density of lakes are interpreted as areas with the most intense erosion with the exception of alpine regions. The highest density of lakes in the study area exceeds 8% and is located on upland plateaus where mean elevations range from 400 to 800 m a.s.l. Low lake density (0–2%) is observed in steep alpine areas where steep topography does not favor lake development. The GIS analysis is combined with geomorphic mapping to provide ground truth for the GIS interpretations and to locate paleo-ice flow indicators and landforms. The patterns identified in this study illustrate distinct regions of glacial erosion and flow paths that are best explained by two independent ice sheets covering northwest Iceland during the Last Glacial Maximum (LGM). Areas of alpine glacial landforms and the presence of nunataks within the glaciated region support interpretations that ice-free regions or cold-based ice cover existed on parts of northwest Iceland during the LGM. The methods developed in this study are easily transferable to other formerly glaciated regions and provide tools to evaluate subglacial properties of former ice sheets. The data generated yield important subglacial boundary conditions for ice sheet models of Iceland.

DOI: 10.1657/1938-4246(07-065)[PRINCIPATO]2.0.CO;2

Introduction

The location of Iceland in the central North Atlantic Ocean makes its climate sensitive to changes in oceanic and atmospheric circulation (Malmberg, 1969, 1985; Ruddiman and McIntyre, 1981; Boulton, 1986; Stotter et al., 1999; Eiríksson et al., 2000; Bradwell et al., 2006), and glaciers on Iceland respond rapidly to fluctuations in climate (Elliot et al., 1998). Evidence from marine sediment cores and seismic studies indicates that the outer margins of the Icelandic ice sheet were offshore around much of the island during the last global glacial maximum (LGM) (Olafsdóttir, 1975; Egloff and Johnson, 1979; Boulton et al., 1988; Syvitski et al., 1999; Andrews et al., 2000, 2002; Geirsdóttir et al., 2002; Andrews and Helgadóttir, 2003; Andrews, 2005; Principato et al., 2005). However, discrepancies between different ice reconstructions of the Icelandic ice sheet exist, ranging from extensive glaciation with no ice-free areas (Larusson, 1983; Buckland and Dugmore, 1991) to a refugia model with ice-free areas on the high plateaus and vascular plants surviving glaciation (Hoppe, 1982; Einarsson and Albertsson, 1988; Ingólfsson, 1991). It is also commonly assumed that two independent ice sheets were present on Iceland during the LGM, one covering the mainland and one covering Vestfirðir, the northwest peninsula of Iceland (Hoppe, 1982; Norðdahl, 1991), but this assumption has not been tested. Ice streams and ice divides have been proposed for the Icelandic ice sheet during the LGM (Bourgeois et al., 1998, 2000; Hubbard et al., 2006), but the patterns of glacial erosion have not been closely examined.

Understanding and quantifying patterns of glacial erosion and ice scour features provides information regarding past ice sheet dynamics and facilitates the reconstruction of former ice sheets (e.g., Sugden, 1978; Andrews et al., 1985; Rea et al., 1998; Marshall et al., 2000; Kaplan et al., 2001; Li et al., 2005; Harbor et al., 2006). Boundaries between glacially scoured landscapes and non-scoured areas generally represent a change in basal thermal regime, and the density of lake basins has been used as a proxy for glacial scour in studies of the Laurentide, Fennoscandian, and British Ice Sheets (Sugden, 1978; Andrews et al., 1985; Rea et al., 1998). Cosmogenic nuclide evidence is also commonly used to determine rates of erosion and timing of glacial landform development (e.g., Kaplan et al., 2001; Fabel et al., 2002; Briner et al., 2003, 2005; Li et al., 2005; Harbor et al., 2006). Accurately reconstructing patterns of glacial erosion and basal thermal regime provide important boundary conditions for glaciological models, as flow rates and bed deformation are related to bed conditions. The application of a Geographic Information System (GIS) has been used in a variety of glacial geology studies, but most focus on glacier inventories and reconstructions of ice sheets (i.e., Balascio et al., 2005; Greenwood et al. 2007; Schneider et al., 2007). The

1523-0430/09 $7.00

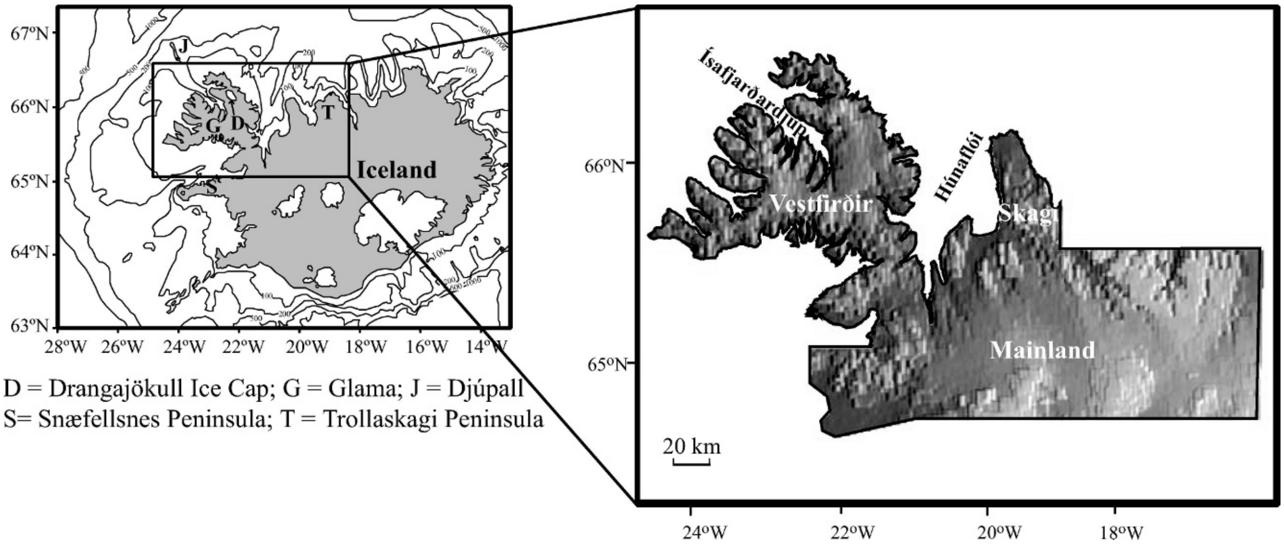


FIGURE 1. Location of study area. (A) Map of Iceland with localities mentioned in the text; D = Drangajökull Ice Cap, G = Glama, J = Djúpall, S = Snæfellsnes Peninsula, T = Tröllaskagi Peninsula. (B) The three subregions of the study area: Skagi, Vestfirðir, and the northwest mainland of Iceland.

utility of GIS in glacial geomorphology studies linked with ice sheet modeling was recently demonstrated in Li et al. (2007) and Napieralski et al. (2007) where the correlation between field data (striations and/or moraines) and the results of ice sheet models were quantified.

The purpose of this study is to use GIS to quantify the glacial erosion patterns that are thought to result primarily from shifts in basal thermal regime of the ice sheet covering the northwest region of Iceland (Fig. 1). Although other erosional processes such as mass movements and large rock slope failure occur on northwest Iceland in steep alpine areas, we focus our analysis on ice scour lakes in order to interpret subglacial characteristics of the ice sheet. Close examination of basal ice scour features on northwest Iceland will provide an opportunity to evaluate the proposed ice sheet configuration, including ice streams and ice divides, during the LGM (Norðdahl, 1991; Bourgeois et al., 1998, 2000; Hubbard et al., 2006). These data will be used to evaluate the possibility that two independent ice sheets covered northwest Iceland during the LGM. A new technique for quantifying glacial erosion using GIS has been developed, and this technique simplifies the analysis of the combination of variables such as the location of lake basins, topography, and geomorphic features documented from field mapping.

