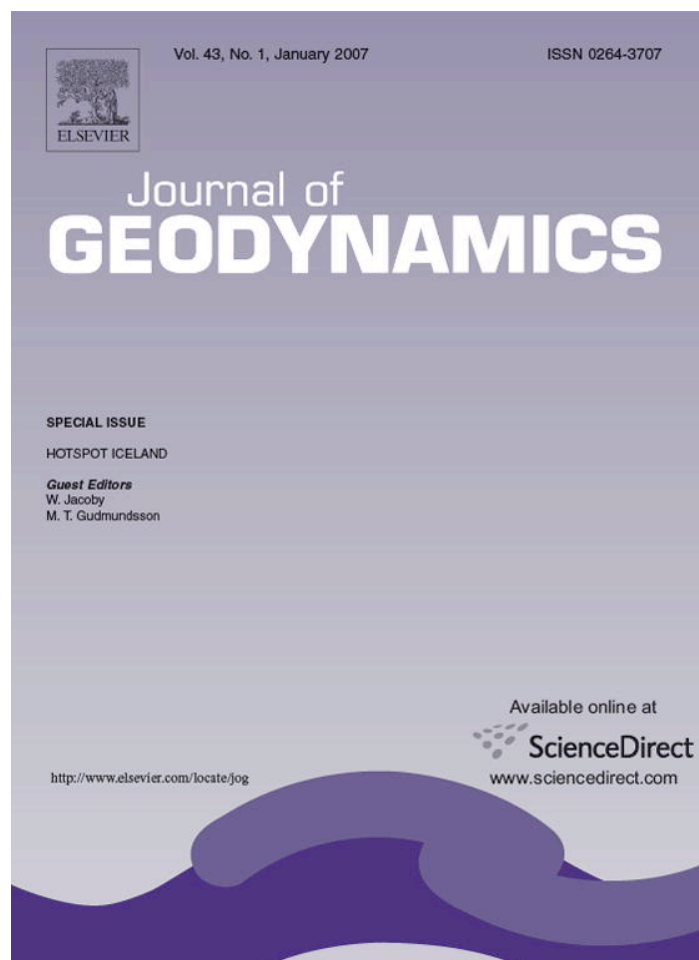




This article was originally published in a journal published by Elsevier, and the attached copy is provided by Elsevier for the author's benefit and for the benefit of the author's institution, for non-commercial research and educational use including without limitation use in instruction at your institution, sending it to specific colleagues that you know, and providing a copy to your institution's administrator.

All other uses, reproduction and distribution, including without limitation commercial reprints, selling or licensing copies or access, or posting on open internet sites, your personal or institution's website or repository, are prohibited. For exceptions, permission may be sought for such use through Elsevier's permissions site at:

<http://www.elsevier.com/locate/permissionusematerial>

Glaciation, erosion, and landscape evolution of Iceland

Áslaug Geirsdóttir^{a,*}, Gifford H. Miller^b, John T. Andrews^b

^a Earth Science Institute & Department of Geosciences, University of Iceland, Askja, Sturlugata 7, 101 Reykjavík, Iceland

^b INSTAAR & Department of Geological Sciences, University of Colorado, Campus Box 450, Boulder, Colorado, USA

Received 12 August 2005; received in revised form 15 August 2006; accepted 5 September 2006

Abstract

Stratigraphic and sedimentological studies indicate that Iceland has experienced over 20 glaciations during the last 4–5 Myr, in reasonable agreement with the number of glaciations reconstructed from the $\delta^{18}\text{O}$ record in deep-sea sediment. The pattern of glacial erosion was to a large part controlled by constructive volcanic processes resulting in increased topographic relief after 2.5 Myr. Between 2.5 and 0.5 Ma valleys up to 400 m deep were excavated into the Tertiary basalts of eastern and south Iceland with an average erosion rate of 10–20 cm ka⁻¹. During the last 0.5 million years rates of erosion increased to 50–175 cm ka⁻¹, with an additional 200 to over 1000 m of valley excavation. Previous estimates of the rate of landscape erosion during the Holocene vary widely, from 5 to 70,000 cm ka⁻¹. We present new studies that define the rates of landscape denudation during the major part of the Holocene (the last 10,200 years): one based on the Iceland shelf sediment record, the other from the sediment record in the glacier-fed lake, Hvítárvatn. Both studies indicate average Holocene erosion rates of about 5 cm ka⁻¹ similar to our erosion rate estimate for 4–5 Ma old strata that has not been subjected to regional glaciation.

© 2006 Elsevier Ltd. All rights reserved.

Keywords: Pliocene; Quaternary; Holocene; Denudation; Sedimentation; Glacial cycles

1. Introduction

The Cenozoic is characterized by a significant cooling of the high latitudes, which ultimately led to the Quaternary situation, with oscillations between colder and warmer polar regions, colder and warmer oceanic deep waters, and extensive glaciations in both hemispheres interrupted by warmer interglacial phases. Available evidence largely extracted from marine sediment cores in the Greenland–Iceland–Norwegian Seas suggests that Northern Hemisphere glaciations began between 10 and 5 Ma, with the onset of large-scale glaciations around 2.75 Ma (cf. Raymo et al., 1986; Jansen et al., 2000; Shackleton et al., 1990; ODP leg 151, 1994; Jansen et al., 1990; Wolf and Thiede, 1991; Jansen and Sjöholm, 1991; Maslin et al., 1998). Northern Hemisphere glaciations proceeded throughout the Quaternary. Based on the North Atlantic deep-sea oxygen isotope record, altogether there were more than 20 recurrent full glaciations.

Direct terrestrial evidence is lacking for most Quaternary glaciations (cf. Fronval and Jansen, 1996). However, glaciations are better preserved in Iceland than in any other terrestrial location around the North Atlantic because of its position within a rifting zone where intermittent volcanic activity occurs. The formation of laterally extensive flood

* Corresponding author. Tel.: +354 525 4800; fax: +354 562 9767.

E-mail addresses: age@hi.is, age@rhi.hi.is (Á. Geirsdóttir), gmler@colorado.edu (G.H. Miller), andrewsjt@colorado.edu (J.T. Andrews).

basalts has served to protect older, underlying glacial and non-glacial sediments (Geirsdóttir and Eiríksson, 1994, 1996; Geirsdóttir, 2004). This inimitable geographic and climatic position enhances the island's importance in glacial geological and palaeoclimatic research.

