The Little Ice Age in the North Atlantic Region

Part VIII: Geologic Observations

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Abstract

Earlier papers in this series addressed the climatology and historic observations of the Medieval Warm Period and Little Ice Age and how the data obtained from the Little Ice Age should constrain our study of climate change and our speculations regarding previous glaciations. In this final paper of the series, geologic observations resulting from the Little Ice Age are presented. As climatologic observations from recent centuries should constrain paleoclimatology, so also should geologic observations from Little Ice Age deposits constrain our interpretation of apparently glacial deposits elsewhere.

Extent of Glaciation

In most places where continental glaciation is inferred to have taken place, the Little Ice Age was orders of magnitude less in its effects. In our study area (Figure 1), this is also true, but much less so than in many parts of the world. In Iceland, especially, the Little Ice Age produced observed impacts to landforms on a scale much closer to the effects from the inferred Great Ice Age. In general, the extent of glaciers in Iceland during the Little Ice Age duplicated the maximum previous extent based on locations of terminal moraines (Grove, 1988; McKinzey et al., 2005), though it is widely speculated that at least once in its history, Iceland was nearly covered with ice, which extended off the coast (Símonarson, 1980). In some cases, Little Ice Age advances overran these features (Evans and Twigg, 2002). In other cases, the Little Ice Age maximum extent fell short of terminal moraines (Grove, 1988; Haberle, 1991; but note disputed dates, e.g. Ives, 2007). Data from Norway and Greenland (see Klevberg and Oard, 2012b; 2014a) are less conclusive than the Icelandic data but generally in close agreement. In some other parts of the world (e.g., northern part of Canadian Rockies, Cascades, Himalayas), Little Ice Age advances apparently fell short of previous glacier terminal positions; these are generally continental environments, not maritime. Maritime climates would more adequately simulate the likely climatic conditions in the early postdiluvian period when warm oceans would have produced abundant moisture (Oard, 1990).

Applicability of Little Ice Age Observations

As the extent of Little Ice Age glaciation in parts of the study area was similar to previous (Great Ice Age) glaciation, geologic work can in general be inferred to have been similar in these locations, and we have paid particular attention to Iceland. Higher rates of work may have

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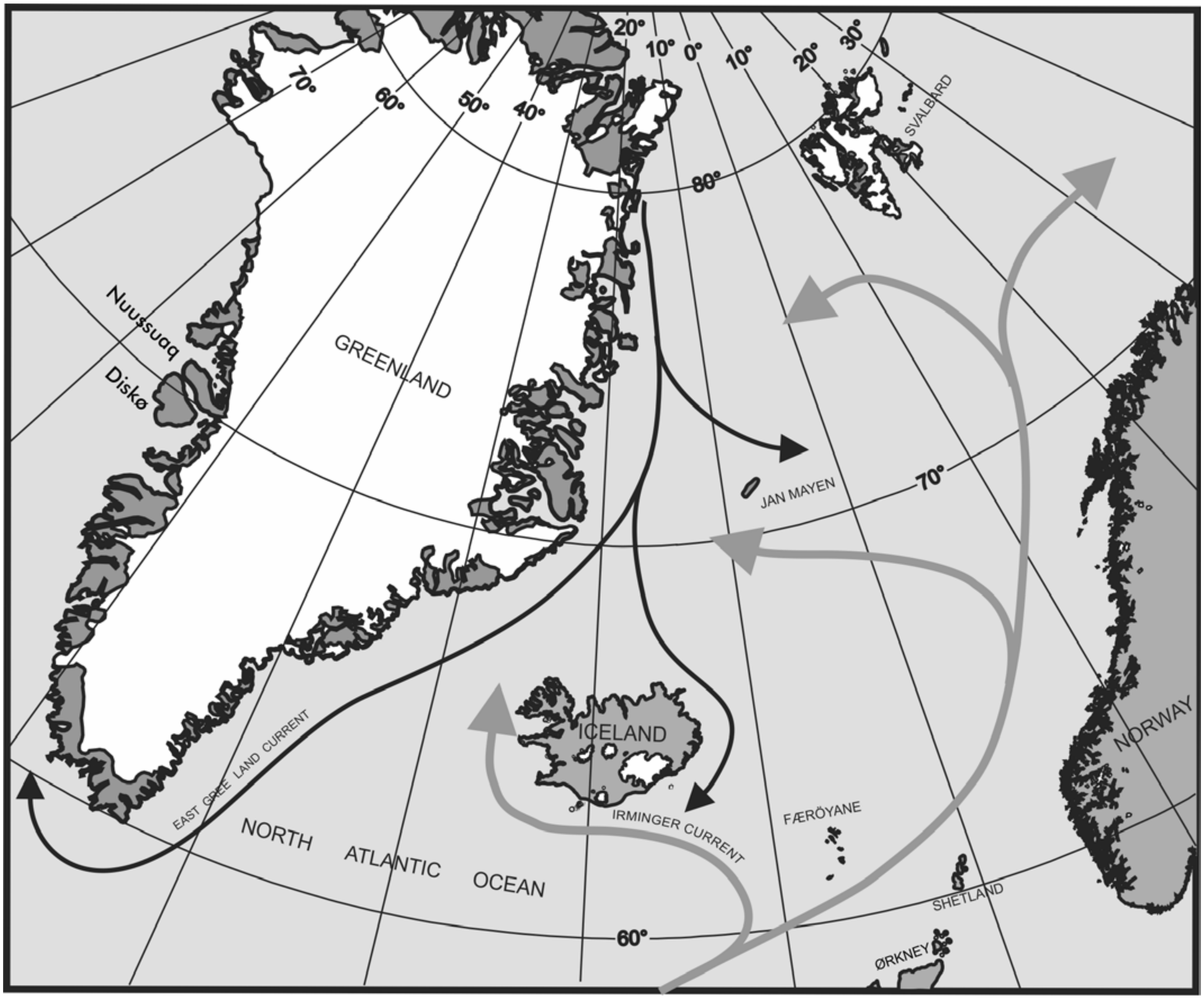

Figure 1. Map of study area.

resulted from higher rates of accumulation and transport, as well as more rapid melting, but the types of deposits and landforms created tend to be similar. For those unfamiliar with glacial landforms, a detour to the glossary and Appendix A may be in order. The aerial photographs in Appendix A are from southeastern Iceland and show many features that are documented to have formed during the Little Ice Age.

Geologic work can be conveniently categorized as erosional and depositional, though specific processes often erode and then deposit sediments. Effects can also be classified as deposits and landforms. Since glacial advances are prone to destroy previous landforms, many of the data available in glacial geology are derived from extant processes observed during the recession of glaciers that commenced at the end of the Little Ice Age.

The first paper in this series (Klevberg and Oard, 2011a) summarized paleoclimatic methods and the superiority of good historical records when these are available. While dates vary both by defining criteria and region (Klevberg and Oard, 2011b), the Little Ice Age in the study area lasted from approximately AD 1350 to 1890. All dates in this paper are therefore AD.

Glacial Erosion

Erosion consists of weathering and transport. Glacial weathering is largely physical, and glaciers are very effective

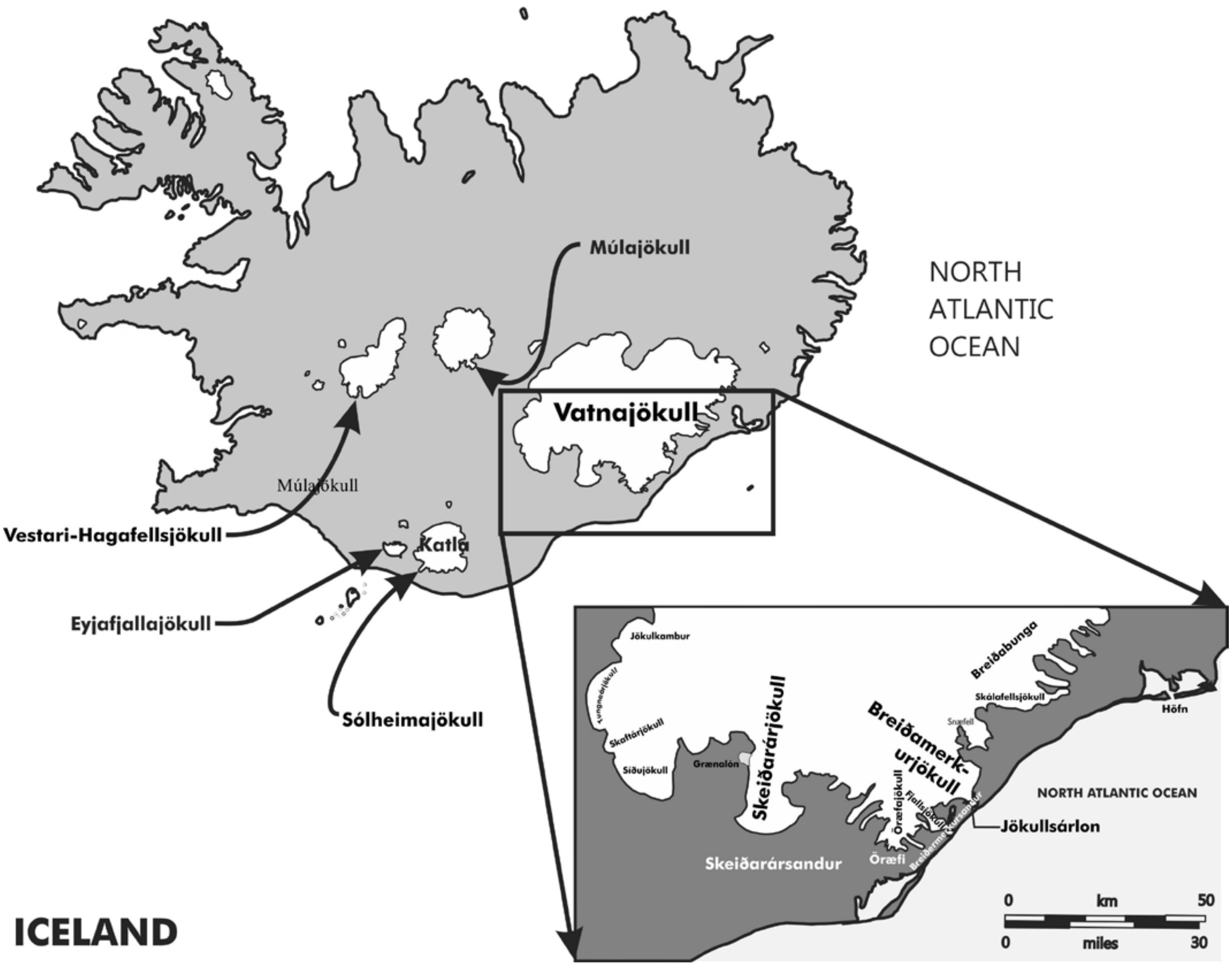

Figure 2. Map of Iceland showing important locations mentioned in text.

at developing high stresses to scratch and pluck bedrock.

Rates of Weathering and Transport

"There is relatively little information on Holocene chemical weathering rates in periglacial environments despite their implications for weathering-based dating and for the assumptions of cosmogenic dating" (Owen et al., 2007, p. 829). Such dating methods have produced anomalous results in areas of post-Little Ice Age recession (Hughes et al., 2012). What has been interpreted as chemical weathering due to age of exposure may in many cases be physical weathering resulting from recycling of sediments, with the most distal sediments being the most weathered as a result. This appears to have been confirmed for Bødalsbreen in Norway (Burki et al., 2010). Estimates of removal of gneiss bedrock at Fåbergstølsbreen in Norway for areas inferred to be glaciated during the Great Ice Age and adjacent areas known to have been glaciated during the Little Ice Age indicate glacial erosion averaged 158 mm/ka (and as much as 350 mm/ka), two orders of magnitude greater than the baseline chemical weathering rate (Owen et al., 2007). This is a significant rate of erosion for hard bedrock. Estimated contemporary erosion for Bødalsbreen, where both unconsolidated and consolidated materials have been eroded, was 800 mm/ka (0.8 mm per year), dropping to 700 mm/ka since the Little Ice Age (Burki et al., 2010). Evans and Twigg (2002, citing Björnsson, Boulton and

Figure 3. Vatnajökull, the world's largest ice cap (though a distant third behind the ice sheets of Antarctica and Greenland). It has been an area of intense study on the effects of the Little Ice Age.

others) estimate the minimum Little Ice Age erosion rate in the vicinity of Jökullsárlón in Iceland as 37 cm per year; the average rate for the period 1100 to 1900 was approximately 18 cm per year, with the estimated rate during the period of glacier advance 1765–1794, an impressive 4.9 m per year!