Origin of Lake Basins

One of the primary assumptions of this study is that the lake basins are created by ice scour. This interpretation is justified based on field and aerial photograph evidence and by eliminating other possible causes for the origin of the lakes. In several locations in the field, scouring to bedrock was verified, and on the upland plateau on Vestfirðir striations were measured adjacent to lake basins (Principato and Johnson, 2005; Principato et al., 2006). It was not feasible to visit all lake basins, and aerial photographs were used to examine the morphology of the landscape in sites that could not be visited in the field. The GIS analysis makes extrapolations based on several sites where ground truthing verifies our interpretations. Detailed geomorphic mapping by Kaldal (1978) and Vikingsson (1978) also documents numerous striations on other regions of the study area, providing further credibility to our extrapolations and interpretations of ice scoured bedrock in the study area. Other possible causes for the origin of lake basins, such as moraine dammed lakes and kettle ponds, are eliminated because there are no moraines damming the lakes and minimal or no glacial drift is present adjacent to the lakes. (The only exception to this is on the Skagi Peninsula, which will be discussed later in the manuscript.) Lakes in the study area are also clearly not rift basin lakes because they show no preferred orientation or elongation with the current (or former) rift zone in Iceland. In addition to these justifications that the lakes are created by ice scour, we also compare the lakes in this study with ice scour lakes documented and quantified in other studies in the Arctic (i.e. Sugden, 1978; Andrews et al., 1985; Rea et al., 1998). Despite differences in bedrock geology and geography for each study, ice scour lakes are clearly present in many locations in the Arctic (i.e. Sugden, 1978; Andrews et al., 1985; Rea et al., 1998).

Regional Setting

The study area is located on northwest Iceland, north of the Snæfellsness Peninsula and west of Tröllaskagi (Fig. 1). The study area is subdivided into three regions based on geographic location and topography: Vestfirðir, Skagi, and the northwest mainland of Iceland (abbreviated as mainland).

VESTFIRÐIR

Vestfirðir is connected to the mainland through a neck that is less than 20 km wide. At least 30 fjords are carved into Vestfirðir, the largest of which is Ísafjarðardjúp. Ísafjarðardjúp dissects the center of Vestfirðir and probably contained an ice stream during the LGM (Bourgeois et al., 1998; 2000; Andrews et al., 2002; Geirsdóttir et al., 2002). The fjords and valleys on Vestfirðir lead from two upland plateaus with mean elevations between approximately 400 and 800 m a.s.l. and peaking above 1200 m a.s.l. The geomorphology of the uplands, valleys, and fjords on Vestfirðir defines the Icelandic type of glacial trough (Linton, 1963), which is an area with ice accumulation on a high plateau draining down steep ice falls into valleys that dissect the plateau. The 160 km^2 Drangajökull Ice Cap is located on the high plateau on the eastern part of Vestfirðir (Björnsson, 1979), and the high plateau of Glama on the western part of Vestfirðir does not support a modern ice cap.

Vestfirðir is composed of Upper Tertiary flood basalts with thin interbedded sedimentary layers (Einarsson, 1973; Kristjansson and Jóhannesson, 1994; Hardarson et al., 1997), and it is located more than 150 km from the active rift zones in Iceland (Flovenze and Saemundsson, 1993). There are some small isolated regions with low temperature hot springs, located in the lowland coastal areas, but there are no active volcanoes on Vestfirðir (Flovenze and Saemundsson, 1993).

SKAGI

Skagi is a northern peninsula connected to the mainland of Iceland and is located over 50 km east of Vestirðir. It is separated from Vestfirðir by Húnaflói, a large bay (Fig. 1). A mountainous region is located on the southern part of the peninsula, while the northern part of Skagi has low relief with many lakes. At least some of the lakes on northern Skagi near the coastline are isolation lake basins that formed as relative sea level dropped during deglaciation (Rundgren et al., 1997). The deglacial history of these lakes is examined by Ingólfsson et al. (1997), Rundgren et al. (1997), and Rundgren and Ingólfsson (1999). Skagi is composed of Tertiary basalts and late Pleistocene basaltic rocks (Einarsson and Albertsson, 1988; Kristjansson and Jóhannesson, 1994). The peninsula is located more than 125 km from the active rift zone in Iceland and does not support any active volcanoes.

MAINLAND

The mainland subregion refers to the northwest quadrant of Iceland, north of Langjökull and Hofsjökull and south of the peninsulas of Vestfirðir, Skagi, and Tröllaskagi (Fig. 1). The region studied is located more than 60 km from the active rift zone, although the southern part of this region is the closest of the three subregions to active volcanoes on Iceland. The bedrock geology of the mainland consists of a mixture of Tertiary and late Pleistocene basalts (Einarsson and Albertsson, 1988; Kristjansson and Jóhannesson, 1994). The Snæfellsnes Peninsula was not included in the analyses because that region is an active volcanic area.

Methods

In order to determine patterns of glacial erosion on northwest Iceland, a GIS was used to calculate lake density. Lake density is used as a proxy for glacial erosion following the methods of Sugden (1978) and Andrews et al. (1985). Sugden (1978) defined zones of contrasting basal thermal regime under the Laurentide Ice Sheet and implied that there should be a region of no erosion (i.e., no glacially scoured lakes) underneath the position of former ice divides. Andrews et al. (1985) used topographic maps and LANDSAT imagery to focus on glacial erosion in the Eastern Canadian Arctic using lake basins and distance from coastline as a proxy for ice thickness. Andrews et al. (1985) assumed that the ice sheet margin was parallel to the coastline, with minimal thickness near the coast and increasing thickness landward of the coast. Glacial erosion studies in other regions of the Arctic show that sometimes relict landforms from previous glaciations or young erratics present on top of the bedrock complicate interpretations of glaciation, and we take these factors into consideration in our discussion (Kleman et al., 1992; Kleman, 1994; Kleman and Stroeven, 1997; Briner et al., 2003, 2005). Modeling studies on Iceland by Hubbard et al. (2006) provide interpretations of basal flow velocities, and Bourgeois et al. (2000) proposed ice streams and ice divides. These previous studies on Iceland provide a baseline for us to compare our GIS model of glacial erosion for northwest Iceland, and our fieldwork adds ground truth to proposed models presented in this study and by others.

We quantify the density of lake basins as a proxy for glacial erosion on northwest Iceland using ArcGIS. The GIS analysis is combined with geomorphic mapping on northwest Iceland to add ground truth and provide chronologic constraints. This approach provides an alternative methodology for evaluating glacial erosion on northwest Iceland and assesses the scenarios proposed in ice sheet models (Bourgeois et al., 2000; Hubbard et al., 2006).