Mapping of Pliocene and Quaternary strata in Iceland has revealed a number of sedimentary layers of glacial origin intercalated within the basaltic lava flows. This has made it possible to pinpoint, to a certain extent, the age of individual glacial cycles by the use of paleomagnetic studies, correlation with the paleomagnetic reversal timescale, and radiometric dating of the under- and overlying lava flows (i.e. Geirsdóttir and Eiríksson, 1994, 1996). Comparisons between the North Atlantic deep-sea isotopic record and Icelandic glacial–interglacial cycles suggests that the late Tertiary and Quaternary glacial record in Iceland reflects the large-scale palaeoclimatic processes seen in the deep-sea record and can thus be taken as a relatively continuous record of glaciations through the last Ice Age (Geirsdóttir and Eiríksson, 1994, 1996; Geirsdóttir, 2004). The mapping of glacial deposits in Iceland has also revealed a progressive spread of the Icelandic ice sheet through time, making it possible to draw inferences about the intensities of individual glaciations, changes in topography and landscape evolution since the initiation of glaciation in Iceland.

This paper provides an overview of the regional pattern of glaciations and environmental change through time in Iceland, including an assessment of changes in glacier intensities and landscape evolution in eastern and southern Iceland since the Pliocene. In a dynamic setting such as Iceland, landscape evolution reflects the competition between volcanic processes that add new land, and glacial, fluvial, eolian, and coastal erosion that removes it. Estimates of the rate of landscape erosion vary widely from 5 to 70000 cm ka^{−1}. Although we do not have an estimate of the rate of glacial erosion on Iceland during the last glacial cycle, nevertheless it does appear that the rate of sediment accumulation on the adjacent slopes and in the deep-sea basins is relatively small, about 100–200 cm between ~10 and 25 ka (Andrews and Cartee-Schoofield, 2003; Andrews, 2005). This implies a limited amount of glacial transport to the shelf break.

We present new studies that define the rate of landscape denudation during the Holocene: one based on the Iceland shelf sediment record, the other from the sediment record in the glacier-fed lake, Hvítárvatn. Both suggest Holocene denudation rates of ca. 5 cm ka^{−1} during the last 10200 yrs.

2. Glaciation of Iceland

Rifting plate boundaries that divide the island between the Eurasian and North American plate control the geological structure of Iceland (Fig. 1). The configuration of plate margins on the island itself is complex and thought to be related to a mantle plume forming a hot spot under Iceland, approximately beneath the glacier Vatnajökull in the southeast. The Reykjanes ridge in the south and the Kolbeinsey ridge in the north are connected through the E–W trending South Iceland Seismic Zone (Saemundsson, 1979; Jóhannesson and Saemundsson, 1998). As a result of this configuration, the oldest rocks of ca. 15 Myr occur in the easternmost and westernmost parts of the island and the youngest rocks along the rifting zone. Unusually high volcanic productivity caused by the superposition of the mantle plume and mid-ocean-ridge magmatism have made Iceland an environment where constructive geologic processes outweigh destructive processes. The results are an excellent preservation of the Tertiary and Quaternary depositional record in Iceland, where sediment horizons are covered and protected from erosion by basaltic lava flow sequences (Fig. 2). Lava flows are deposited in ice-free regions and the general consensus is that they represent interglacials or interstadials, whereas hyaloclastites (subglacially formed volcanics) and till represent glaciations. Mapping and dating of remnants of glacial deposits found intercalated within the basaltic lava flows of Iceland has revealed an intermittent record of glaciation since the late Pliocene with the earliest glacial deposits found in the eastern and western Iceland rock sequences (Fig. 1; Geirsdóttir and Eiríksson, 1994, 1996). This pattern of preservation and erosion through time is consistent with near constant outpouring of lava and volcanic matter along the rift boundaries during both glaciations and interglaciations. Erosion dominates along the margin of the ice sheets during glaciations, resulting in the excavation of valleys, fjords and troughs across the insular shelf.

2.1. Pliocene to Late Quaternary glaciations

Sporadic outcrops of glacial deposits within the deeply eroded eastern Pliocene rock sequences suggest initial glaciation of Iceland occurred between 5 and 3 Ma (Figs. 1 and 3) (Geirsdóttir and Eiríksson, 1994, 1996; Helgason and