Mountain Glaciers

Studies of temperate North American cirque glaciers indicate headwall erosion proceeds most rapidly in bergschrunds. Freeze-thaw wedging is a known physical weathering mechanism, while fracture from dry thermal contraction is far less effective. "Several pioneering studies, however, have demonstrated that rock fracture by ice segregation (i.e., the fracture of intact rock by ice lenses that grow by drawing water from their surroundings during periods of sustained subfreezing temperatures) is a more effective weathering process than freeze-thaw" (Sanders et al., 2012, p. 779). This accelerated weathering in bergschrunds can explain the headward erosion of glaciated valleys and the resulting ridge asymmetry where climate is marginal for glaciation (Naylor and Gabet, 2007). "Cooling shifts the most favorable environment for frost damage to deep in the bergschrunds. … A minor cooling (e.g., -3 °C) results in bergschrund temperatures that are dominantly within the frost cracking window" (Sanders et al., 2012, p. 781). Mass wasting readily feeds the frost-loosened material onto the glacier for transport.

Many glacial deposits are short lived, especially when overrun by new glacial advances or glaciofluvial processes. Some prominent moraines formed by the large Skeiðarárjökull in Iceland vanished in jökulhlaups (Grove, 1988).

Glacial Deposits

Certain types of unconsolidated sediments, particularly unstratified deposits, have been considered glacially diagnostic, but more recent research has found most of these to be *equifinal* (the same end product can be produced by more than one process) or *polygenetic* (more than one process involved in forming the deposit). Historical records are needed to resolve these questions conclusively, and more for the Little Ice Age have thankfully been found of late (Anonymous, 2012; Connor et al., 2009; Nussbaumer et al., 2011).

Extent of Little Ice Age Deposits

In general, Little Ice Age deposits are greater in magnitude than deposits from the past century but considerably less than those inferred to have occurred during the Great Ice Age. This is true throughout our study area, as well as elsewhere in the world.

The south coast of Iceland has been changed dramatically since *Landnám* (in the Medieval Warm Period), primarily through deposition of sediment into broad, flat, outwash plains extending from the mountains to the sea and often crossed by braided streams. These are called *sandar* (singular *sandur*). The largest is Skeiðarársandur (Figure 4). Significant bays and inlets have been nearly or completely replaced by *sandar*, e.g., Hjörleifshöfði (Landnåmsboken, 1997, p. 47). While some of the erosion and deposition preceded or followed the Little Ice Age (Klevberg and Oard, 2012a), probably the greater part happened during the Little Ice Age.

Till

One of the most abundant glacial deposits is till, but the word "till" is a genetic term, describing the mode of deposition. Till is usually unstratified, a diverse mix-

Figure 4. Skeiðarársandur, the world's largest *sandur*, photographed from the southwest in 2002.

Figure 5. View west-northwest across Skeiðarársandur from inside (north of) Skeiðarárjøkull end moraine. Mountains rise abruptly 1,000 m (3,300 ft.) from edge of plain. Moraine complex has been nearly eliminated by jökulhlaup erosion and redeposition. Photographed in 2002.

ture of particle sizes from clay to gravel, most often with a fine-grained matrix (Figure 6). An unstratified and diversely graded mixture of unconsolidated sediment is a *diamict*, which is a scientific (i.e., descriptive) term with no genetic implication. Thus, nearly all till is diamict, but not all diamict is till. Many deposits have been used as evidence to argue for ice ages millions of years ago, a concept that has been refuted elsewhere (Molén, 1990; Oard, 1997).

Till (i.e., glacially deposited diamict) at Fjallsjökull displays layers of deformed materials, sometimes with identifiable unconformities (Rose et al., 1997). "Stationary glacial margins in Iceland are capable of superimposing numerous till layers to produce large composite moraines" (Evans and Twigg, 2002, p. 2167). Larsen and Mangerud (1992, p. 166) stated, "Till is only deposited beneath ice at the pressure melting point." To at least a limited extent, sediment can be transported into the englacial environment by being frozen to the base of the glacier and then thrust up and over other blocks of ice (Croot, 1988; Kjær and Krüger, 2001) or folded and incorporated into the glacier (Hambrey and Glasser, 2003). Where cliffs adjoin glaciers, mass wasting processes can efficiently deposit material on top of the glacier. After transport via ice, melting can deposit the material in an unstratified condition. Multiple till layers are known to form by these processes (Evans and Twigg, 2002).

Surging may affect the character of till. Kjær et al. (2006) investigated till from Brúarjökull, an outlet glacier

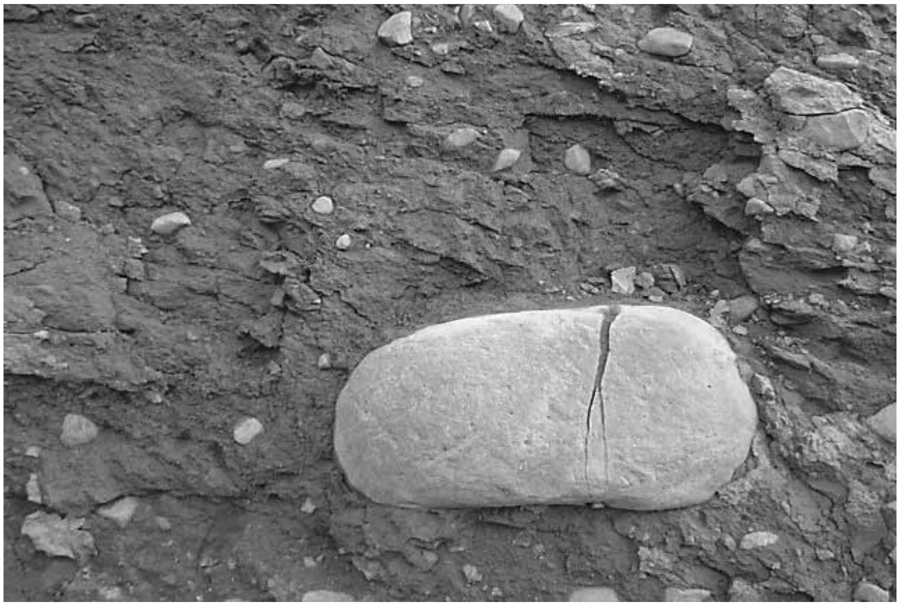

Figure 6. Lodgement till in drumlin, Sólheimajökull forefield, photographed in 2004 (from Ingólfsson, 2008).

on the northeast side of Vatnajökull (Figure 2) and stated, "Beneath the till plain, the 6 m of glacial sediments were accumulated during multiple surge advances and retreats as indicated by superimposed till beds interbedded by sorted sediments and the signature left by several generations of deformation" (p. 2707). The thin shear zone was evidenced by truncated upper drag fold flanks and shear-rotational structures and overturned folds. Ductile-brittle deformations extend down to the bedrock surface, however, so not all deformation was limited to the thin upper shear zone. Water-lain "interlaminated sediments" parallel the bedrock surface and truncate the base of the overlying sediments, indicating high subglacial porewater pressures during surges.

Figure 7. View west-northwest across Skeiðarársandur from Skeiðarárjøkull end moraine. Boulders have been transported by ice (foreground) and jökulhlaups (visible on sandur surface). Photographed in 2002.

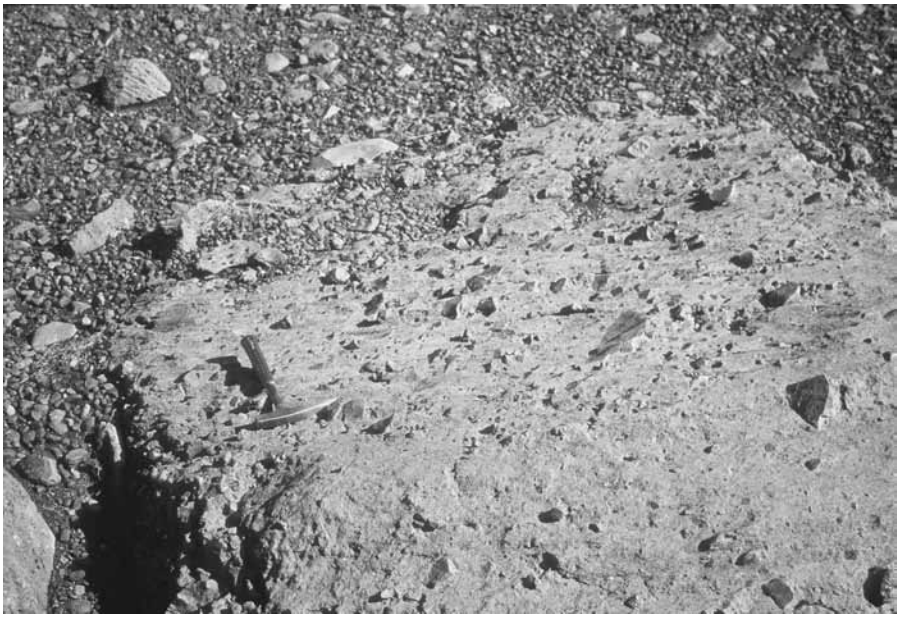

Figure 8. Breccia boulder deposited by Skeiðarárjökull, photographed in 2002.

a great deal (Figure 9). Fabric strength should therefore be used as one clue among many of the possible origin of a deposit; it is not a diagnostic criterion. Poorly sorted, structureless, matrix-supported deposits, massive deposits, and clast-supported fabrics have been documented to form in recent times from outburst floods and not just by means of glacial transport mechanisms (Rushmer, 2006). However, stratification alone is not diagnostic of fluvial processes, either. "Basal ice processes are dominated by entrainment of ice and sediment from the cavity floors, and compressive deformation of existing basal ice, to produce a complex stratified sequence" (Knight et al., 2007, p.208). Sediments in the jökulhlaup channel "are indicative of rapid rising stage deposition of sediment-rich flows" (Rushmer, 2006, p. 47), the rapid deposition resulting from "a rapid loss of transport capacity and mass suspension sedimentation" (p. 48). These nonstratified jökulhlaup deposits are associated with clearly fluvial deposits such as gravel foresets and horizontally bedded gravel units or diffuse gravel sheets. "The dominance of *a*-axis-parallel clast orientation within the structureless deposits at Kverkfjöll, additionally reflects rapid deposition from highly concentrated flows, whereby non-Newtonian processes occur within an overall turbulent, fluidal, Newtonian flow" (Rushmer, 2006, p. 48). Hyperconcentrated flows have been observed in other jökulhlaups (Figures 2 and 10).

> In the Ejyafjallajökull eruption, peak discharge and peak sediment flux were decoupled, and the dominant ice-proximal surface landforms are the result of a series of late-stage, lower discharge jökulhlaups over a period of weeks. … At Ejyafjallajökull, a changing source water:sediment ratio and proximal flood routing produced different flood rheologies. (Dunning et al., 2013, p. 1125)

Till fabrics can be relatively strong. Those observed in deposits from the

Boulders

"Lodged and striated boulders are ubiquitous" in Breiðamörk deposits (Evans and Twigg, 2002, p. 2159), and "the large percentage of striated clasts and the clast roundness and shape … indicate considerable clast wear in the basal traction zone of the glacier" (p. 2164). Bullet-shaped clasts have been observed to be abundant in Múlajökull channels (Johnson et al., 2010), a typical example of the often intimate association of glacial and glaciofluvial processes. While angularity can serve as a clue to glacigenic versus nonglacigenic boulders, boulders transported by warm-based ice can be rounded (Owen et al., 2010), and angular materials (e.g., rip-up clasts) can be eroded and deposited by jökulhlaups (Waller et al., 2001). Large clasts may be excavated by ice but transported by a variety of mechanisms (Figures 7 and 8). Boulders of several tons have been transported great distances by ice avalanches and debris flows generated from mountain glaciers (Kellerer-Pirklbauer et al., 2012). Obviously, significant elevation difference is needed to provide the potential energy to drive these processes.