GIS INPUT

The two primary sets of GIS data used in this study include hydrographic data and topographic data (Fig. 2). Hydrographic data for northwest Iceland was obtained from the Hydrology Division of the Iceland National Energy Authority with permission of the Iceland Geodetic Survey (Hydrological Service, Orkustofnun, 2003 and 2004). The delivery of hydrography data is from the database of the Hydrological Service, Orkustofnun, Iceland, no. 2004/42 (Jónsdóttir, personal communication). The projection of the data is Lambert conformal conic projection based on the datum of WGS84, and units are in meters. The data set includes streams, lakes, and glaciers, as well as detailed metadata describing lake area, perimeter, and water depth. The hydrographic data were converted into polygon shapefiles using the ArcGIS Desktop Suite. The streams and glaciers were separated from the lake basin hydrographic data because only the lake basins are used as a proxy for glacial scour (Sugden, 1978, Andrews et al., 1985). The hydrographic data also contained the coastline (the boundary line between the land and ocean), which was converted into its own shapefile. A digital elevation model (DEM) for Iceland was derived from ETOPO2 from the National Geophysical Data Center (Fig. 2). The 900 m^2 cell size resolution provides a useful estimation of topographic variation over the study area. Broad categories of elevation are used in the analysis to reduce errors associated with this DEM model.

GIS METHODOLOGY

The GIS analyses were completed using the ArcGIS Desktop Suite. A grid consisting of 25 km^2 cells was generated and clipped to the study area. The analysis was also completed using a 100 km^2 grid, but the resolution of the analysis was much lower. Thus, we focus on the 25 km^2 grid in order to provide more detailed changes in erosion patterns throughout the three regions. Lake density was calculated using two different methods: the first sensitive to the total number of lakes and the second sensitive to total lake area. The first method extracted a centroid of each lake polygon, and summed the number of lake centroids within each 25 km^2 grid cell. The second method calculated the percent lake area (compared to land area) for each 25 km^2 grid cell. The polygon lake shapefile was converted to a raster data set with a cell size of 0.1 km^2. This conversion allowed the percent lake area within each 25 km^2 grid cell to be calculated using the Spatial Analyst extension of ArcGIS.

In addition to lake density, the elevation of each lake was quantified using the ArcGIS Spatial Analyst extension. In order to determine the relationship between elevation and the density of

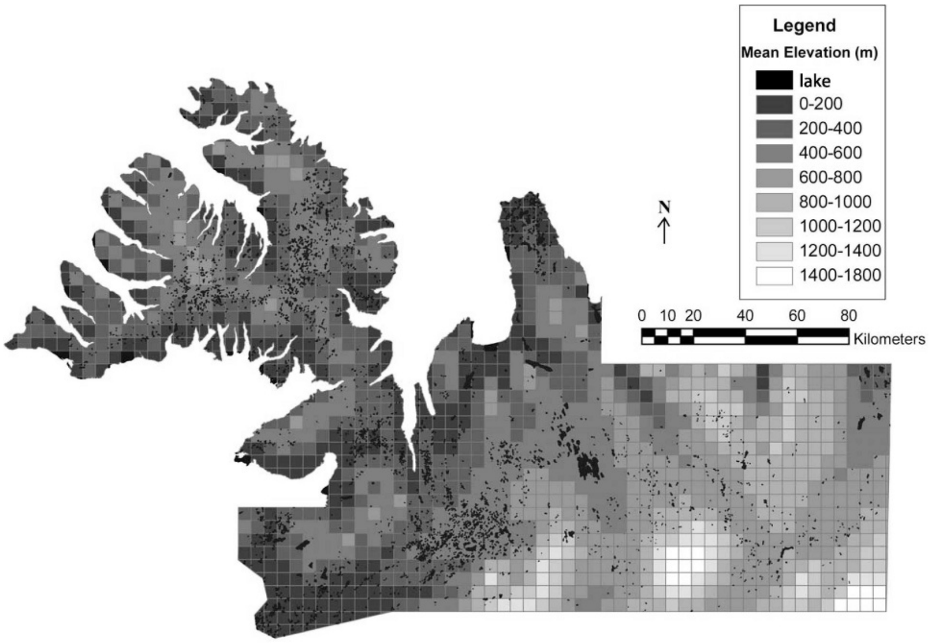


FIGURE 2. The distribution of lakes entered into the GIS and the average elevation for each 25 km^2 grid cell. Gray scale corresponds to elevation classes and black polygons are lakes.

lakes, the mean elevation for each 25 km^2 grid cell was calculated (because the DEM was a different resolution, and all data were converted to raster format). Summary statistics and analyses of Pearson's Product Moment Correlation were used to evaluate the relationship between elevation and lake density.

MAPPING AND GROUND TRUTH

Field mapping and 1:50,000 to 1:250,000 topographic maps provide ground truth to the GIS input data. The locations of lakes in the GIS were cross checked with topographic maps to confirm locations and to ensure that additional lakes were not created as an artifact of the GIS input data. The locations of striations and streamlined landforms were marked in the field using a Garmin GPS unit and entered into the GIS to identify paleo-ice flow directions (Principato, 2003; Principato and Johnson, 2005; Principato et al., 2006). Select bedrock surfaces and moraines in part of the study area were dated using ^{36}Cl exposure dating to provide terrestrial chronology of deglaciation and yield ages ranging in age from the LGM through the Younger Dryas (Principato et al., 2006).

Results

ELEVATION AND SPATIAL DISTRIBUTION OF LAKES

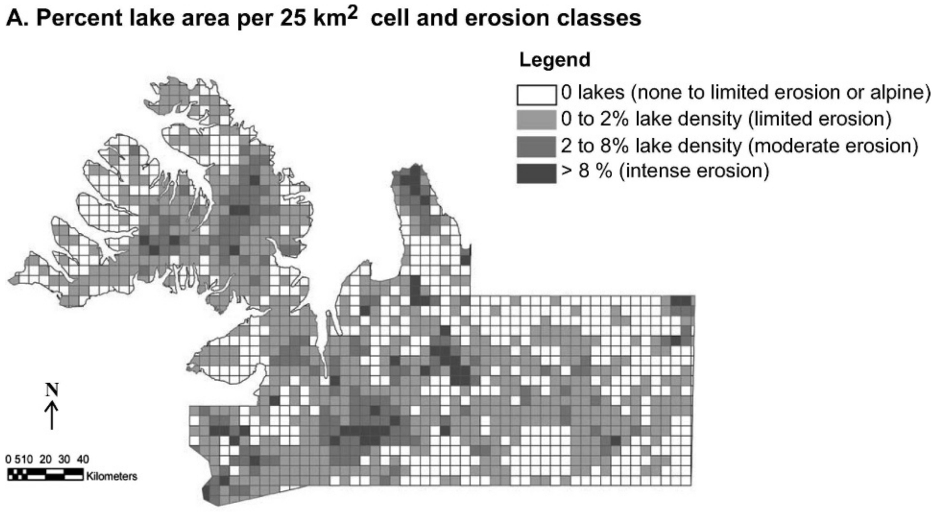
The results for lake density calculated using the two methods are similar, suggesting that differentiating between lake area and number of lakes per grid cell is not an important factor in the analyses (Fig. 3). In order to simplify the discussion of the results and reduce redundancy, we focus on results calculated using percent lake area per 25 km^2 grid cell. The lake density data is positively skewed, with a mean density of 1.22% lake area per grid cell. Analysis of the spatial distribution of lakes across the study area shows at least three regions with high lake density (greater than 8%): central Vestfirðir, the northern coast of Skagi, and the central and northwest mainland (Fig. 3). At least some of the lakes on the northern foreland of Skagi within 5 km of the modern coastline are isolation lake basins and not necessarily created by glacial erosion (Rundgren et al., 1997). Low lake densities (0–2%) are observed in steep alpine areas in all three subregions of the study area, in the land covered by Drangajökull, and in additional cells scattered throughout the study area, especially on the northeast part of the mainland.