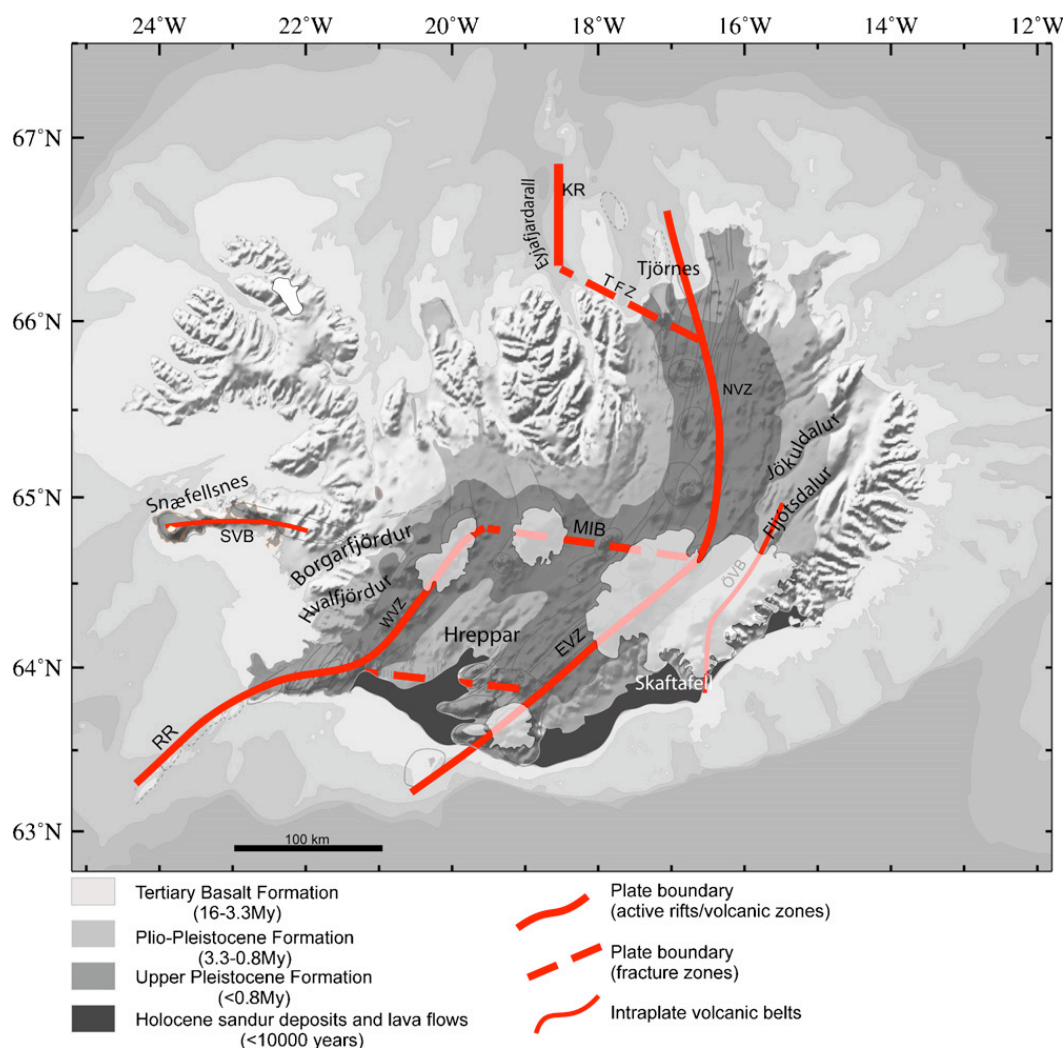


Fig. 1. The geological map of Iceland, including the main volcanic zones and belts. RR, Reykjanes Ridge; WVZ, West Volcanic Zone; MIB, Mid-Iceland Belt; EVZ, East Volcanic Zone; NVZ, North Volcanic Zone; TFZ, Tjörnes Fracture Zone; KR, Kolbeinsey Ridge (KR); ÖVB, Öraefi Volcanic Belt; and SVB, Snæfellsnes Volcanic Belt. Also shown are sites mentioned in the text.

Duncan, 2001). In the Skaftafell area at the southern margin of Vatnajökull Helgason et al. (2001) identify a 4.6–4.7 Myr old glacial deposit associated with hyaloclastites and pillow lavas. Similarly, Geirsdóttir and Eiríksson (1994, 1996) identified two to three separated glacial deposits intercalated within ca. 3–4 Myr old lava flows in Fljótisdalur, eastern Iceland. Because none of these glacial deposits are traceable over long distances, they are interpreted as representing local glacier activity rather than regional ice-sheet glaciation (Fig. 3).

The first indication of a progressively advancing ice sheet in Iceland dates to ca. 2.9 Ma, based on a correlation between glacial deposits found in two valleys, Fljótisdalur and Jökuldalur, eastern Iceland, K–Ar dated lava flows (Watkins and Walker, 1977; Gudmundsson, 1978) and the paleomagnetic polarity time scale (Figs. 1 and 4a and b) (Cande and Kent, 1995). Four additional glacial deposits found in lava sequences of eastern and western Iceland (Borgarfjörður and Hvalfjörður) dated between 2.9 and 2.5 Ma suggest even more extensive glaciations (Figs. 3 and 4) (Geirsdóttir, 1990; Geirsdóttir and Eiríksson, 1994, 1996). However, mapping and correlation of these deposits indicates the glaciations were restricted to the highlands. The oldest glacial deposit found in the Tjörnes stratigraphy (Fig. 1), indicates a northward and hence more regional expansion of the ice sheet around 2.5 Ma (Geirsdóttir and Eiríksson, 1994). This increase of Iceland Ice Sheet intensity is supported by palaeomagnetic studies and K–Ar radiometric dating on the stratigraphy of Skaftafell, southeast Iceland (Helgason and Duncan, 2001). A renewed period of glacier expansion and intensity around 2.2–2.1 Ma, after a 0.4 Myr interval lacking glacial deposits, is defined by the oldest tillite in the 2.5–1.0 Myr-old Hreppar Formation, southern Iceland (Fig. 5a), a formation characterized by interbedded glacial and volcanic deposits (Geirsdóttir et al., 1993). By 1.5 Ma ca. seven near full-scale