Varves

Varves are supposedly annual pairs of laminae in sediments deposited downstream of glaciated areas. There appear to be some present-day lakes that act adequately as sediment traps from glaciated areas to produce true varves (Schiefer et al., 2006); however, most alleged varves are natural history conjectures and often refuted by other field evidence (Molén, 2008; Oard, 2009). Rhythmites (alternately laminated sediments) can be produced by a variety of processes, including turbulent deposition (Berthault, 1994) and should not be assumed to have been deposited as varves.

Fabrics

Till depositional histories have been differentiated on the basis of fabric strength (Dowdeswell and Sharp, 1986). As has been shown from deposits in Montana, USA (Klevberg and Oard, 2005), glacigenic and nonglacigenic fabrics overlap

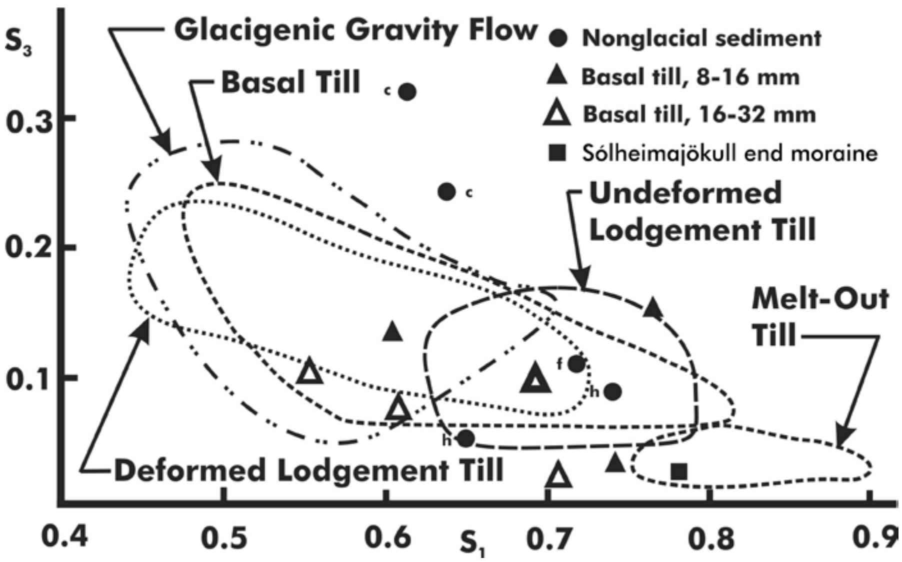

Figure 9. Fabrics in unconsolidated sediments can be useful indicators of probable origin, but they are not diagnostic. Fabric strength envelopes from Dowdeswell and Sharp (1986). These were derived primarily from Breiðamerkurjökull (See Figure 2 for locations). Nonglacial fabrics (·) from Klevberg and Oard (2005): c—colluvium, f—fluvial floodplain gravel, h—hypothetical (computer-generated fluvial). Also shown are basal till fabric data from 1980 surge of Vestari-Hagafellsjökull (Carr and Goddard, 2007) for 8–16 mm fraction (▲) and 16–32 mm (Δ), and end moraine fabric from Brynjólfsson (2004) left after the advance of Sólheimajökull that ended in 1995 (■).

Figure 10. Eyjafjallajökull during eruption of May 2010. Jökulhlaups caused by this eruption produced a great many useful sedimentation data. Photograph by Helge Klevberg.

surging Icelandic Brúarjökull are stronger in the center of flutes (eigenvalues average 0.80±0.04) than the sides (0.65±0.08) according to Kjær et al. (2006). Thus, fabric data can be very useful but also very problematic and nondiagnostic for inferring mechanisms of transport and deposition.

Ice avalanches and debris flows generated from glaciers can produce clast orientation. Orientation of the *a*-axis (long axis) of clasts parallel to flow with imbrication either upstream or downstream (depending on the site) has been observed in a debris flow from Nördliches Bockkarkees in Austria, as has till pebble orientation either parallel to or transverse to ice flow direction (Kellerer-Pirklbauer et al., 2012). Fabric measurement from a study location at Nördliches Bockkarkees produced eigenvalues matching deformation till in Figure 9.

Recent efforts to discriminate between subglacially and supraglacially transported clasts using statistical analysis of percentages of angular and rounded rocks appear promising (Reinardy et al., 2013). It may also have wider application (Kellerer-Pirklbauer et al., 2012). Additional research will be needed to ascertain the degree of reliability and usefulness of this method (Figures 11–13).

Other

Flutes are present on the upgradient side of moraines deposited by the Little Ice Age in Iceland (Evans and Twigg, 2002) and Norway (Owen et al., 2010; Reinardy et al., 2013). They may result from till squeezing into cavities in ice on the downstream side of boulders (Figure 14). Fluted terrain is present behind the Little Ice Age moraines at Midtdalsbreen (Hardangerjøkulen) and Tverrbytnede (Jotunheimen) in Norway, but not beyond these moraines (Owen et al., 2010; Reinardy et al., 2013). Brúarjökull has produced "a streamlined till plain superimposed on larger bedrock

Figure 11. View west from end moraine of Skeiðarárjøkull (Figure 1) in 2002, showing typical gravel composed of rocks of mixed angularity.

Figure 12. Coarse gravel deposits from glaciers in vicinity of Öræfi. Photographed in 2002.

features and subglacial landforms" (Kjær et al., 2006, p. 2707). Flutes sometimes exceed 1.5 km in length and result from boulders. Fluted terrain that is erosional, rather than depositional, is present in Canada (Shaw et al., 1996).

Clastic dikes have been observed in Little Ice Age and recent deposits; these are interpreted as evulsion features from overpressured water (Evans and Twigg, 2002; Kjær et al., 2006). Larsen and Mangerud (1992) showed that many features interpreted as ice wedge casts may actually be clastic dikes. While till can certainly fill cracks in underlying sediment, clastic dikes may form subglacially by till being squeezed into cracks in the overlying sediment. Clastic dikes may also result from injection of a slurry and may form stratified or laminated crack fillings. Hydraulic splitting from subglacial water pressure cracks the host sediments. Till dikes sometimes have laminated off-shoots or grade into laminated dikes with distance from the source, indicating fluidity and sorting of the sediment during emplacement. Impregnation of host material with fines from slurry along dike margins indicates host material was not frozen, though clastic dikes could certainly also form in frozen sediments. In at least some cases, glacigenic clastic dikes may differ from nonglacigenic clastic dikes solely in the origination of the former from relief of overpressured subglacial water through cracking of subjacent sediments and dissipation of the pressure. Water escape structures (evulsion structures) have been reported for till strata formed during or after the Little Ice Age (Johnson et al., 2010).

Glacial pavements may have been generated by subglacial winnowing (Evans and Twigg, 2002). Post-Little Ice Age till with a pebble-size clast pavement has been observed from Múlajökull in Iceland (Johnson et al., 2010). Pebble-armored slopes have been observed to develop in Greenland from deflation of fines on moraine slopes, and boulders accumulate at slope toes (Knight et al., 2007).

Glacial Landforms

Glacial landforms may be depositional or erosional. Depositional types are often of smaller scale but more varied than erosional landforms. Glacial processes and movements are often inferred from depositional fabrics and landforms, but all are known to have been produced during the Little Ice Age and the subse-

Figure 13. Skeiðarárjökull moraine complex, showing predominance of well-rounded gravel. Footprints provide scale. Photographed in 2002.

Figure 14. Small flute in front of Sólheimajökull, 2004 (photograph from Ingólfsson, 2008).

quent glacial recession (Andrzejewski and Molewski, 2007; Decaulne et al., 2007; Price, 1969).

Moraines

Moraines are one of the most prominent glacial landforms (Figure 15). Prominent moraines from the Little Ice Age and later are well documented (Figure 16).

Evans and Twigg (2002), in their investigation of Little Ice Age deposits on Breiðamerkursandur, found that moraines were largely mosaics of many small deposits:

> The maritime, cold-temperate climate of the region is probably responsible for the late winter readvances of the receding glacier margins in southeast Iceland … thereby giving rise to the deposition of numerous, often annual, recessional push moraines. (p. 2145)

They posit the prominent moraine Brennhóla-Alda is a thrust moraine (thrust block) with older peat plastered on top. "Thrust moraines in Iceland are associated exclusively with surging margins … and constitute a major land element in the surging glacier landsystem" (Evans and Twigg, 2002, p. 2157). They interpret low, intermediate ridges in Iceland as overridden moraines, either from earlier in the Little Ice Age or before it. Such subdued ridges have been observed to form in this manner (Knight et al., 2007).

Kjær et al. (2006) studied the surging Brúarjökull. They opine that water escape pits at heads of stream channels indicate transition from ground water to surface water. Where water escaped the subsurface through more permeable sediments, shear likely increased and may explain the formation of end moraines:

> The widespread occurrence of hydrofractures within the Brúarjökull forefield implies evacuation of large quantities of meltwater along the substrate/bedrock interface, which

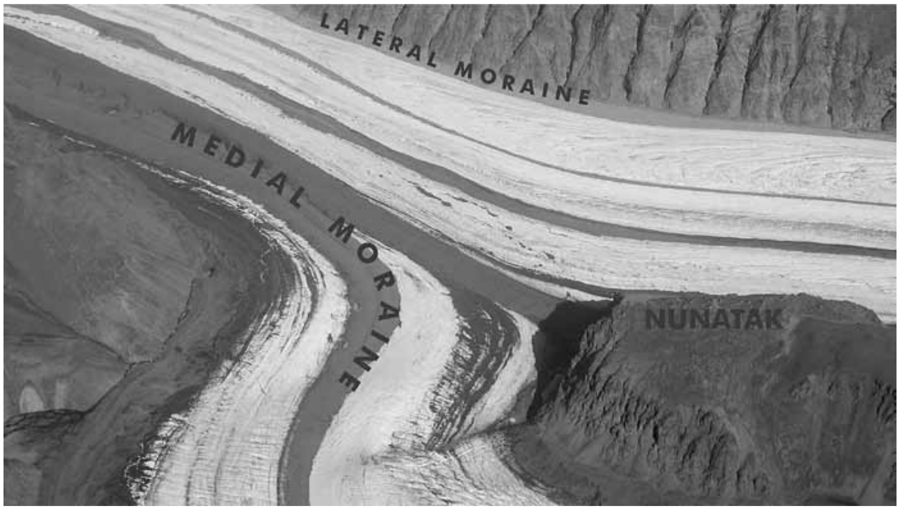

Figure 15. Moraines and Nunatak on Nuussuaq Peninsula, Greenland. Base image from Wikipedia Commons.

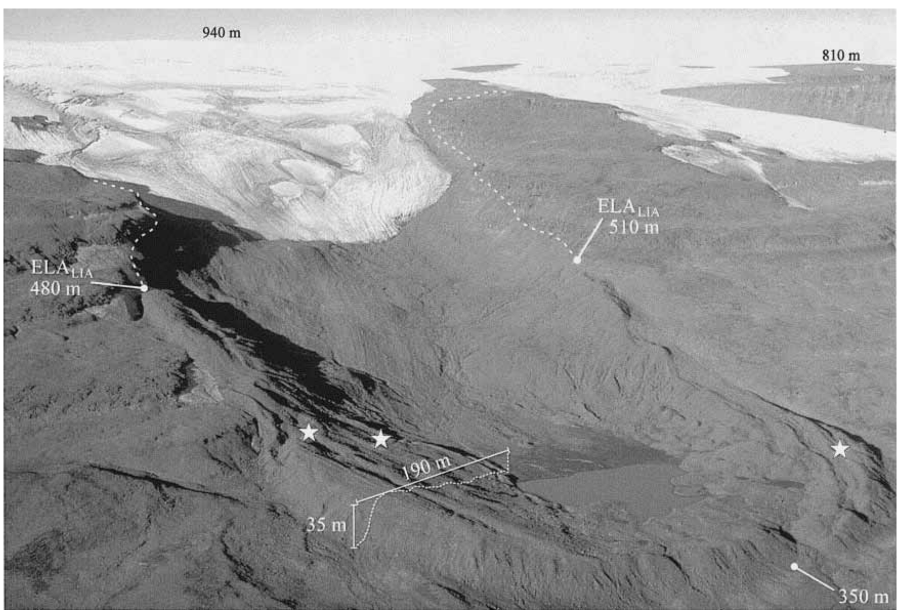

Figure 16. Moraines from Little Ice Age with equilibrium line altitude (ELA) contemporary with moraine formation indicated. Rock glacier on southwest Diskø, Greenland (Figure 1). Star symbols represent sampling locations. Figure from Humlum (2000).