Unlike erosional studies of the Laurentide Ice Sheet that are complicated by the contrasting lithologies underlying the Laurentide Ice Sheet (e.g., Davenport et al., 2002), there are no major lithological differences between areas with lakes and areas without lakes on northwest Iceland. Iceland is composed nearly entirely of volcanic rocks, primarily basalt (Einarsson, 1973; Einarsson and Albertsson, 1988; Kristjansson and Jóhannesson, 1994; Hardarson et al., 1997).

LAKE DENSITY AND BASAL EROSION CLASSES

The most intense basal glacial erosion is interpreted from areas with the highest density of ice scour lakes (Fig. 3). The lakes provide evidence for shifts from cold-based to warm-based ice and intense erosion (Boulton, 1972, 1974; Sugden, 1978; Hughes, 1987). The regions with no ice scour lakes are classified by limited to no erosion with the exception of areas that experienced alpine style glaciation (Ingólfsson, 1991; Principato et al., 2006) (Fig. 4). The interpreted relationship between lake density and glacial erosion intensity does not apply in alpine regions where the topography and style of erosion differ from areas overlain by ice sheets. Based on field observations in our study region and numerous studies from other alpine glaciated regions, the alpine areas also clearly experience intense erosion by glaciers and by mass movements and large rock slope failure (Ballantyne, 2002; Jarman, 2002), but these erosional processes are not quantified by our GIS model. Many of the erosional processes in alpine regions are also post-glacial and ongoing, and this is beyond the scope of our study.

The relationship between erosion classes and ice divides over the study area differs from studies of the Laurentide Ice Sheet in the Canadian Arctic (Sugden, 1978; Andrews et al., 1985). In the Canadian Arctic, Sugden (1978) and Andrews et al. (1985) suggested that a zone of low lake density and less intense glacial erosion are present beneath former ice divides. On Vestfirðir, by contrast, the areas interpreted as ice divides by Bourgeois et al.


A. Percent lake area per 25 km^2 cell and erosion classes

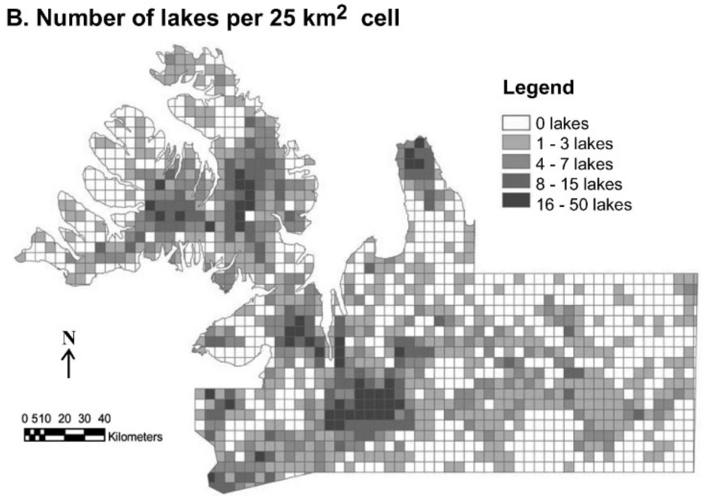

B. Number of lakes per 25 km^2 cell

FIGURE 3. Results from the GIS analyses. (A) Lake density expressed as percent lake area per 25 km^2 grid cell with erosion classes labeled. Zero lakes refers to zones of no erosion or alpine areas that experience erosion not quantified by the GIS model (see Fig. 4). (B) Lake density expressed as number of lakes per 25 km^2 grid cell.

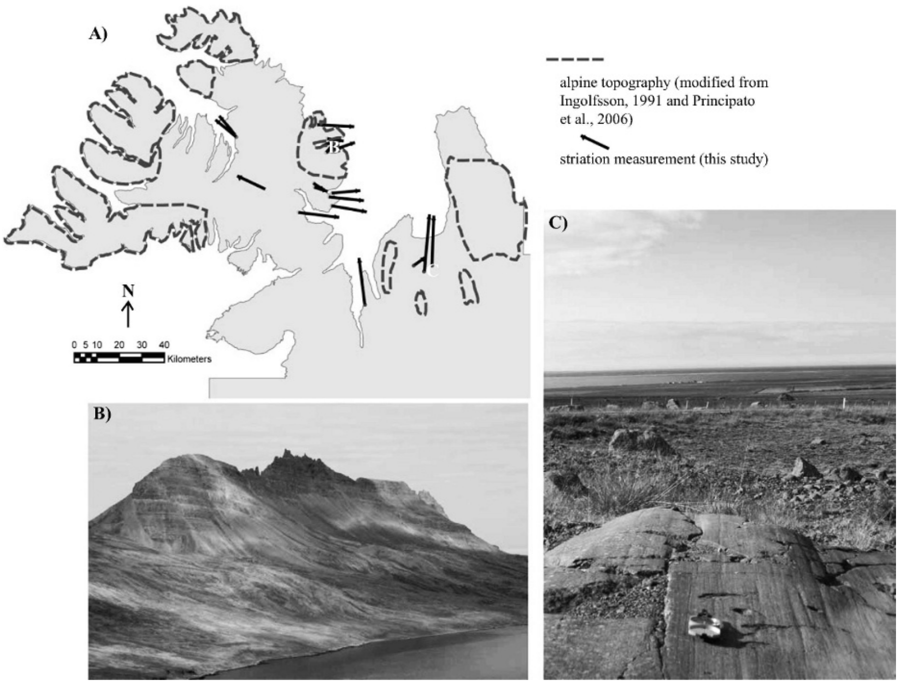


FIGURE 4. (A) Areas of alpine style glaciation and striation measurements (modified from Ingólfsson, 1991, and Principato et al., 2006). High topographic features in the alpine regions are areas that could have been ice-free or covered by cold-based ice during the LGM. (B) View of the bedrock ridge (arête) on the western Húnaflói coast between two fjords. (C) View from striated bedrock looking north towards Húnaflói, with a Brunton compass for scale.

TABLE 1

Statistical results showing the relationship between lake density and elevation calculated using Pearson's Product Moment Correlation.

Location		Elevation (m)	Sample size
Vestfirðir	Number of lakes (per 25 km^2 grid cell)	0.433**	471
Skagi	Number of lakes (per 25 km^2 grid cell)	−0.186	102
Mainland	Number of lakes (per 25 km^2 grid cell)	−0.373**	560

** Correlation is significant at the 0.05 level.

(2000) are based on topography and are areas of high lake density on upland plateau surfaces. On the mainland, areas of high lake density also overlap with parts of the ice divides proposed by Bourgeois et al. (2000), but the overlap is not as complete as on Vestfirðir. Differences between ice divides identified on the mainland by various authors reflect differences in the criteria used (Einarsson and Albertsson, 1988; Bourgeois et al., 1998; Bourgeois et al., 2000; Principato and Johnson, 2005).

GEOMORPHIC MAPPING

Steep peaks and ridges, interpreted as horns and arêtes, dominate the landscape of the western Húnaflói coastal region, which is adjacent to a high upland plateau further inland on Vestfirðir. In contrast, wide valleys, ice sculpted bedrock, and thick deposits of diamicton, are present on parts of the southern Húnaflói coastal region, and large scale lineations are visible from aerial photographs and satellite images (Principato and Johnson, 2005). The dramatic geomorphic differences evident on the mainland, south of Húnaflói, as compared with Vestfirðir, west of Húnaflói, suggest different styles of glaciation modified each region. Areas of alpine glaciation are noted on both Vestfirðir and the Skagi Peninsula (Ingólfsson, 1991; Principato et al., 2006) (Fig. 4). Striations are present on the upland plateau on Vestfirðir and on topographically low bedrock surfaces on all three subregions of the study area and provide evidence for ice flow paths (Fig. 4) (Kaldal, 1978; Vikingsson, 1978; Principato, 2003).