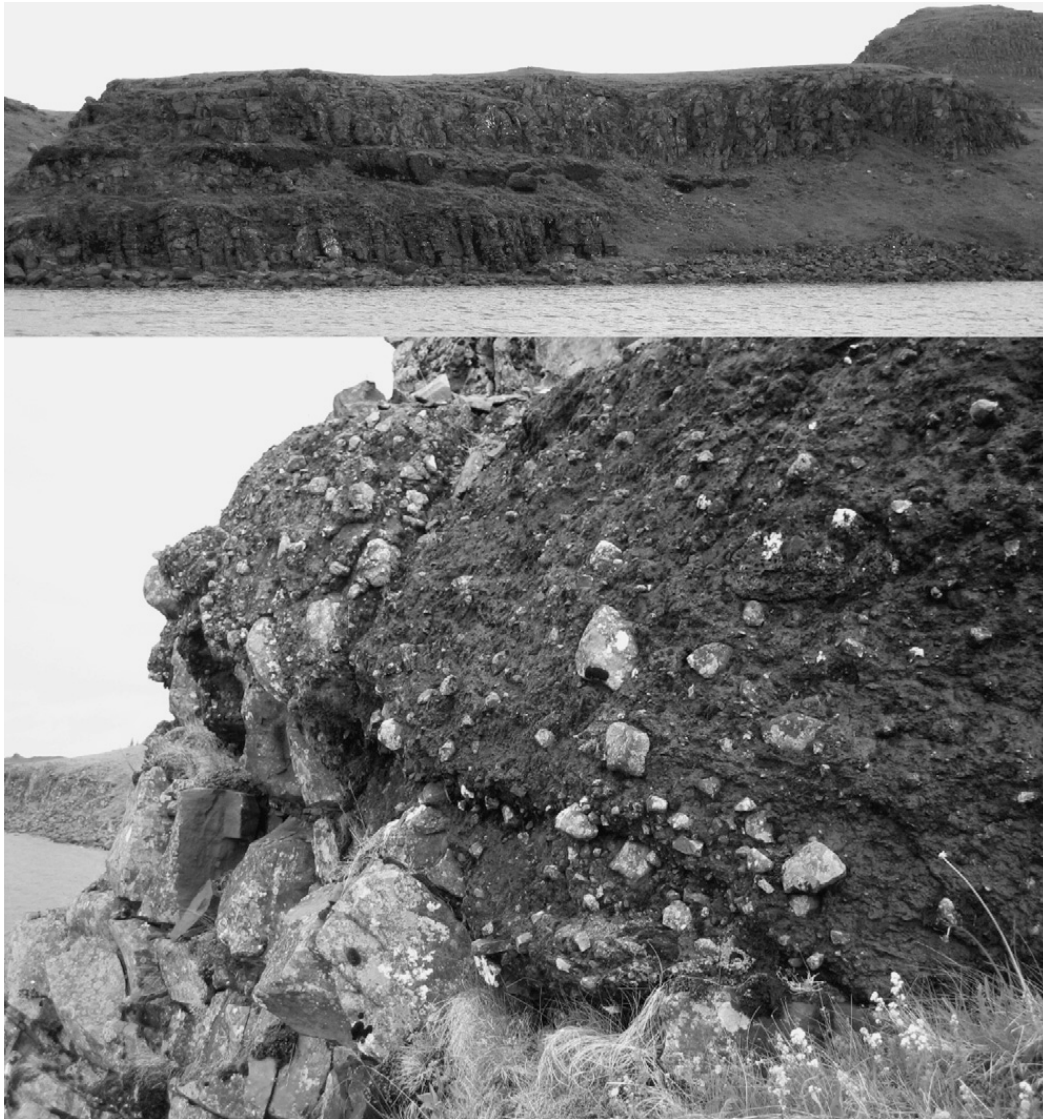


Fig. 2. Mapping of sediment layers sandwiched between basaltic lava sequences in Iceland has revealed an excellent preservation of the Tertiary and Quaternary depositional record in Iceland, where sediment horizons are covered and protected from erosion by basaltic lava flow sequences. Lava flows are deposited in ice-free regions and the general consensus is that they represent interglacials or interstadials, whereas hyaloclastites (subglacially formed volcanics) and till represent glaciations.

glacial–interglacial cycles are found in the eastern Iceland section with glacial deposits (glacial advances) lying on striated lava flows but underlying fluvial and lacustrine sediment (deglacial) capped by younger lava flows (interglacial) (Fig. 5a and b).

The glacial stratigraphy of Iceland from ca. 1.5 Ma to the last deglaciation is fragmentary, apart from the Tjörnes section in Northern Iceland, which contains nine stratigraphically separated glacial deposits in the last 1.5 Myr (Eiríksson, 1985). The lack of continuous records elsewhere in Iceland through the Quaternary may be due to a lack of systematic research and radiometric dates; old glacial and interglacial deposits of unknown age have been reported from various sites all around Iceland. Tillites from the Middle Pleistocene have been reported from North Iceland (Jancin et al., 1985), and on the Snæfellsnes Peninsula in West Iceland (Fig. 3, Einarsson, 1994; Leifsdóttir, 1999), where paleomagnetic correlations suggests that glacial deposits were probably formed between 2 and 0.7 Ma. Discontinuity in the glacial record may also be due to differential preservation potential of glacial deposits where constructive forces (production of volcanic material) outweigh destructive forces (erosional) around the plate boundaries (in many cases below the presumed ice divide). The Tjörnes section is located at the flank of the rifting zone, where constructive and destructive forces compete continuously offering a full preservation of the glacial record for the last 0.5 Myr. The unequal battle

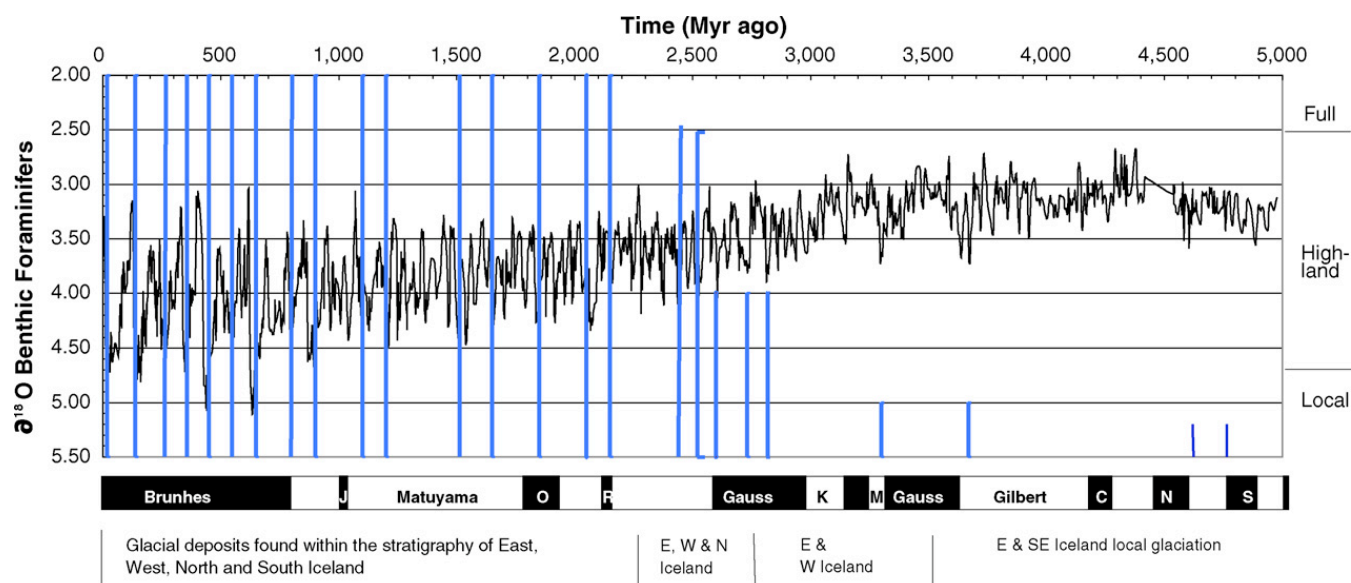


Fig. 3. Correlation of identified glacial deposits in the Iceland stratigraphy with the Tropical Pacific benthic isotope record from core ODP849 for 0–5 Ma. Also shown is the Magnetic polarity time scale of Cande and Kent (1995). Lines show the approximate position of glacial deposits found in the Icelandic stratigraphy (Mix et al., 1995a,b).

between constructive and destructive processes elsewhere in Iceland reflects the pattern of glacier growth (and retreat) in Iceland through time. The focus of volcanic activity was along the northern volcanic zone (Fig. 3) between 4 and 0.1 Ma, but around the Hreppar area (the eastern volcanic zone) in southern Iceland only after 3 Ma. No Pliocene or Pleistocene glacial deposits have been found within the stratigraphy of the Vestfirðir Peninsula of NW Iceland, despite