> suggest that overpressurized water carried both the sediment burden and the weight of the glacier" (p. 2711).

Ice marginal moraines can be formed by glacial "bulldozing," running water, or a combination (Lukas, 2012). Converging ice at glaciers on Spitsbergen (in Svalbard) produce folding and foliation to generate medial moraines, thus forcing sediment to the surface (Hambrey and Glasser, 2003). In 1890, Brúarjökull surged 10 km and piled up a push moraine 20 m high (Björnsson, 1980).

Hummocky moraines from Breiðamerkurjökull and Fjallsjökull appear to result from deposition as medial moraines or from glacial reworking (Evans and Twigg, 2002). Burial of large pieces of ice in moraines will produce hummocky terrain when the ice melts (Figures 17 and 18).

Drumlins

Drumlins are streamlined landforms that project above the surrounding land surface (Figure 19). Drumlins are a salient feature among landforms ascribed to glaciation, and some have been produced by the Vatnajökull outlet glaciers.

> A number of drumlins, most of which are spindle types up to 1 km in length, occur on the foreland of east Breiðamerkurjökull and are superimposed by flutings and push moraines. … Former outwash fan apices have developed into stiff drumlin cores, resulting in the partial preservation of ice-contact glacifluvial fans beneath streamlined till surfaces. (Evans and Twigg, 2002, pp. 2159, 2174)

As shown in Part III of this series (Klevberg and Oard, 2012a), these are Little Ice Age features. Perhaps the only example of drumlin formation in recent decades is from Múlajökull, where small drumlins formed subglacially through a combination of till deposition, deformation, and erosion where the ice experienced compressive flow near the glacier's margin and high subglacial water pressure (Johnson et al., 2010). Small drumlins (and large flutes) have been observed in modern environments (Figure 20).

While drumlins are known to form subglacially, not all drumlins are neces-

Figure 17. Skeiðarárjökull moraine complex as it appeared in 2002.

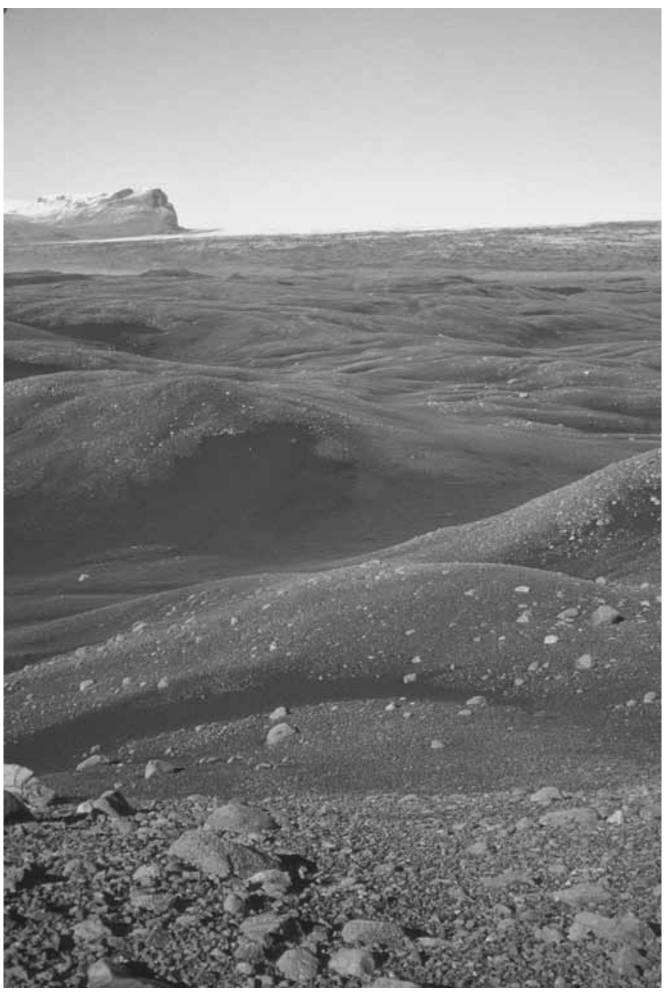

Figure 18. View north toward Skeiðarárjökull from moraine field in 2002.

Figure 19. Famous drumlin at Morley Flats, Alberta, Canada. Photograph posted by University of Lethbridge.

Figure 20. Small drumlin in the Sólheimajökull forefield, photographed in 2004 (from Ingólfsson, 2008).

Figure 21. Supraglacial debris on Sólheimajökull in 2004 (from Ingólfsson, 2008).

sarily primarily depositional. Shaw and Sharpe (1987) cite drumlin fields where stratigraphy can be traced through multiple drumlins, indicating these formed erosionally. A prime example they give is from Beverley Lake, Nunavut (formerly the Canadian Northwest Territories), but other areas with what appear to be erosional drumlins are also found.

"The apparent lack of modern drumlin fields may not necessarily indicate that modern glaciers differ from Pleistocene ice sheets, but that current glaciers, most having reached their maximum during the Little Ice Age, have not yet retreated far enough to reveal them" (Johnson et al., 2010). Differences in depositional drumlins between the Great Ice Age and Little Ice Age largely devolve to size, number, and extent of drumlin fields. We are not aware of modern analogues for erosional drumlins.

Eskers and Hummocky Terrain

Where steep mountain glaciers are concerned, debris can readily accumulate on the glaciers' surfaces from rock fall and landslides off the adjacent cliffs, but this mechanism does not operate in areas of low relief or areas buried by ice. As noted by Evans and Twigg (2002), it is difficult to conceive of how debris could get on top of glaciers such as those they studied in Iceland so that eskers could form under normal conditions (some eskers have ice cores). They posit surging as the only ready explanation. Surging glaciers could conceivably pick up considerably more debris as they repeatedly advance and retreat, often with large amounts of meltwater released (Figure 21). Jökulhlaups have been observed to provide not only these sudden surges of subglacial, englacial, and supraglacial water, but also to transport sediment up onto the glacier's surface (Waller et al., 2001). Shearing may also occur between sediment frozen to the base of a glacier and deeper, unfrozen sediment, with thrusting of ice slabs permitting limited incorporation of sediment into the ice, as has been observed with annual moraine formation (Boulton, 1970). Esker formation has also occurred directly as the result of jökulhlaup deposition (Russell et al., 2007), though "normal" formation by bedload deposition from englacial streams has also been documented (Figure 22).

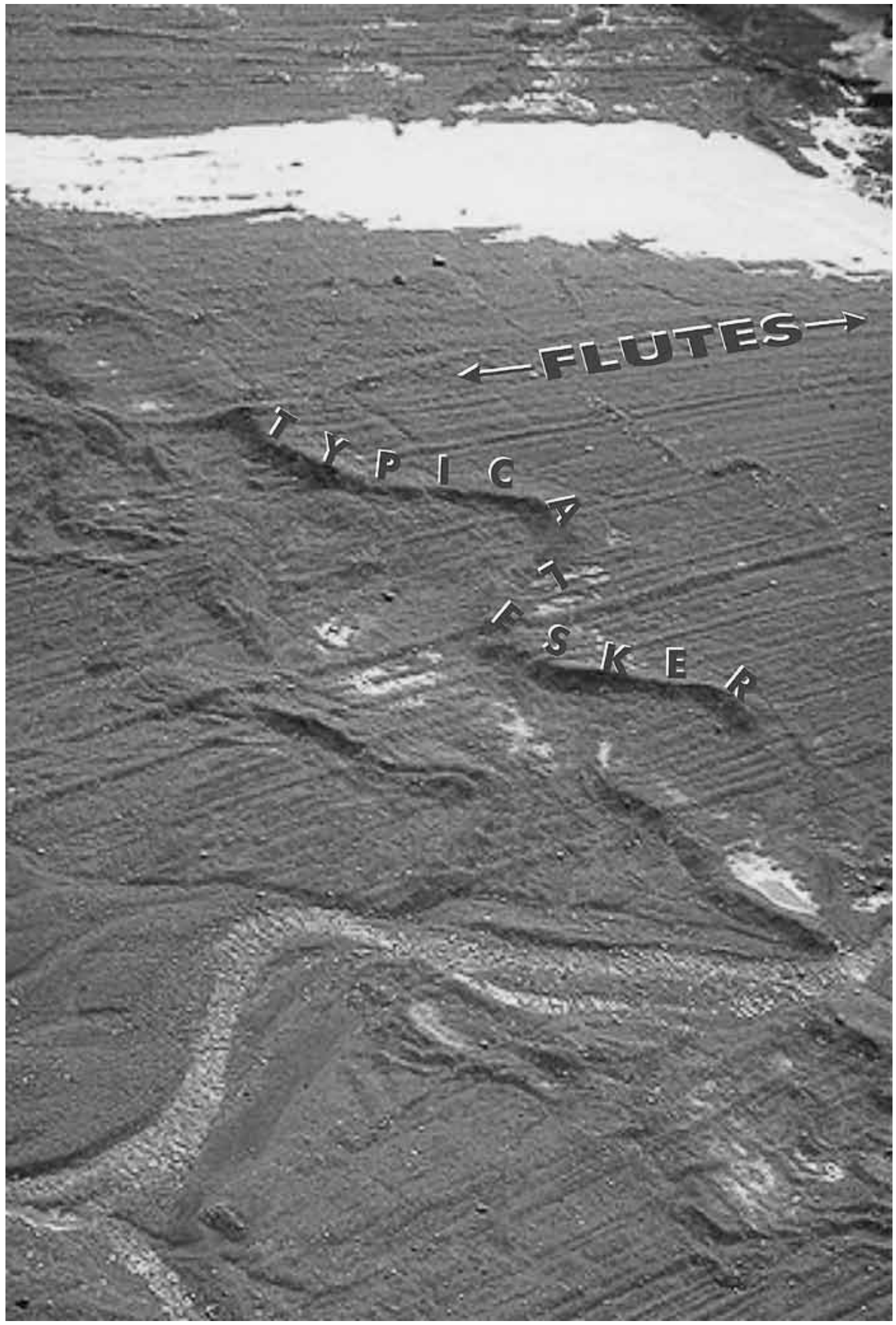

Figure 22. Flutes and eskers indicated on aerial base image of Bear Glacier, Kenai Peninsula, Alaska. This forefield lies behind the Little Ice Age terminal moraine. Base image from Eastern Illinois University (http://www.ux1.eiu.edu/~cfjps/1300/glacier_photos.html).

Figure 23. Kettle-hole lake, Little Ice Age moraines, in 2004 at Sólheimajökull (from Ingólfsson, 2008).

Figure 24. A typical kettle-hole lake in Finland (image from Wikipedia Commons).

Hummocky, "dead ice topography" is a less ordered result of a similar process to esker formation. Hummocky terrain from the Little Ice Age has been reported from Midtdalsbreen in Norway, where meltout of inverted topography was observed (Reinardy et al., 2013). Hummocky terrain was also produced by jökulhlaups in Iceland in 2010 depositing mixtures of ice and sediment (Dunning et al., 2013).