STATISTICAL ANALYSES

Bivariate correlations were computed using Pearson's Product Moment Correlation to test the hypothesis that there is a linear relationship between lake density and elevation in the three regions (Table 1). According to the statistical results, on Vestfirðir, there is a positive linear relationship, with lake density increasing as a function of increasing elevation. On the mainland, there is a weak negative correlation between lake density and elevation, which shows that lake density decreases with increasing elevation. There is no statistically significant correlation between lake density and elevation on the Skagi Peninsula.

Discussion

INTERPRETATION OF EROSION CLASSES AND BASAL FLOW REGIME

Bedrock basins and lakes associated with ice scouring typically form subglacially in the zone where there is a transition between cold-based and warm-based ice, and plucking occurs (Boulton 1972, 1974; Sugden, 1978; Hughes, 1987). In addition, there are sometimes more complicated scenarios, where regions covered by cold-based ice during the LGM contain either relict landforms from previous glaciations or young erratics present on top of the bedrock (Kleman et al., 1992; Kleman, 1994; Kleman and Stroeven, 1997; Briner et al., 2003, 2005). On northwest Iceland, regions with many lakes are interpreted to be the result of intense glacier erosion associated with former thermal boundaries between warm- and cold-based ice following the models proposed for other formerly glaciated regions by Sugden (1978), Andrews et al. (1985), and Rea et al. (1998) (Fig. 3). Striations and roches moutonnées mapped during fieldwork provide evidence for paleo-ice flow directions at these sites, and the primary ice flow direction is parallel to the axes of fjords and valleys, but crossing striations are present in at least one locality on eastern Vestfirðir (Principato, 2000; Principato et al., 2006) (Fig. 4). The ice flow indicators also provide supporting field evidence for active abrasion and plucking, which is normally associated with warm-based ice (Linton, 1963; Boulton, 1979; Drewry, 1986; Dionne, 1987; Sugden et al., 1992). Areas of low lake density on northwest Iceland are typically inferred to represent areas that were either ice free or covered by cold-based or non-erosive ice during the LGM. The presence of glacial erratics on part of the upland plateaus confirms ice cover in at least some of the locations (Principato et al., 2006). Alpine regions exhibit low lake density. However, lake density in the alpine areas is not considered to represent areas with no erosion for reasons discussed earlier. In addition, ^{36}Cl exposure age dating suggests that at least some of the alpine areas were ice-free and/or covered by cold-based ice during the LGM (Principato et al., 2006).

The geothermal gradient is relatively high under Iceland (Flovenze and Saemundsson, 1993), and this plays a role in glacial sliding in at least some parts of Iceland (Bourgeois et al., 1998, 2000). The geothermal gradient is highest near the active volcanic rift zone and decreases with distance from the spreading axis (Flovenze and Saemundsson, 1993). The northwest quadrant of Iceland does not experience active volcanic activity and did not experience volcanic activity during the LGM. The GIS analyses demonstrate that there is no relationship between the location of lakes and the minor geothermal activity on northwest Iceland.

In addition to differences in lake density across the study area, there are other large scale geomorphic differences. The presence of horns and arêtes on parts of Vestfirðir and Skagi suggests that nunataks were present at least on the northern and northwestern peninsulas of Iceland during the LGM (Rundgren and Ingólfsson, 1999; Principato et al., 2003, 2006; Principato and Johnson, 2005; Hubbard et al., 2006). In contrast, the area south of Húnaflói on the mainland is dominated by wide valleys and rounded uplands covered by thin till, although some alpine features are present on the northern Hvammstangi peninsula (Principato and Johnson, 2005). The landscape adjacent to southern Húnaflói contains ice molded bedrock, large scale lineations, and striated surfaces that indicate there was a large ice flux and possible an ice stream through Húnaflói, as suggested by Bourgeois et al. (2000) and Andrews and Helgadóttir (2003). Based on geomorphic mapping and cosmogenic isotope exposure ages on Vestfirðir (Principato et al., 2006), the ice extent is inferred

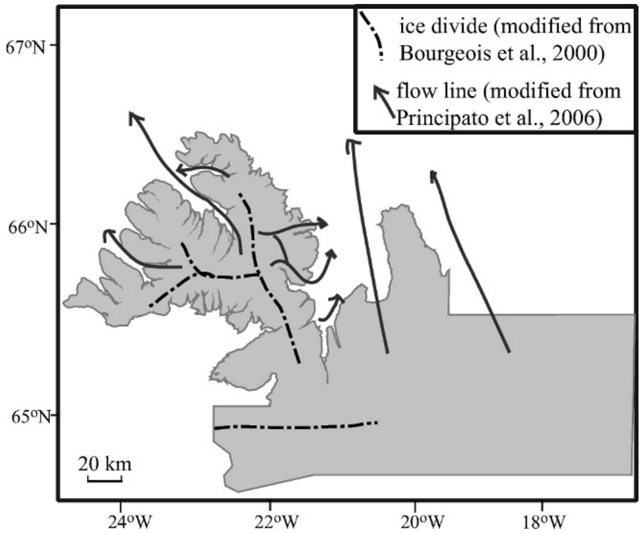


FIGURE 5. Ice divides and ice flow paths (modified from Bourgeois et al., 2000; Principato et al., 2006).

to be more restricted on eastern Vestfirðir while ice flowing from the mainland through southern Húnaflói was more extensive.

LOCATION OF ICE DIVIDES

The location of presumed ice scour lakes on the uplands of Vestfirðir underneath an ice divide proposed by Bourgeois et al. (2000) is perplexing (Fig. 5). The model by Bourgeois et al. (2000) is based primarily on topographic controls with ice divides located on topographic highs with channeling of ice by the major valleys and fjord systems. However, this region experienced multiple glaciations during the Pleistocene (Eiríksson and Geirsdóttir, 1991; Geirsdóttir and Eiríksson, 1994), and it is possible that at some time during the Pleistocene the ice was thick enough to scour these surfaces and flow independent of the underlying valleys. It is likely that warm-based ice was present on the upland surfaces at some time during the Pleistocene. The striations adjacent to lake basins at approximately 450 m a.s.l. on eastern Vestfirðir (Principato and Johnson, 2005; Principato et al., 2006) demonstrate that ice scour occurred on the uplands at least on eastern Vestfirðir. Although we interpret that the origin of lakes is from ice scour based on field and aerial photograph evidence and by eliminating other possible causes for the origin of the lakes, if our interpretations are incorrect then another possible scenario is that the lakes on the uplands originated from non-glacial processes and have been overrun and only lightly modified by ice. It is also possible that ice scour occurred beneath ice divides in this topographic setting or that the proposed ice divide locations are incorrect. In order to fully understand the relationship between lakes on uplands and proposed ice divide locations, additional fieldwork and cosmogenic isotope exposure dating is needed to determine the timing of ice scour on these surfaces and determine rates of erosion on the upland plateau.