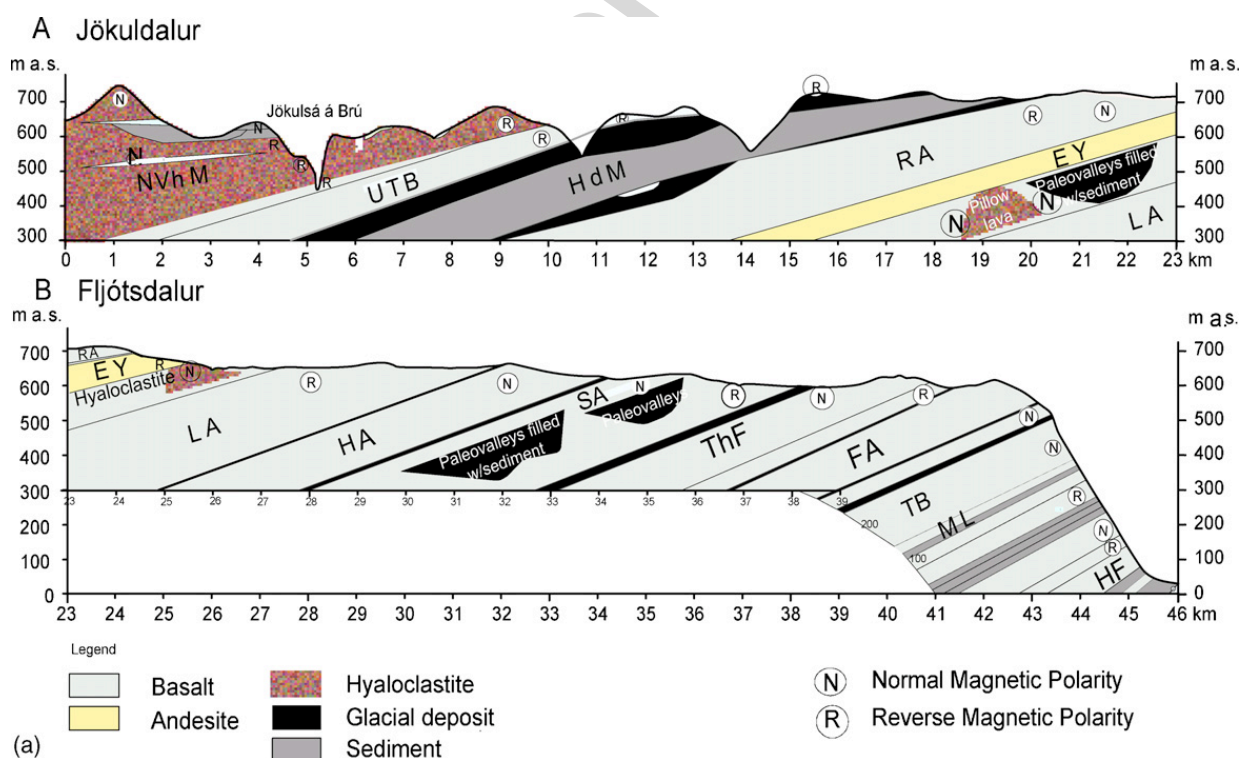


Fig. 4. (a) A cross section through the Fljótsdalur and Jökuldalur strata. Capital letters refer to rock formations within the stratigraphy. (b) Cumulative stratigraphy of the Fljótsdalur and Jökuldalur area correlated with the Paleomagnetic time scale of Cande and Kent (1995). Also shown are K/Ar dates made on basaltic rocks within the stratigraphy (Watkins and Walker, 1977; Gudmundsson, 1978). Capital letters refer to rock formations within the stratigraphy as in (a).

Fljótsdalur - Jökuldalur

Cumulative stratigr

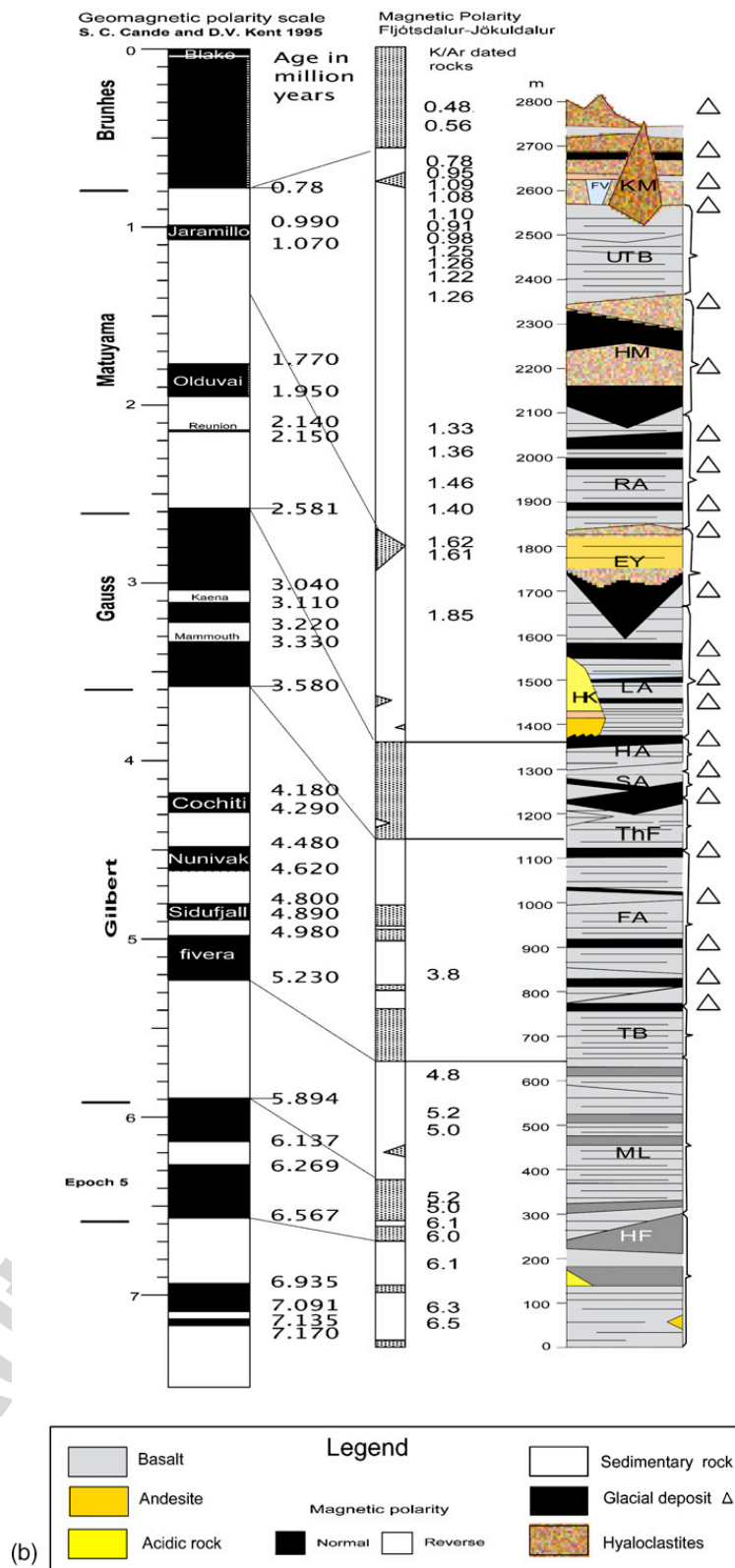


Fig. 4. (Continued).

classic glacial erosional landforms, probably because no volcanic activity has taken place there during the last 6 Myr (erosive processes dominate).