Kames and Alluvial Terraces

Thompson and Jones (1986) observed paired (both sides of stream) and unpaired river terraces on the southwest side of Öræfi (Figure 2), attributable to Little Ice Age glacial fluctuations and a 1727 jökulhlaup. Subjacent sediments from the eruption and jökulhlaup of 1362 provide dating control. Up to 28.5 m of sediment was eroded by Kotá stream erosion since 1727 to form a series of terraces cut in the "dead ice" topography of the 1727 (uppermost) surface. Svinafellsá is incised as much as 7.9 m to form five paired terraces. Svinafellsjökull retreated in 1870. Contemporary kame formation was reported from elsewhere in Iceland (Molewski et al., 2007; Szmanda et al., 2007). Aggradation appears related to advance or stagnation of the glaciers, accelerated downcutting with rapid retreat. The rate of downcutting has been related to the rate of retreat or the rate of sediment supply. Virtually all of this work was performed by glaciofluvial or jökulhlaup processes rather than glacial ones. Multiple terraces have been produced by single jökulhlaups (Rushmer, 2006) and multiple jökulhlaups (Dunning et al., 2013).

Kettles, Rock Glaciers, Outwash Plains

Kettles are known to form where glaciers bury large blocks of ice that later melt out to form the prominent holes known as kettles (Figures 23 and 24). Less well known is the fact that kettles can form

Figure 25. Pitted sandur surface after melting of ice debris deposited during the 1999 Sólheimajökull jökullhlaup, photographed in 2004 (from Ingólfsson, 2008).

from ice blocks buried by jökulhlaups (Dunning et al., 2013; Rushmer, 2006).

Ice-cored moraines (Evans and Twigg, 2002) and rock glaciers (Martin et al., 1991) are not uncommon to this day in Iceland as well as in Greenland (Figure 16), though even in the colder subcontinent rock glaciers appear to result from the unusual climatic conditions of the Little Ice Age (Humlum, 1998; Owen et al., 2010). Ice-cored moraines generally date from the Little Ice Age, though some may be from more recent advances.

Outwash plains are proglacial plains of glacial drift. They typically are crossed by anastomosing flood channels and braided streams. The *sandar* of Iceland are often shaped largely by jökulhlaups (Figure 25). These sometimes deeply rework existing strata and sometimes simply bury them.

> Based on the stratigraphic evidence and bedrock topography discovered above, it is clear that Breiðamerkurjökull and Fjallsjökull advanced during the Little Ice Age over considerable tracts of glacifluvial outwash without disrupting their general form. … This suggests that sandur fans are relatively stable forms that become adorned with subglacial features such as drumlins and flutes during glacier overriding but remain dominant as topographic features. (Evans and Twigg, 2002, p. 2168)

Where erosional features formed, they tend to be dramatic. Maizels (1991) argues that the large Skeiðarársandur farther west probably originated more from catastrophic jökulhlaups than from ordinary fluvial processes, though ordinary fluvial processes are also known to accomplish much work in relatively short periods of time (Price, 1982; Price and Howarth, 1970). The 1934 Skeiðarársandur jökulhlaup is estimated to have released 10 to 15 km^3 of water (Grove, 1988), and the 1996 jökulhlaup involved a peak flow of about 52,000 $m^3 s^{-1}$ and transported an estimated 60 million m^3 of sediment (Smith et al., 2000). There have been many others (Ives, 2007). Both glacial and glaciofluvial processes are at work forming these outwash plains (Figures 26 and 27).

Overdeepened Valleys

The Little Ice Age provided dramatic evidence of the cutting power of glaciers. Trenches were cut by Breiðamerkurjökull (Figure 28) to depths as much as 300 m below sea level in basalt bedrock (Evans and Twigg, 2002)!

> During the very rapid retreat after 1930 proglacial lakes have formed in front of Skeiðarárjökull and Breiðamerkurjökull. The largest lake is Jökullsárlón on Breiðamerkursandur which reaches 120 m below sea level. The material released from the glaciers has not been sufficient to fill up the lakes. (Björnsson, 1980, p. 209)

The most notable, Jökullsárlón (Figure 29), is not the only example of this impressive erosional phenomenon. "In fact, the base of several of the larger glaciers extends below sea level" (Ives, 2007, p. 205). Retreating glaciers have left other impressive basins that have formed lakes: Fjallsárlón, Breiðárlón, and Stemmulón on Breiðurmörk (Figure 2). Most other proglacial lakes are shallow. The Jakobshavn Isbræ in western Greenland discharges through a trough 1,200 to 1,500 m below sea level, though this trough may well predate the Little Ice Age (Roberts and Long, 2005).

Bedrock Forms

Glaciers may plane, polish, and scratch bedrock surfaces. They may also create streamlined forms where knobs of rock resist the flow of the ice. Glacial recession since the end of the Little Ice Age has revealed streamlined roche mountonnées (with rough or plucked lee ends) and whalebacks (with smooth, unplucked lee ends) at Jakobshavn Isbræ in Greenland. This glacier drains

Figure 26. Stratified sandur deposit, Sólheimajökull forefield, photographed in 2004 (from Ingólfsson, 2008).

Figure 27. Stratified outwash gravels and sands, Sólheimajökull, photographed by H. Norðdahl in 2004 (from Ingólfsson, 2008).

approximately 7% of the Greenland Ice Sheet (Roberts and Long, 2005). The roche mountonnées and whalebacks developed in an area of high glacial velocity but likely differing ice thickness (i.e., differing vertical pressure). These observations from Greenland indicate "the major controls over plucking are bed separation and cavity opening, pressure melting, fluctuations in subglacial water pressure and refreezing. [Whaleback] morphology suggests that bed separation, cavity formation and plucking do not occur during their formation" (Roberts and Long, 2005, p. 26). Striations, roche mountonnées, and whalebacks recorded two or more flow directions at Jakobshavn Isbræ. Little Ice Age glacial movement smoothed hard gneiss bedrock at Fåbergstølsbreen over the course of approximately one hundred years (Owen et al., 2007).

Patterned Ground

Patterned ground has been observed to form where glaciers have retreated from their Little Ice Age maximum extent (Ballantyne and Matthews, 1982). Some have speculated the size of the periglacial forms (cf. permafrost circles) is related to age, but it appears these patterns can form within just a few years, with pedogenesis and vegetative stabilization hindering or halting development with time (Haugland, 2006). The size of the circles or polygons relates strongly to conditions conducive to frost heave, especially microclimate and sediment grain size distribution (Feuillet and Mercier, 2012).

Patterned ground in the form of rock circles in the Rondane Mountains of Norway is associated with solifluction lobes and block fields. Block fields in south-central Norway are common, but erratic boulders are rare, and block fields tend to be on high terrain, higher than diamict interpreted as till (Follestad and Fredin, 2007). They may therefore have been produced by periglacial or nonglacial processes.

Figure 28. View northwest toward Breiðamerkurjökull in April 2002.

Figure 29. Jökulsárlon, the proglacial lake at the foot of Breiðurmerkurjökull on the southeast side of Vatnajökull (Figure 2), which was eroded well below sea level.

Glacial Movement and Processes

As a very viscous fluid, ice is capable of excavating and transporting large volumes of earth materials. This was particularly evident in Iceland and Greenland during the Little Ice Age. The power of glaciers to erode and deposit sediment was observed during the Little Ice Age, is observable today, and is inferred for the Great Ice Age. Paleocurrent indicators for glacial movements, such as moraines, boulder trains, and intermixed diamictons, are present in the Oslofjord of Norway, on the Canadian prairies, and the upper states of the United States, for example, places that were not touched by permanent ice during the Little Ice Age.

Flow Rates and Processes

Rates of ice flow can vary markedly. Speaking of the Vatnajökull outlet glaciers in Iceland, Björnsson (1980, p. 205) states, "Velocities of over 1 m/day are common." Kjær et al. (2006) have studied Brúarjökull, a northern outlet glacier of Vatnajökull that surged over a period of three months during winter followed by 70 to 90 years of quiescence. The surges occurred in 1890 (10 km) and 1963 (8 km), "affecting an area of roughly 1400 km^2 … The peak velocity was at least 125 m/day over a period of almost three months" (Kjær et al., 2006, p. 2705). This involved an estimated 40% of the area of Vatnajökull (Björnsson, 1980). Subsequent retreat was passive.

Surging glaciers exhibit the following transport modes: basal sliding (decoupling at ice/sediment interface), deformation of water-saturated subglacial sediment (the deformable bed model), and as at Brúarjökull, a dual-coupled model (glacier coupled to bed, sediment deforms, and sediment decouples from impermeable bedrock). Sediment deformation tends to be thin and discontinuous based on modern observations and laboratory experiments (Kjær et al., 2006).

Much geologic work may be associated with surging glaciers, of which many have been identified. Very large surges of Brúarjökull, Skeiðarárjökull, and Breiðamerkurjökull have been documented (Grove, 1988; Ives, 2007). Cold-based glaciers (i.e., those frozen to their beds) necessarily flow at slower rates than warm-based or polythermal (mixed) glaciers. This has a significant bearing on the amount of geologic work that may be accomplished in a given period of time. Lateral meltwater channels have been used to infer cold-based or polythermal ice, but temperate (warm-based) glaciers also exhibit these (Syverson and Mickelson, 2008), and glacial work that has been attributed to cold-based ice may actually have been accomplished by warm-based ice (Reinardy et al., 2013). Experiments under the west lobe of Breiðamerkurjökull identified two layers: an upper layer that is dilatant and flows ductilly and a lower layer that flows by brittle or brittle-ductile shearing. "It was calculated that more than 90% of the forward movement of the glacier was produced by this deformation of the substrate" (Evans and Twigg, 2002, p. 2159). Iverson et al. (2003) performed experiments using the Svartisen subglacial laboratory in Norway to measure basal traction stresses beneath the glacier and stated, "Our results are not consistent with common assumptions regarding basal movement of glaciers. Data from the soft-bed experiments indicate that high pore-water pressure may weaken the ice-till interface more than till at depth, causing slip of ice over the bed" (p. 83). Thus, actual glacier movement may be more and erosion beneath glaciers shallower than commonly estimated. Surging is limited to warm-based glaciers and is episodic. Kuannersuit Glacier in western Greenland (Diskø) surged 10.5 km between 1995 and 1998 (Yde and Knudsen, 2005), and even larger surges have been measured. Surging can greatly accelerate geologic work, even accomplishing in a day what might ordinarily require a year or a decade (Benediktsson et al., 2007). Basal melting can result not only in surging but also in detachment and transformation into debris flows, such as occurred in Russia in 2002, where the Kolka Glacier reached a maximum velocity in the range of 65 to 80 m/s (Evans et al., 2009)!

Water-ice interaction is very important. Evidence has been presented for thinning of outlet glaciers in eastern Greenland from decreasing basal friction resulting from increased water (Krabill et al., 1999). Cowton et al. (2012) summarize their work in western Greenland:

> We have presented a detailed study of the sediment flux and associated current rate of erosion of a large catchment beneath the Greenland ice sheet. Across the catchment, which covers an area of ~600 km^2 and extends to more than 50 km from the ice sheet margin, we calculate a subglacial erosion rate of 4.8 ± 2.6 mm a^{-1}. This is 1–2 orders of magnitude higher than previously reported rates. … Our data therefore challenge the notion that erosion below polar glaciers and continental ice sheets is dominated by slow mechanical processes associated with ice advance and retreat. … Instead, we find that the efficient subglacial drainage of surface meltwater is critical in creating a zone of rapid erosion around the margins of the ice sheet. (p. 346)

Sediment Accumulation and Transport

Mass wasting processes are important in providing sediment for supraglacial and englacial transport (Owen et al., 2010; Porter et al., 2010) and for modifying glacial landforms (Knight et al., 2007; Sanders et al., 2012). Sediment is frequently deposited and then re-entrained by new glacial advances (Burki et al., 2010; Knight et al., 2007; Lukas, 2012), often destroying previous fabrics and landforms. The efficiency of these processes for entraining sediment is highly dependent on topographic relief to provide the driving potential energy.

Seasonal change in glacier thermal regime can be an important means of enhancing erosion as the sediment freezes to the bed of the glacier during the winter and then is transported through a combination of glacial thrusting and glaciofluvial processes during the warmer months, often forming annual moraines (Croot, 1988; Kjær and Krüger, 2001; Krüger, 1985, 1993, 1995, 1996; Reinardy et al., 2013). Studies of the Russell Glacier in western Greenland show "the debris-rich basal ice layer is the dominant route for sediment transfer through the ice over long sections of the ice-sheet margin" (Knight et al., 2007, p.204). In the Breiðurmerkursandur area, stratified glaciofluvial sediments are overlain or disturbed by tills and glaciotectonites (Evans and Twigg, 2002).