IMPLICATIONS FOR INDEPENDENT ICE SHEETS

The results of this study provide at least three lines of evidence that support the interpretation of two independent ice sheets on northwest Iceland during the LGM: one on Vestfirðir and one on the mainland of Iceland (Hoppe, 1982; Norðdahl, 1991). First, there are different patterns of glacial erosion on the mainland that contrast with Vestfirðir, suggesting that the different ice sheet configurations impacted each region uniquely. Second, the narrow neck that connects Vestfirðir to the mainland contains minimal to no lakes (0–2%). The lack of ice scour lakes on the neck region suggests that there was minimal basal glacial erosion, which could be interpreted as an ice-free region or an area covered by cold-based ice. (However, steep slopes in some coastal regions of the neck inhibit lake development.) Third, geomorphic mapping and a cosmogenic isotope exposure date provide evidence that parts of Vestfirðir were ice-free or covered by cold-based ice during the LGM and limit the timing of potential coalescence of ice from Vestfirðir and the mainland in Húnaflói to before 24 ka B.P. (Principato et al., 2006). Previous work on Hornstrandir on the northern tip of Vestfirðir by Hjort et al. (1985) and on eastern Vestfirðir by Principato et al. (2006) suggest limited ice extent on Vestfirðir, while marine core studies suggest that extensive ice filled Húnaflói and flowed towards the shelf break (Andrews et al., 2000; Andrews and Helgadóttir, 2003). The contrasting scenarios of ice extent from Vestfirðir and the mainland support the interpretation that an independent ice cap covered Vestfirðir, while the mainland of Iceland was covered by a larger ice sheet. However, it is also possible that the ice on Vestfirðir was thicker and more extensive when the ice scour lakes were created, and then more restricted during the LGM. Increased dating control and provenance studies are needed to determine the extent and timing of the coalescence of the two ice sheets in Húnaflói and to further constrain the timing of deglaciation.

Previous work on Skagi by Rundgren and Ingólfsson (1999) suggests the presence of ice-free regions, and alpine style glaciation is documented on Skagi (Ingólfsson, 1991). Limited ice flux from both Skagi and Vestfirðir requires that a larger proportion of the ice discharging into Húnaflói originated from the mainland of Iceland. The pattern of ice scour lakes and the wide valleys with striated and ice sculpted bedrock south of Húnaflói support the scenario that increased ice flux from the mainland extended to the glacial margin identified from marine core studies (Andrews et al., 2000; Andrews and Helgadóttir, 2003). If the ice feeding the shelf was derived primarily from the mainland Icelandic ice sheet, then it is possible that during the LGM an independent ice cap with a more restricted extent covered Vestfirðir. Increased dating control on bedrock surfaces from the three subregions of this study are required in order to provide additional chronologic constraints to the extent of ice cover and the patterns of glacial erosion over the study area during the LGM. However, even without increased chronologic constraints, the GIS analyses provide important clues to the reconstruction of ice covering the study area by identifying patterns of glacial erosion.

NORTH ATLANTIC REGIONAL IMPORTANCE

Sediments in marine cores recovered several degrees of latitude south of Iceland are interpreted to have originated from Iceland, and the cores record several episodes of increased iceberg discharge from Iceland during the late Quaternary (Bond and Lotti, 1995; Elliot et al., 1998). A better understanding of the dynamics and configuration of ice on northwest Iceland helps determine the potential contributions of Icelandic glacial ice to the North Atlantic and provides subglacial boundary conditions for ice sheet models. The GIS and geomorphic results from this study provide terrestrial evidence for a large ice flux derived from southern Húnaflói, and support the model of at least one ice stream proposed by Bourgeois et al. (2000). The results of this study also suggest that reconstruction of ice cover on northwest Iceland with one large, inundating ice sheet is an oversimplification. Because the ice covering northwest Iceland responds to changes in climate in the North Atlantic region, the ice configuration and patterns of glacial erosion are not simple localized signals of past climate fluctuations. They provide important information and ground truth for ice sheet models and paleoclimate reconstructions.

Conclusions

This study presents the first GIS analysis of glacial erosion patterns on northwest Iceland with the intensity of erosion interpreted from the density of ice scour lakes. The areas with the highest density of ice scour lakes are located on the upland plateau of Vestfirðir, the west-central mainland of Iceland, and the northern part of Skagi (although some lakes adjacent to the coast on Skagi are isolation basins). On Vestfirðir, the region of high lake density overlaps with the location of inferred former ice divides (Bourgeois et al., 2000), which differs from patterns reported from the Laurentide Ice Sheet (Sugden, 1978; Andrews et al., 1985). The patterns of glacial erosion provide evidence for two independent ice sheets: one on Vestfirðir and one on the mainland of Iceland. Areas of alpine glaciation and the presence of nunataks support interpretations that ice-free regions or cold-based ice cover existed on parts of Iceland during the LGM.

Measuring the density of ice scour lakes provides a low cost and efficient method for interpreting paleo-subglacial conditions and provides important information required to understand past ice sheet configuration. The methods developed in this study to quantify the density of ice scour lakes and interpret glacial erosion are broadly applicable and could be used in other formerly glaciated regions. In addition, zones of glacial erosion provide important boundary conditions for glaciological models.

Acknowledgments

This project was funded by a Gettysburg College Research and Professional Development Grant. We gratefully acknowledge Jóna Finndís Jónsdóttir and Jórunn Hardardóttir at the Hydrology Division of the Iceland National Energy Authority for the hydrographic GIS data and for help with translation of the data. Discussions with John T. Andrews on an earlier pilot study provided inspiration for this project. Rud Platt is also thanked for assistance with GIS procedures. Saedís Ólafsdóttir, Meghan Flynn, Kristin Igusky, and Tess Barton assisted in the field. The comments of two anonymous reviewers, the Associate Editor, and the Editor on an earlier version of this manuscript are appreciated.

References Cited

Andrews, J. T., 2005: Late Quaternary marine sediment studies of the Iceland shelf—Palaeoceanography, land/ice sheet/ocean interactions and deglaciation: a review. *In* Caseldine, C., Russell, A., Hardardóttir, J., and Knudsen, O. (eds.), *Iceland—Modern Processes and Past Environments.* Developments in Quaternary Science 5. Amsterdam, Netherlands: Elsevier B.V., 5–24.

Andrews, J. T., and Helgadóttir, G., 2003: Late Quaternary ice extent and deglaciation of Hunafloaall, north Iceland: evidence from marine cores. *Arctic, Antarctic, and Alpine Research*, 35: 218–232.

Andrews, J. T., Clark, P., and Stravers, J. A., 1985: The patterns of glacial erosion across the Canadian Arctic. *In* Andrews, J. T. (ed.), *Quaternary Environments: Eastern Canadian Arctic, Baffin Bay, and West Greenland*. London: Allen and Unwin, 69–92.

Andrews, J. T., Hardardóttir, J., Helgadóttir, G., Jennings, A. E., Geirsdóttir, A., Sveinbjornsdóttir, A. E., Schoolfield, S., Kristjansdóttir, G. B., Smith, L. M., Thors, K., and Syvitski, J. P. M., 2000: The north and west Iceland Shelf: insights into Last Glacial Maximum ice extent and deglaciation based on acoustic stratigraphy and basal radiocarbon AMS dates. *Quaternary Science Reviews*, 19: 619–631.

Andrews, J. T., Hardardóttir, J., Geirsdóttir, A., and Helgadóttir, G., 2002: Late Quaternary ice extent and glacial history from the Djúpáll trough, off Vestfirðir peninsula, northwest Iceland: a stacked 36 cal ky environmental record. *Polar Research*, 21: 211–226.

Balascio, N. L., Kaufman, D. S., Briner, J. P., and Manley, W. F., 2005: Late Pleistocene glacial geology of the Okpilak-Kongakut Rivers region, northeastern Brooks Range, Alaska. *Arctic, Antarctic, and Alpine Research*, 37: 416–424.

Ballantyne, C. K., 2002: Paraglacial geomorphology. *Quaternary Science Reviews*, 21: 1935–2017.