Geological studies of the Tjörnes section in northern Iceland suggest an increase in the intensity of glaciation after 1 Ma when the 100 kyr ice-volume cycle developed (Fig. 3, Eiríksson, 1985; Geirsdóttir and Eiríksson, 1994, 1996). This is in accordance with the findings of Helgason and Duncan (2001) in southeast Iceland. However, the Tjörnes section is the only site known in Iceland with a complete glacial stratigraphy for the last 0.5 Myr (Eiríksson, 1985).

2.2. The last glacial cycle

The precise timing of the Last Glacial Maximum (LGM) and the full extent of the Iceland ice sheet is poorly constrained, although the deglacial cycle is reasonably well defined. Accumulating data indicate that during the LGM, ice streams and outlet glaciers from ice divides in central Iceland terminated at or close to the shelf edge (Fig. 6a) (Kaldal and Víkingsson, 1990; Stokes and Clark, 2001; Andrews et al., 2000, 2002a; Bourgeois et al., 2000; Geirsdóttir et al., 2002; Andrews and Helgadóttir, 2003; Helgadóttir et al., 2005). Small ice-free areas may have existed along the coastal mountains, particularly in the northwest, north and east (e.g. Einarsson and Albertsson, 1988; Ingólfsson, 1991; Norddahl, 1990; Ingólfsson and Norddahl, 1994; Andrews et al., 2000; Rundgren and Ingólfsson, 1999). The Vestfirðir Peninsula in NW Iceland may have supported a dynamically independent ice cap and/or valley glaciers with outlet glaciers or ice streams originating within an ice-divide near the centre of the peninsula (Hjort et al., 1985; Hoppe, 1982; Andrews et al., 2002a; Geirsdóttir et al., 2002; Principato, 2003; Principato et al., 2006).

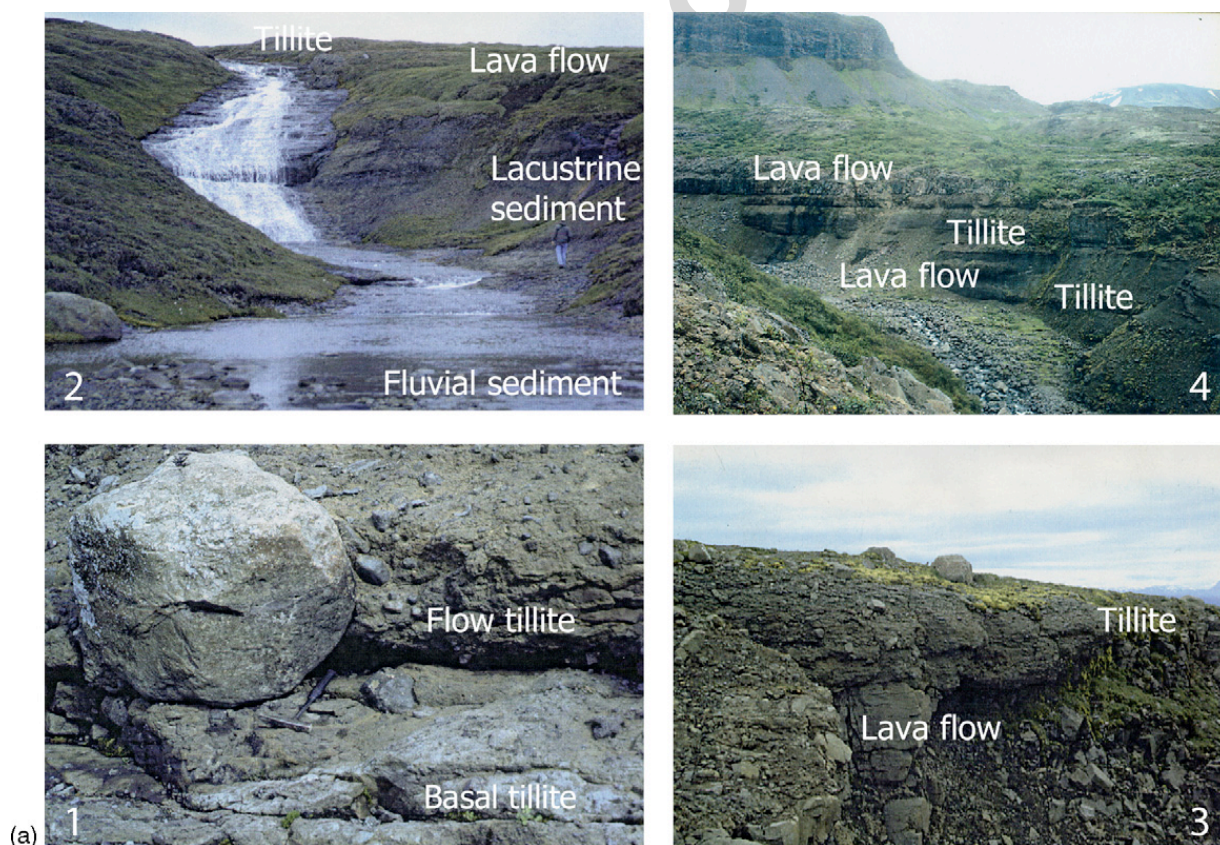


Fig. 5. (a) By 1.5 Myr ca. seven near full-scale glacial–interglacial cycles are found in Fljótsdalur, eastern Iceland, with glacial deposits (glacial advances) lying on striated lava flows but underlying fluvial and lacustrine sediment (deglacial) capped by new lava flows (interglacial) (photos 1 and 2 to the left). Photos 3 and 4 show ca. 2.8 Ma old tillites interbedded with basaltic lava flows in Hvalfjörður, western Iceland. (b) The 2.5–1.0 Ma old Hreppar Formation, southern Iceland, is a formation characterized by interbedded glacial and volcanic deposits (top photo). The oldest glacial deposit is around 2.2 Ma old (bottom photo).