Formation of glacial deposits tends to be highly episodic:

> When the margin lies behind a moraine ridge, glacigenic sediment is largely stored in the ice-proximal zone and distal sediment production is limited. As the margin overtops the moraine, distal sediment production increases markedly both because the opportunity for ice-proximal storage is reduced and because moraine sediments are reactivated. (Knight et al., 2007, p.214)

Multiple Directions, Multiple Glaciations?

Evidence of changes in direction of ice flow has been used by believers in old-earth chronology to argue for multiple ice ages (Oard, 1990), but observed changes in direction during and after the Little Ice Age indicate that a single event can produce striae, roche moutonnés, and other ice-flow indicators showing two or three distinct flow directions as thinning ice begins to be deflected by obstructions such as ridges and emerging nunataks (Roberts and Long, 2005; Syverson and Mickelson, 2008). Owen et al. (2010, p. 421) astutely observe, "For a variable period of time following glacier retreat, processes of landscape modification, erosion, sediment transport and deposition operate at rates greatly exceeding their 'normal,' background rates."

Glaciomarine Features

What are interpreted as iceberg scour marks on the bed of the North Sea and glacial features on the bed of the Norwegian Sea and the Barents Sea are attributed to the "Pleistocene" ice ages or, as we describe it, "The Great Ice Age" (Klevberg and Oard, 2012b; Mattingsdal et al., 2007). The Little Ice Age did not produce these subsea features (Klevberg and Oard, 2014c), probably partly due to effects of scale of processes and partly to differences in sea level contemporary with glaciation. However, scour marks and glaciomarine deposits were formed on a smaller scale during the Little Ice Age, suggesting the processes were the same, though different in scale.

Interpreting Apparently Glacial Features

As described in Part VII (Klevberg and Oard, 2014c), the Little Ice Age is a useful but imperfect model for the Great Ice Age. Glacial processes and periglacial processes sometimes coincide and sometimes do not. Follestad and Fredin (2007) opine,

> It appears that many glacial landscapes in Scandinavia have more in common with landscapes formed at modern polar ice caps, as for example in Arctic Canada and Russia … than with landscapes formed at modern temperate glaciers on Iceland and in Scandinavia, which traditionally have been used as analogues for former Fennoscandian ice sheets. (pp. 281–282)

Any model is imperfect, and science is limited in its role in natural history research (Reed, 1999; Reed and Klevberg, 2014a, 2014b). Thus, apparent glacial deposits and landforms remain solely apparent except where historical research can confirm their origin. The inference is more likely where a given deposit or landform occurs in association with other likely glacial features.

One must also keep in mind that even during the Little Ice Age, other geologic forces were at work. Forces that were involved in noticeable changes to the Icelandic landscape between *Landnám* and the Little Ice Age—tectonics, erosion, volcanic eruptions (Pálsson, 2000)—did not cease during this glacially active period. Many geologic features from recent centuries may be the result of a multiplicity of processes. For example, Little Ice Age glacial erosion produced post-Little Ice Age mass wasting many places (Owen et al., 2010; Matthews and Shakesby, 2004). Reinardy et al. (2013) state:

> Preservation potential also differs from landform to landform. Detailed geomorphology and sedimentology are commonly used to interpret palaeoglacier dynamics and their climatic implications. … Midtdalsbreen provides an interesting modern analogue in which some of these assumptions can be tested. Thus, the chronological evolution seen within the geomorphological record at Midtdalsbreen may simply reflect the difference in preservation potential between different landforms … rather than a significant change in glacier dynamics. (pp. 907–908)

Glaciation Can Produce Many Fluvial Deposits

Canadian researchers have shown that many features traditionally attributed to glacial processes are likely the result of glaciofluvial or purely fluvial processes (Shaw and Sharpe, 1987; Shaw et al., 1996), including percussion marks, which are clearly nonglacial (Klevberg and Oard, 1998). Sometimes it is difficult to discern between glacial and nonglacial processes, as similar results can occur from different processes (i.e., equifinality). Polygenetic processes appear to be the rule rather than the exception in glaciated areas, both within and downstream of the ice margin.

The southern coast of Iceland at Mýrdalssandur grew between 2.2 and 2.5 km from 1660 to 1960 (Björnsson, 1980, p. 209). While some of this was directly attributable to eruptions of the Katla volcano, some of it was attributable to glacially induced erosion and to jökulhlaups resulting from volcanic-glacial interaction. Maizels (1991) attributes most of the sandur deposits to jökulhlaups. Major events appear responsible for most of the geologic work (Lawler, 1991).

> Most of the early settlements [on Mýrdalssandur] were destroyed by hlaups from Kötlujökull between the ninth and eleventh centuries. … The Kötluhlaup of November 1660 carried away all the houses and the church of Höfðubrekka, so that hardly a stone was left on the original site and so much material was carried down to the shore that a dry beach appeared where previously fishing boats had operated in waters 20 fathoms deep. (Grove, 1988, pp. 27–29)

Even on a much smaller scale, melting ice provides water for fluvial transport (i.e., glaciofluvial process) often in combination with glacial and mass wasting processes (Figure 30), which can produce glacial drift, including depositing nonstratified and complex moraines (Lukas, 2012). Sandar can be created and destroyed quickly, often catastrophically (Price, 1971).

Gerrard (1991) and Dugmore and Buckland (1991) believe anthropogenic factors have been more important than climate change in inducing mass wasting and soil erosion in Iceland, though individual situations vary widely. Deposits in Mediterranean Europe attributed to anthropogenic soil disturbance may be better explained by deluges (i.e., >200 mm precipitation in 24 hours) during the Little Ice Age (Grove, 2001), and

Figure 30. Meltwater channel at margin of Sólheimajökull, photographed by H. Norðdahl in 2004 (from Ingólfsson, 2008).

Figure 31. Megaripples in gravel formed on sandur south of Katla, Mýrdalsjökull in background. Photographed by H. Norðdahl in 2004 (from Ingólfsson, 2008).

geologic work since the Little Ice Age has been characterized by downcutting rather than deposition. In either case, the combination of lack of vegetation and heavy precipitation resulted in geologic work of much greater scale than is commonly observed today.

Large-scale geologic work could also occur if heavy rainfall combined with melting ice. This supports the general bias of diluvialists that geologic activity since the biblical Deluge has largely been of a considerably different character from diluvial processes, and even in the postdiluvian period has been largely dominated by episodic or catastrophic processes (Figure 31). Some of these may have been on a scale far larger than those with a traditional old-earth bias are willing to consider (Oard, 2004; Shaw et al., 1996; Shoemaker, 1995).

Summary and Conclusions

Geologic history is natural history, not observational science, and is therefore speculative. Historical data from the Little Ice Age and subsequent centuries provide us with good checks on our assumptions and inferences regarding the Great Ice Age. The inference is more likely where a given deposit or landform occurs in association with other likely glacial features and less so where the given deposit or landform is the only glacial indicator.

1. Observed glacial deposit and landform types generally compare favorably with what are commonly accepted as Great Ice Age features, though the latter are significantly greater in extent.
2. Rates of weathering and transport during the Little Ice Age were often much higher than expected based on traditional old-age scenarios for the "Pleistocene" ice ages. Chemical weathering, with ages often inferred based on ratios of cosmogenic isotopes, is likely less and physical weathering more than commonly assumed. This has been illustrated from sites in Norway and Greenland.
3. Relatively minor cooling (3°C) would be adequate to greatly hasten bergschrund development in Rocky Mountain glaciers. Presumably similar results could be obtained elsewhere in the world.
4. Not all diamict is till. Diamict has been deposited in recent decades by jökulhlaups. Likewise, some till or glacial drift is stratified. Stratification or lack thereof does not constitute an adequate criterion to determine if a deposit is glacigenic. "Pre-Pleistocene ice age" deposits probably formed mostly as submarine landslides.
5. Boulders were shaped, transported, and deposited by many processes during the Little Ice Age. In many cases, multiple processes were involved (i.e., polygenetic), while effects were the same for different processes (i.e., equifinality), meaning only historical data could differentiate processes.
6. True varves have been observed forming in some extant proglacial lakes, though most laminated sediments are not varves, and many classic "varve" sequences are not annual layers.
7. Fabric analyses are not diagnostic but can be helpful in conjunction with other criteria to determine the most probable mode(s) of origin of a given deposit. Additional research may improve shape and fabric methods, though one cannot expect them to be adequate to discriminate among all potential modes of origin.
8. Depositional flutes are observed at locations in Norway and Iceland from the Little Ice Age but not from the proglacial landscape in front of the Little Ice Age moraines. Erosional flutes are observed in Canada, where they predate the Little Ice Age.
9. Clastic dikes sometimes form where unfrozen sediment provides an outlet for overpressured subglacial water. Clastic dikes form where sediment infills crack. This sediment is sometimes diamict, sometimes laminated or stratified, and shows transitions from one to the other.
10. Glacial pavements formed during and after the Little Ice Age from current winnowing and deflation of fines.
11. Moraines often form on an annual basis in front of retreating glaciers and sometimes form more rapidly before surging glaciers. Moraines frequently form from juxtaposition of small, heterogeneous deposits and may be polygenetic. Source material may be transported via any combination of subglacial, englacial, and supraglacial routes and glacial, glaciofluvial, glaciotectonic, fluvial, and mass wasting processes. Where ice is incorporated into the moraine, a hummocky surface typically develops.
12. Depositional drumlins did form in Iceland during the Little Ice Age. Though they are rare, it is possible that more will appear as glaciers recede. Erosional drumlins are also known, but these predate the Little Ice Age. Great Ice Age drumlins are larger, more numerous, and of both depositional and erosional types. In some cases, subglacial megafloods appear the only plausible explanation proffered thus far.
13. Eskers were produced during the Little Ice Age by surging glaciers in combination with supraglacial streams and inverted topography, and also by jökulhlaups alone. Eskers are thus an example of equifinality.
14. Kames and terraces were developed during the Little Ice Age via glacial and glaciofluvial processes. Multiple terraces were observed to form from a single jökulhlaup.
15. Kettles formed during the Little Ice Age both glacially and glaciofluvially.

16. Rock glaciers occupy a narrow climatic niche and in at least some cases appear to be relict features from the Little Ice Age.
17. Outwash plains formed rapidly, episodically, extensively, and catastrophically during the Little Ice Age. Sandar in Iceland significantly altered the southern coastline.
18. Overdeepened valleys formed during the Little Ice Age. Jökullsárlón in Iceland was excavated between 120 and 300 m below sea level.
19. Hard bedrock was planed, polished, scratched, plucked, shaped into roche moutonnées and whalebacks, and ground down during the brief centuries of the Little Ice Age at rates far above those estimated for previous millennia by believers in the old earth paradigm.
20. Patterned ground quickly formed in permafrost areas following recession of glaciers. Periglacial processes formed rock circles and likely block fields.
21. Surging can greatly accelerate geologic work. Many glaciers have been observed to surge from more than a meter per day to as much as 10.5 km and possibly more. Some features that have been used to infer that glaciers were cold based are equivocal. Traction stresses are more related to pore water pressure than bed projections and may indicate faster ice transport, less bed shearing, and more bed deformation than previously thought. Where gradients are steep and glaciers detach from their beds, debris flows and avalanches may result. Water-ice interaction is very important and has been invoked to explain rates of erosion one to two orders of magnitude higher than previously assumed.
22. Mass wasting is a highly effective transport mechanism both for contributing to glacial sediment load and modifying landforms, but it is only effective for the former where steep and rugged terrain exists. It is therefore irrelevant to ice sheets or continental glaciers, which would thus tend to be starved for sediment.
23. Seasonal freezing and thawing promotes incorporation of sediment from the glacier bed in conjunction with ice thrusting and overpressured subglacial water. These conditions are most likely in glaciers with relatively steep gradients or conditions conducive to jökulhlaup generation.
24. Release of sediment into the proglacial area tends to be highly episodic due to changes in the ice margin relative to moraines.
25. Multiple directions in paleocurrent (ice flow) indicators do not imply a hiatus or multiple glaciations.
26. Glaciomarine effects of the Little Ice Age were much less than inferred for the Great Ice Age due to the much smaller ice extent during the former (particular at coasts) and the likely lower sea level during the Great Ice Age.
27. Many features resulting from the Little Ice Age are equifinal or polygenetic, many glacial landforms are relatively short lived, and inferences regarding the historically undocumented past must therefore be guarded and contingent.
28. Glaciation results in much glaciofluvial activity, from catastrophic jökulhlaups to "ordinary" glacial and proglacial streams. Lack of vegetation, as is common in glaciated areas, combined with heavy rainfall can produce very high sediment loading in streams. However, evidence exists for floods of regional extent in the past, far greater than the largest historically documented glacial outburst floods. Establishment thinking often opposes these catastrophes, but even they pale before the unique event described in Genesis 8–11. Much geologic work traditionally attributed to glaciation may be glaciofluvial or diluvial, and diluvialists need to explore these possibilities when speculating about the natural history of the features we observe today.