Björnsson, H., 1979: Glaciers in Iceland. *Jökull*, 29: 74–80.

Bond, G. C., and Lotti, R., 1995: Iceberg discharges into the North Atlantic on millennial time scales during the last glaciation. *Science*, 267: 1005–1009.

Boulton, G. S., 1972: The role of thermal regime in glacial sedimentation. *Polar Geomorphology*, Special Publication—Institute of British Geographers, London, 4: 1–19.

Boulton, G. S., 1974: Processes and patterns of glacial erosion. *In* Coates, D. (ed.), *Glacial Geomorphology: Proceedings of the 5th Geomorphology Symposium*. Binghamton, New York, 41–87.

Boulton, G. S., 1979: Processes of glacier erosion on different substrata. *Journal of Glaciology*, 23: 15–37.

Boulton, G. S., 1986: Push-moraines and glacier-contact fans in terrestrial and marine environments. *Sedimentology*, 33: 677–698.

Boulton, G. S., Thors, K., and Jarvis, J., 1988: Dispersal of glacially derived sediment over part of the continental shelf of South Iceland and the geometry of the resultant sediment bodies. *Marine Geology*, 83: 193–223.

Bourgeois, O., Dauteuil, O., and van Vliet-Lanoe, B., 1998: Pleistocene subglacial volcanism in Iceland: tectonic implications. *Earth and Planetary Science Letters*, 164: 165–178.

Bourgeois, O., Dauteuil, O., and van Vliet-Lanoe, B., 2000: Geothermal control on flow patterns in the Last Glacial Maximum ice sheet of Iceland. *Earth Surface Processes and Landforms*, 25: 59–76.

Bradwell, T., Dugmore, A. J., and Sugden, D. E., 2006: The Little Ice Age glacier maximum in Iceland and the North Atlantic Oscillation: evidence from Lambatungnajokull, southeast Iceland. *Boreas*, 35: 61–80.

Briner, J. P., Miller, G. H., Davis, T., Bierman, P. R., and Caffee, M., 2003: Last Glacial Maximum ice dynamics in Arctic Canada inferred from young erratics perched on ancient tors. *Quaternary Science Reviews*, 22: 437–444.

Briner, J. P., Miller, G. H., Davis, T., and Finkel, R. C., 2005: Cosmogenic exposure dating in arctic glacial landscapes: implications for the glacial history of northeastern Baffin Island, Arctic Canada. *Canadian Journal of Earth Sciences*, 42: 67–84.

Buckland, P., and Dugmore, A., 1991: If this is a refugia, then why are my feet so bloody cold? *In* Caseldine, C., and Maizels, J. K. (eds.), *Environmental Change in Iceland: Past and Present*. Dordrecht, Netherlands: Kluwer Academic Publishers, 107–125.

Davenport, P., Boisvert, E., Quat, M., Okulitch, A., Brodaric, B., Colman-Sadd, S., Nolan, L., Struik, B., MacIntyre, D., Tzeng, P., Scott, D., Gilbert, C., Abbott, G., Bassan, A., Journeay, M., Francis, J., and Houlahan, T., 2002: A scalable, digital map database of bedrock geology for Canada; a progress report. *U.S. Geological Survey Open-File Report* OF 02-0370, 47–66.

Dionne, J. C., 1987: Tadpole rock (rock drumlin); a glacial streamline moulded form. *In* Menzies, J., and Rose, J. (eds.), *Drumlin Symposium*. Rotterdam: Balkema, 149–159.

Drewry, D. J., 1986: *Glacial Geologic Processes*. London: Edward Arnold, 276 pp.

Egloff, J., and Johnson, G. L., 1979: Erosional and depositional structures of the Southwest Iceland insular margin; thirteen geophysical profiles. *In* Watkins, J. S., Montadert, L., and Dickerson, P. W. (eds.), *Geological and Geophysical Investigations of Continental Margins*. Tulsa: American Association of Petroleum Geologists Memoir, 29: 43–63.

Einarsson, T., 1973: Geology of Iceland. *In* Pitcher, M. G. (ed.), *Arctic Geology*. Tulsa: American Association of Petroleum Geologists Memoir, 19: 171–175.

Einarsson, T., and Albertsson, K. J., 1988: The glacial history in Iceland during the past three million years. *Philosophical Transactions of the Royal Society of London, B*, 318: 637–644.

Eiríksson, J., and Geirsdóttir, A., 1991: A record of Pliocene and Pleistocene glaciations and climatic changes in the North Atlantic based on variations in volcanic and sedimentary facies in Iceland. *Marine Geology*, 101: 147–159.

Eiríksson, J., Knudsen, K. L., Haflidason, H., and Henriksen, P., 2000: Late-glacial and Holocene paleoceanography of the North Iceland Shelf. *Journal of Quaternary Science*, 15: 23–42.

Elliot, M., Labeyrie, L., Bond, G., Cortijo, E., Turon, J. L., Tisnerat, N., and Duplessy, J. C., 1998: Millennial-scale iceberg discharges in the Irminger Basin during the last glacial period: relationship with the Heinrich events and environmental settings. *Paleoceanography*, 13: 433–446.

Fabel, D., Stroeven, A., Harbor, J., Kleman, J., Elmore, D., and Fink, D., 2002: Landscape preservation under Fennoscandian ice sheets determined from in situ production of ^{10}Be and ^{26}Al. *Earth and Planetary Science Letters*, 201: 397–406.

Flovenze, O. G., and Saemundsson, K., 1993: Heat flow and geothermal processes in Iceland. *Tectonophysics*, 225: 123–138.

Geirsdóttir, Á., and Eiríksson, J., 1994: Growth of an intermittent ice sheet in Iceland during the late Pliocene and early Pleistocene. *Quaternary Research*, 42: 115–130.

Geirsdóttir, Á., Andrews, J. T., Helgadóttir, G., Olafsdóttir, S., and Hardardóttir, J., 2002: A 36 ky record of iceberg rafting and sedimentation from north-west Iceland. *Polar Research*, 21: 291–298.

Greenwood, S. L., Clark, C. D., and Hughes, A. L. C., 2007: Formalising an inversion methodology for reconstructing ice-sheet retreat patterns from meltwater channels; application to the British ice sheet. *Journal of Quaternary Science*, 22: 637–645.

Harbor, J., Stroeven, A. P., Fabel, D., Clarhall, A., Kleman, J., Li, Y., Elmore, D., and Fink, D., 2006: Cosmogenic nuclide evidence for minimal erosion across two subglacial sliding boundaries of the late glacial Fennoscandian ice sheet. *Geomorphology*, 75: 90–99.

Hardarson, B. S., Fitton, J. G., Ellam, R. M., and Pringle, M. S., 1997: Rift relocation; a geochemical and geochronological investigation of a palaeo-rift in Northwest Iceland. *Earth and Planetary Science Letters*, 153: 181–196.

Hjort, C., Norðdahl, H., and Ingólfsson, O., 1985: Late Quaternary geology and glacial history of Hornstrandir, Northwest Iceland: a reconnaissance study. *Jökull*, 35: 9–29.

Hoppe, G., 1982: The extent of the last inland ice sheet of Iceland. *Jökull*, 32: 3–11.

Hubbard, A., Sugden, D., Dugmore, A., Norðdahl, H., and Petursson, H. G., 2006: A modeling insight into the Icelandic Last Glacial Maximum ice sheet. *Quaternary Science Reviews*, 25: 2283–2296.

Hughes, T., 1987: Ice dynamics and deglaciation models when ice sheets collapsed. *In* Ruddiman, W. F., and Wright, H. E., Jr., (eds.), *North America and Adjacent Oceans during the Last Deglaciation. The Geology of North America*. Boulder: Geological Society of America, 183–220.