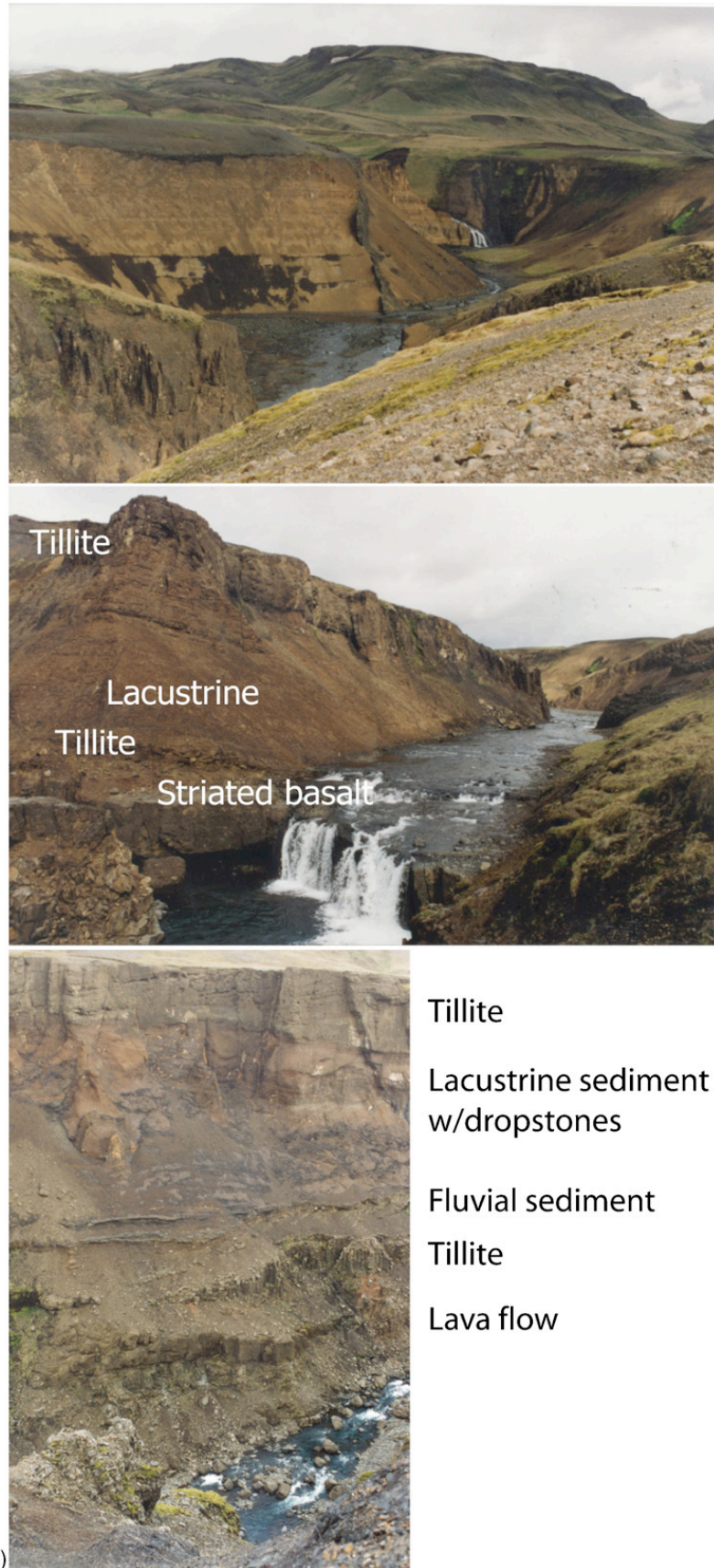


Fig. 5. (Continued).

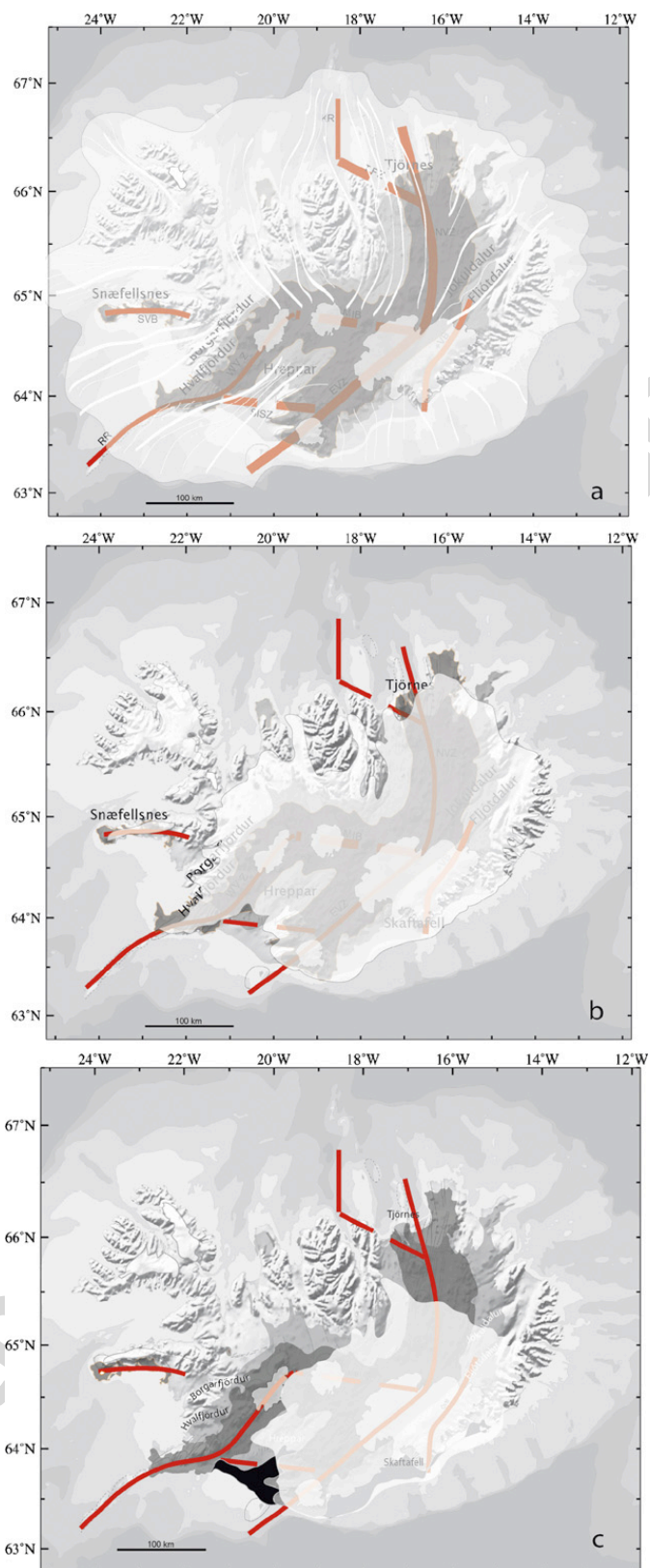


Fig. 6. Stepwise retreat of the Iceland Ice Sheet after 15 cal ka. During the Last Glacial Maximum (LGM), ice streams and outlet glaciers from ice divides in central Iceland terminated at or close to the shelf edge. (b) The occurrence of the Vedde Ash in lake sediments constrains the age of these paleo lakes and shows that during the Younger Dryas Chronozone outlet glaciers in southern Iceland terminated in a paleobay inland from the current coastline, at or just beyond the Búðí moraines but in northern Iceland they extended onto the shelf at least half-way out Eyjafjörður. (c) Another period of prominent glacier advance in Iceland is dated to the early Preboreal time from 11,500 to 10,100 cal ka (10,075–9055 BP), when most of the Búðí moraines were formed.