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Glossary

Bergschrund – the arcuate scarp at the headwall of a glacier; this is where headward erosion occurs, advancing the glacier into the mountain.

Deluge – a common deluge is intense rainfall (and flooding) over a short period of time. When capitalized, it refers to what the Bible calls the *mabbul*, the global flood of Noah's time.

Diamict – unconsolidated sediment consisting of a wide range of particle sizes in a fine-grained matrix. *Glacial till* is a genetic term for some diamicts and how they formed.

Diluvial – pertaining to the Deluge.

Diluvialist – one who believes most geologic work occurred during the Deluge.

Drumlin – a streamlined hill or ridge oriented parallel to fluid (e.g., ice) movement—a giant flute. Drumlins can be erosional or depositional.

Esker - a sinuous ridge, typically of gravel deposited by an englacial stream.

Geologic work – erosion (physical weathering and transport) and deposition, tectonic displacements, and other physical alteration of rocks and soils.

Jökulhlaup – a catastrophic glacial outburst flood caused when pent-up water is released during a volcanic eruption or when an ice dam floats due to the head of water.

Kame – melting of ice can produce a hill or mound where sediment had been dumped into a hole in the ice; such a hill or mound is a kame.

Kettle – a relatively small, deep hole formed when a large block of ice buried with sediment melts.

Moraine – a ridge formed by deposition of sediment from a glacier.

Sandur – a glacial outwash plain; an Icelandic term for the low gradient, coastal plains built by braided streams and jökulhlaups.

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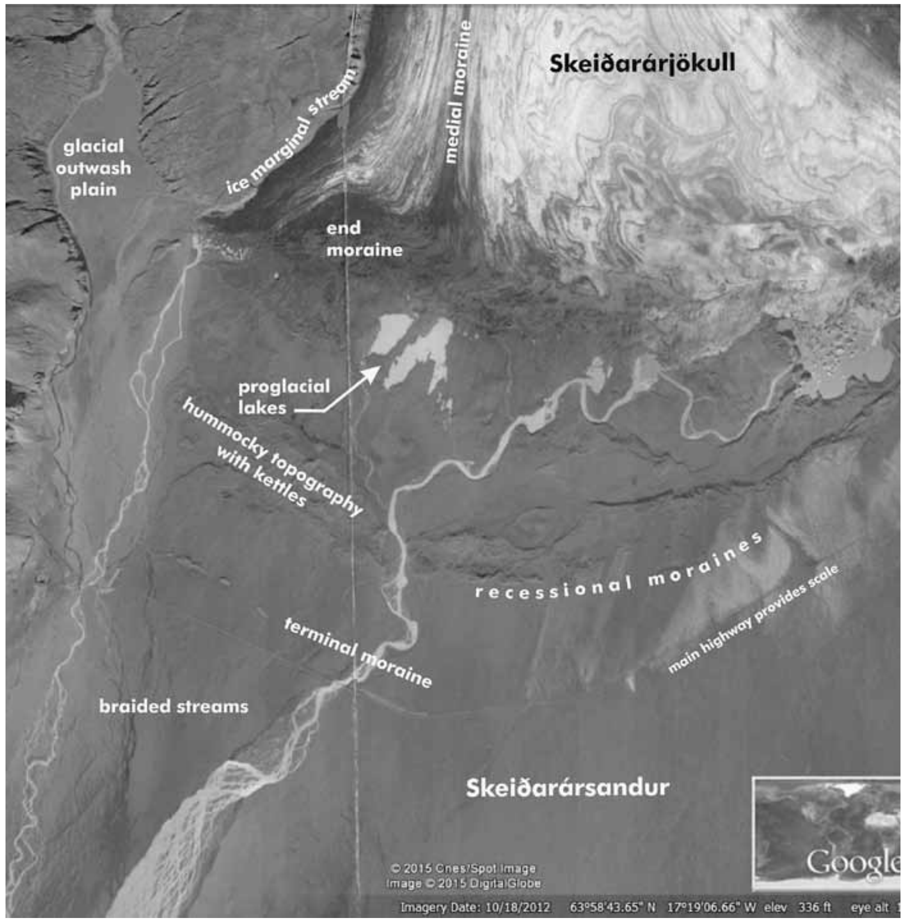


Figure A1. Aerial photomosaic of snout of Skeiðarárjökull with glacial landforms labeled. Meltwater channels have shifted frequently through the years.

Appendix A: Illustrations of Glacial Landforms

As documented in Part III of this series (Klevberg and Oard, 2012a), southeastern Iceland provides some of the best-documented glacial features from the Little Ice Age. Figures A1–A6 are all from the Vatnajökull area.

While water is the most common fluid for transporting sediment, ice is the most viscous. Large quantities of rock and debris sometimes avalanche onto glaciers from oversteepened valley walls, and the ice slowly carries its large sediment burden down the valley. Outlet glaciers drain large inland bodies of ice

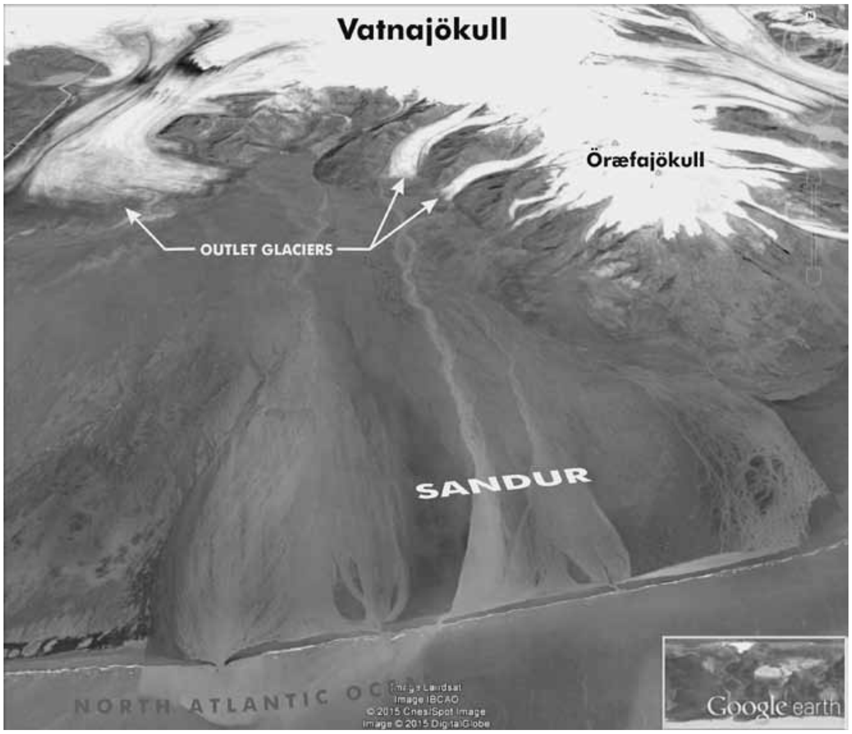
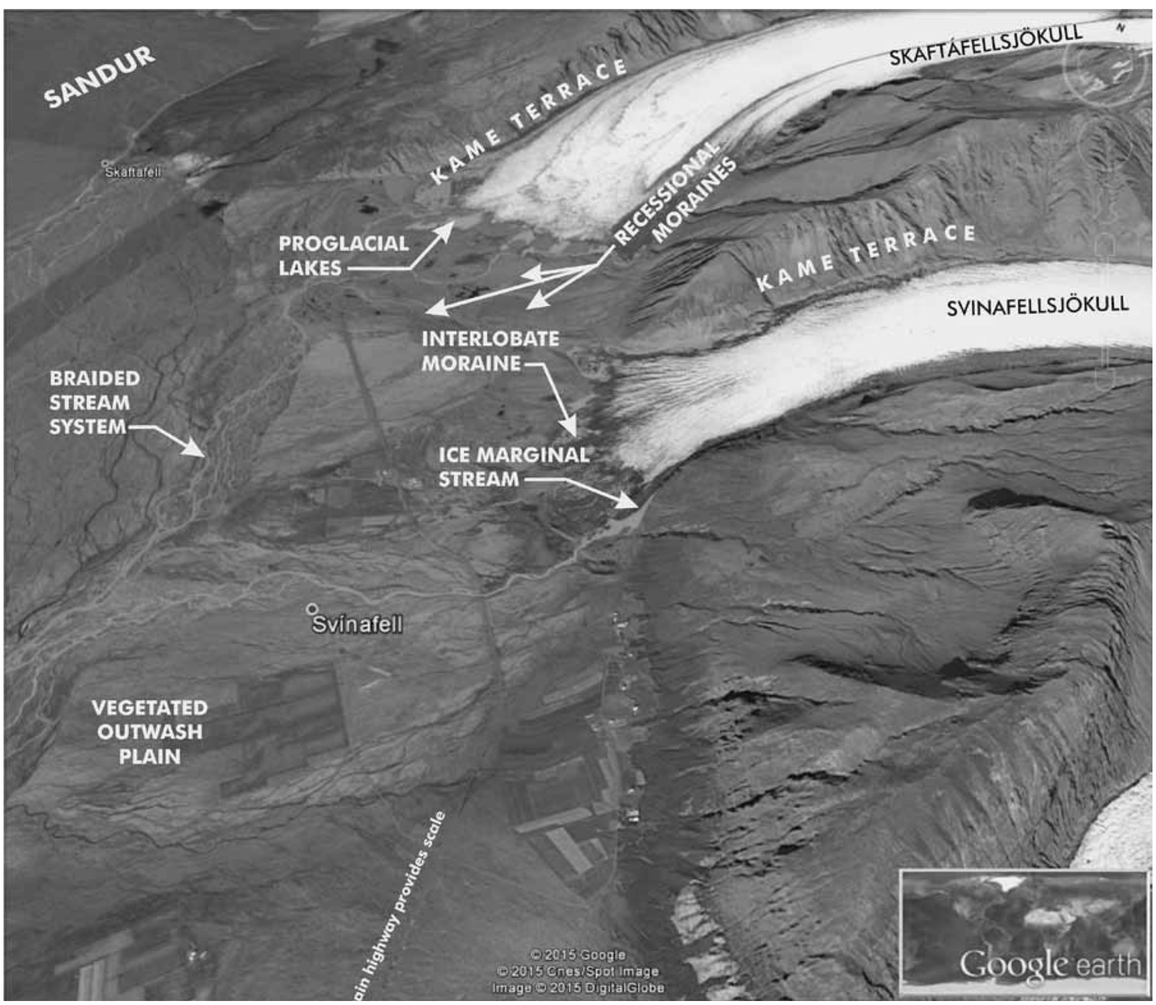


Figure A2 *(left)*. Prominent sandur south of Vatnajökull. The outlet glacier to the left (west) is Skeiðarárjökull; the two indicated to the right (east) are Skaftafelljökull and Svinafelljökull. Oblique Google Earth view.