Ingólfsson, O., 1991: A review of the Late Weichselian and Early Holocene glacial and environmental history of Iceland. *In* Caseldine, C., and Maizels, J. K. (eds.), *Environmental Change in Iceland: Past and Present*. Dordrecht, Netherlands: Kluwer Academic Publishers, 13–29.

Ingólfsson, O., Bjorck, S., Haflidason, H., and Rundgren, M., 1997: Glacial and climatic events in Iceland reflecting regional North Atlantic climatic shifts during the Pleistocene-Holocene Transition. *Quaternary Science Reviews*, 16: 1135–1144.

Jarman, D., 2002: Rock slope failure and landscape evolution in the Caledonian Mountains, as exemplified in the Abisko Area, Northern Sweden. *Geografiska Annaler*, 84A: 213–224.

Kaldal, I., 1978: The deglaciation of the area north and northeast of Hofsjökull, Central Iceland. *Jökull*, 28: 18–31.

Kaplan, M. R., Miller, G. H., and Steig, E., 2001: Low-gradient outlet glaciers (ice streams?) drained the Laurentide ice sheet. *Geology*, 29: 343–346.

Kleman, J., 1994: Preservation of landforms under ice sheets and ice caps. *Geomorphology*, 9: 19–32.

Kleman, J., and Stroeven, A. P., 1997: Preglacial surface remnants and Quaternary glacial regimes in northwestern Sweden. *Geomorphology*, 19: 35–54.

Kleman, J., Borgtrom, I., Robertsson, A. M., and Lillieskold, M., 1992: Morphology and stratigraphy from several deglaciations in the Transtrand Mountains, western Sweden. *Journal of Quaternary Science*, 7: 1–17.

Kristjansson, L., and Jóhannesson, H., 1994: Stratigraphy and paleomagnetism of the lava pile south of Isafjardardjup, NW Iceland. *Jökull*, 44: 3–16.

Larusson, L., 1983: *Aspects of the Glacial Geomorphology of the Vestfirðir Peninsula of Northwest Iceland with Particular Reference to the Vestur-Isafjardarsysla Area*. Ph.D. thesis. University of Durham, Durham, U.K., 322 pp.

Li, Y., Harbor, J., Stroeven, A. P., Fabel, D., Kleman, J., Fink, D., and Caffee, M., 2005: Ice sheet erosion patterns in valley systems in northern Sweden investigated using cosmogenic nuclides. *Earth Surface Processes and Landforms*, 30: 1039–1049.

Li, Y., Napieralski, J., Harbor, J., and Hubbard, A., 2007: Identifying patterns of correspondence between modeled flow directions and field evidence: an automated flow direction analysis. *Computers and Geoscience*, 33: 141–150.

Linton, D. L., 1963: The forms of glacial erosion. *Institute of British Geographers Publications, Transactions, and Papers*, 33: 1–28.

Malmberg, S. A., 1969: Hydrographic changes in the waters between Iceland and Jan Mayen in the last decade. *Jökull*, 19: 30–43.

Malmberg, S. A., 1985: The water masses between Iceland and Greenland. *Journal of Marine Research Institute*, 9: 127–140.

Marshall, S. J., Tarasov, L., Clarke, G., and Peltier, W., 2000: Glaciological reconstruction of the Laurentide Ice Sheet: physical processes and modeling challenges. *Canadian Journal of Earth Sciences*, 37: 769–793.

Napieralski, J., Hubbard, A., Li, Y., Harbor, J., Stroeven, A. P., Kleman, J., Alm, G., and Jansson, K. N., 2007: Towards a GIS assessment of numerical ice-sheet model performance using geomorphological data. *Journal of Glaciology*, 53: 71–83.

Norðdahl, H., 1991: Late Weichselian and Early Holocene deglaciation history of Iceland. *Jökull*, 40: 27–48.

Olafsdóttir, Th., 1975: Jökulgardar a sjavarbotni ut af Breifdadirdi [A moraine ridge on the Icelandic shelf, west of Breidafjordur]. *Natturufraedingurinn*, 45: 31–36 (in Icelandic).

Principato, S. M., 2000: Glacial geology of Reykjarfjördur, N. Iceland. *Geological Society of America Programs with Abstracts*, 32: 18–19.

Principato, S. M., 2003: *The Late Quaternary History of Eastern Vestfirðir, NW Iceland*. Ph.D. dissertation. University of Colorado, Boulder, 258 pp.

Principato, S. M., and Johnson, J. S., 2005: Geomorphic evidence for independent icecaps on northwest Iceland. *Geological Society of America Programs with Abstracts*, 37: 423.

Principato, S. M., Geirsdóttir, A., Andrews, J. T., and Johannsdóttir, G., 2003: The deglacial history of eastern Vestfirðir, NW Iceland. *Geological Society of America Programs with Abstracts*, 35: 109.

Principato, S. M., Jennings, A. E., Kristjansdóttir, G. B., and Andrews, J. T., 2005: A comparison of diamicton units from the SW and N Iceland Shelf: implications for the glacial history of Iceland. *Journal of Sedimentary Research*, 75: 968–983.

Principato, S. M., Geirsdóttir, A., Jóhannsdóttir, G., and Andrews, J. T., 2006: Late Quaternary glacial and deglacial history of eastern Vestfirðir, Iceland, using cosmogenic isotope (^{36}Cl) exposure ages and marine cores. *Journal of Quaternary Science*, 21: 271–285.

Rea, B. R., Whalley, W. B., Evans, D., Gordon, J., and McDougall, D., 1998: Plateau icefields: geomorphology and dynamics. *In* Owen, L. A. (ed.), *Mountain Glaciation, Quaternary Proceedings 6*. Chichester: John Wiley & Sons Ltd., 35–54.

Ruddiman, W. F., and McIntyre, A., 1981: The North Atlantic Ocean during the last deglaciation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 35: 145–214.

Rundgren, M., and Ingólfsson, O., 1999: Plant survival in Iceland during periods of glaciation? *Journal of Biogeography*, 26: 387–396.

Rundgren, M., Ingólfsson, O., Bjork, S., Jiang, H., and Haflidason, H., 1997: Dynamic sea-level change during the last deglaciation of northern Iceland. *Boreas*, 26: 201–215.

Schneider, C., Schnirch, M., Acuna, C., Casassa, G., and Kilian, R., 2007: Glacier inventory of the Gran Campo Nevado ice cap in the Southern Andes and glacier changes observed during recent decades. *Global and Planetary Change*, 59: 87–100.

Stotter, J., Wastl, M., Caseldine, C., and Haberle, T., 1999: Holocene paleoclimatic reconstructions in Northern Iceland: approaches and results. *Quaternary Science Reviews*, 18: 457–474.

Sugden, D. E., 1978: Glacial erosion by the Laurentide Ice Sheet. *Journal of Glaciology*, 20: 367–391.

Sugden, D. E., Glasser, N. F., and Clapperton, C. M., 1992: Evolution of large roches moutonnées. *Geografiska Annaler*, 74A: 253–264.

Syvitski, J. P. M., Jennings, A. E., and Andrews, J. T., 1999: High-resolution seismic evidence for multiple glaciation across the Southwest Iceland shelf. *Arctic, Antarctic, and Alpine Research*, 31: 50–57.

Vikingsson, S., 1978: The deglaciation of the southern part of the Skagafjördur district, Northern Iceland. *Jökull*, 28: 1–17.

MS accepted September 2008