Figure A3 *(below)*. A closer view of the area shown in Figure A2, showing various glacial landforms produced by Skaftafelljökull and Svinafelljökull, mostly during the Little Ice Age.



such as Vatnajökull in Iceland (Figure 2) and the Greenland Ice Sheet (Figure 1). Debris stuck in the ice scratches bedrock, forming *striations*, as well as rounding and polishing the bedrock. As the ice melts, it dumps its load, often quite quickly. This typically results in an unsorted mixture of all different sediment sizes known as *till*. The till forms *moraines*, sometimes shaped as ridges along the middle, edges, or snout of glaciers. Till is also pushed by moving ice and deposited from the ice as it melts and recedes. It may be shaped by flowing ice into *flutes* and *drumlins*.

Much of the glacial landscape is actually formed by running water. Melting ice provides a source of water that flows as englacial streams, subglacial and supraglacial streams, marginal streams, and braided streams. Where water is stored up beneath or behind a glacier and then bursts forth suddenly in a *jökulhlaup*, enormous amounts of geologic work can be done in a very short period of time. Jökulhlaups are primarily responsible for the large *sandar* of Iceland.

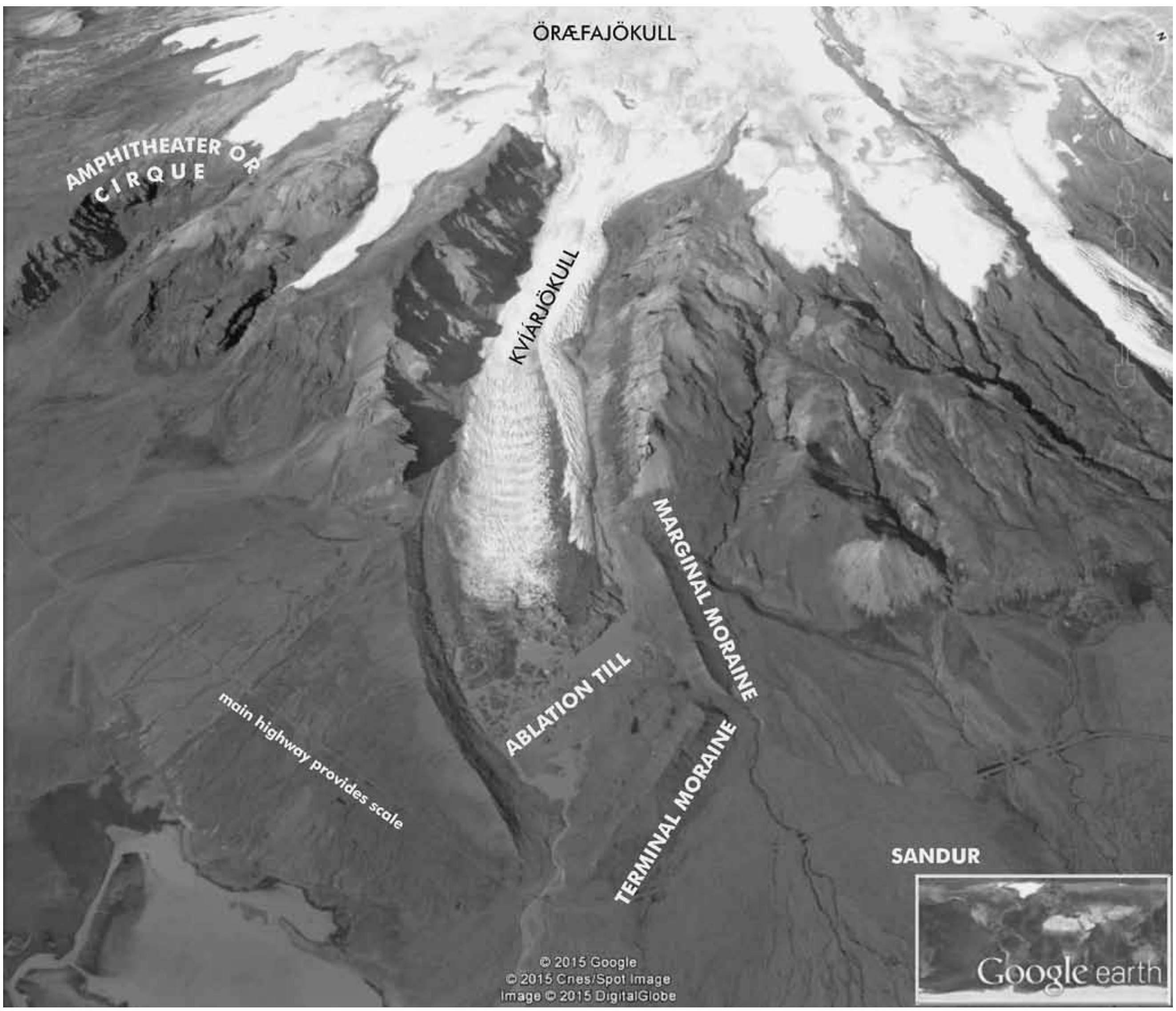


Figure A4. Öræfajökull is the ice cap on Öræfi, the high mountain at the south end of Vatnajökull. Kvíárjökull is the most prominent outlet glacier from Öræfajökull and occupies a deeply cut valley. The terminal moraine arrested the advance of the glacier during the Little Ice Age (Ives, 2007). The other outlet glaciers tend to move less ice and produce less erosion as a result. The prominent erosional feature to the left (northwest) may be an an amphitheater produced by mass wasting, a cirque eroded by a glacier, or as seems likely, an amphitheater in which ice contributed to enlargement during the Little Ice Age. Oblique Google Earth view.

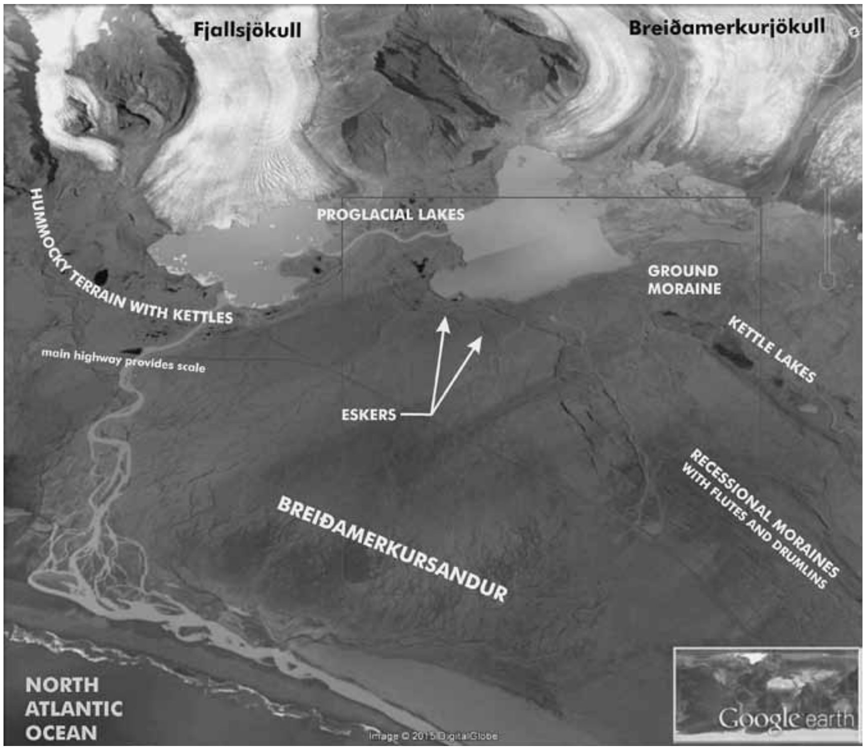
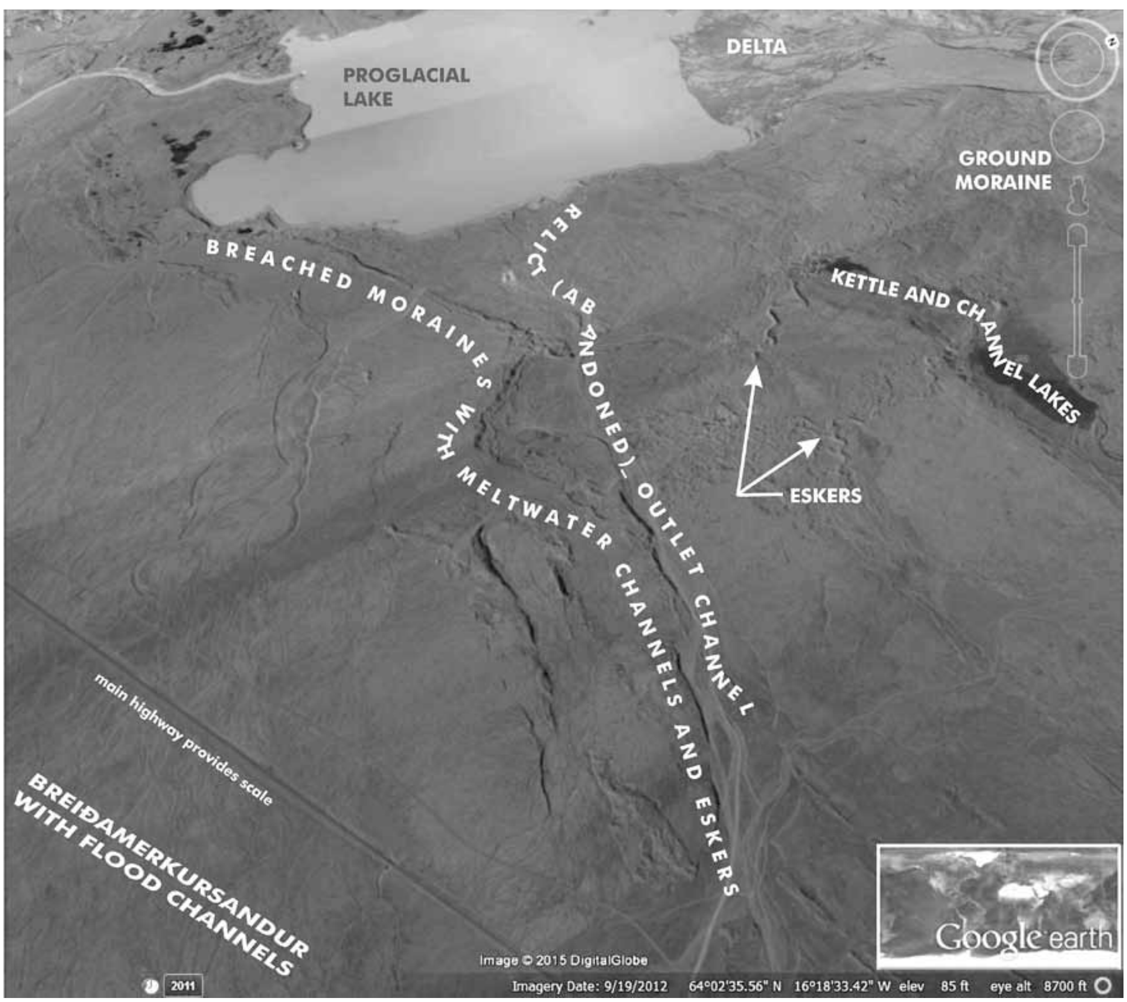


Figure A5 *(left)*. Oblique Google Earth image of Breiðamerkur southeast of Vatnajökull, Iceland, with glacial landforms indicated.

Figure A6 *(below)*. Closer view of part of area shown in Figure A5 with some glacial landforms labeled. This area was completely covered by advancing glaciers during the Little Ice Age (Klevberg and Oard, 2012a).



Appendix B: Recommendations for Future Research

The work summarized in this series shows many possibilities for fruitful research. In particular, we recommend others consider researching the following:

- Evidence for and effects of the Little Ice Age in other regions
- The veracity of transfer functions and whether some proxy data may be used to provide independent rather than interdependent lines of evidence in paleoclimatology
- Evidence for or against the Medieval Warm Period and whether it was global or regional
- Global heat balance questions (insolation, volcanic effects, etc.)
- Nonglacial geologic processes that generate deposits and landforms that can also be generated glacially
- Additional fabric studies in known glacial and nonglacial environments and suspected glacial terranes, including clast roundness ratios
- Isostatic adjustments of Greenland during and after the Little Ice Age