Studies based on sites around Iceland, indicate that the last deglaciation began by 15 ka,¹ and that it was rapid, but step-like (e.g. Ingólfsson, 1991; Norddahl, 1990; Ingólfsson and Norddahl, 1994; Ingólfsson et al., 1997; Syvitski et al., 1999; Andrews et al., 2000; Geirsdóttir et al., 2002; Andrews and Helgadóttir, 2003). The strongest evidence for step-like retreat (or readvance) of the main ice sheet during the last deglaciation is found in the Búði moraines in south-central Iceland (Hjartarson and Ingólfsson, 1988; Geirsdóttir et al., 1997, 2000), and in morainal complexes in northern Iceland (Norddahl, 1990). The occurrence of the Vedde Ash in lake sediment, an 11.8 ka marker tephra layer from the Volcano Katla, South Iceland (Grönvold et al., 1995), shows that during the Younger Dryas chronozone (12.7–11.5 ka) outlet glaciers in southern Iceland terminated in a paleobay inland from the current coastline, at or just beyond the Búði moraines in southern Iceland. In northern Iceland the ice sheet extended onto the shelf at least half-way out the narrow Eyjafjörður (Fig. 6b) during the Younger Dryas (Norddahl and Hafliðason, 1992; Geirsdóttir et al., 2000; Hardardóttir et al., 2001). The reconstructed deglaciation history of North Iceland shows four plausible glacier readvances between 14.7 and 10.9 ka. A period of prominent glacier advance in Iceland is dated to the early Preboreal time from 11.5 to 10.1 ka, when most of the Búði moraines were formed (Fig. 6c) (Hjartarson and Ingólfsson, 1988; Geirsdóttir et al., 1997, 2000).

3. Landscape evolution and rates of erosion since the Pliocene

Stratigraphic and sedimentological studies imply that Iceland has experienced over 20 glaciations of different intensities during the last 4–5 Myr (Fig. 3). Although precise dating of each glacial cycle is difficult, numerous K–Ar dates from lava flows and correlation to the paleomagnetic timescale provide a reliable overall time frame and allow correlation between glacial deposits in different parts of Iceland (Aronson and Sæmundsson, 1975; Sæmundsson and Noll, 1974; Watkins and Walker, 1977; McDougall et al., 1977; Gudmundsson, 1978; Albertsson and Eiríksson, 1989). The number of glacial cycles found within Iceland's stratigraphy is in reasonable agreement with the number of glaciations retrieved from the $\delta^{18}\text{O}$ record from deep sea sediment, suggesting that the late Tertiary and early to middle Pleistocene terrestrial record in Iceland may be regarded as an example of global paleoclimatic processes in the North Atlantic region.

Although the magnitude of erosion during each of the glacial cycles that have occurred since the onset of glaciation in Iceland is poorly constrained, some speculations are warranted about changes in the erosional pattern from the late Pliocene to the last glacial cycle. First, the correlation between glacial deposits found in different parts of Iceland suggests an intermittent growth of the early Icelandic ice sheet from the southeast to the west and north (Geirsdóttir and Eiríksson, 1994). Clear ice-erosional features, together with abrupt changes in lithology over relatively short distances are recognized, especially within the eastern Iceland stratigraphy (Fljótsdalur) and in southern Iceland (Skaftafell and Hreppar formation, Fig. 1). They provide information on alternating glacial erosion and interglacial successions (Geirsdóttir and Eiríksson, 1994; Geirsdóttir et al., 1993; Helgason and Duncan, 2001).

Based on stratigraphic mapping (Ágúst Gudmundsson, personal communication, 2005) and sedimentological studies of 4–5 Ma strata in eastern Iceland (Geirsdóttir and Eiríksson, 1994), local topographic relief at that time is estimated to be 50 m. However, this down cutting was most likely caused by fluvial erosion as no glacial deposits have been found in strata older than 4 Ma (Table 1). Helgason and Duncan (2001) reach a similar conclusion for strata older than 4 Ma in their estimate of erosion in South Iceland. Ice-erosional features and clast-fabric studies of glacial deposits in strata 4–2.5 Myr in eastern Iceland indicate that deep NNE trending valleys were first formed when glaciers were confined to the mid highlands of Iceland (Fig. 4a and b). At this time an estimated 150–200 m of valley down cutting occurred.

At 2.5 Ma enhanced topographic relief and intensified glaciation is detected within the strata (Table 1), which could have led to a change in glacial erosion patterns resulting in the formation of the more easterly oriented valleys of today, such as Fljótsdalur and Jökuldalur (Fig. 1) (Geirsdóttir and Eiríksson, 1994). The glacial erosion pattern may have been controlled by constructive volcanic processes resulting in increased topographic relief after 2.5 Myr. The oldest hyaloclastite (subglacial volcanic) ridge found in the stratigraphy of eastern Iceland is ca. 2.5 Myr (Fig. 4a and b). A westward shift of the rifting zone ca. 1 Ma (Ágúst Gudmundsson, personal communication, 2005) resulted in less volcanic activity in Fljótsdalur/Jökuldalur at the same time that increased ice flow from the highland ice sheet continued to erode deep and wide valleys. These valleys thus became permanent channels for ice flow during successive

¹ All age determinations given in calibrated years BP.

Table 1

Valley down cutting (local topographic relief) in eastern and southeastern Iceland 0.1–5 Ma (ages based on K/Ar dates on lava flows and correlation with the paleomagnetic time scale of Cande and Kent, 1995)

Eastern Iceland (Ágúst Guðmundsson personal communication, 2005, 1978)			Southern Iceland (Helgason and Duncan, 2001; Fig. 2)		
Myr	Downcutting (m)	Erosion rates (cm ka ⁻¹)	Myr	Downcutting (m)	Erosion rates (cm ka ⁻¹)
0.1–0.5	400–600: 200	50	<0.8	600–2000: 1400	175
0.5–1.5	300–400: 100	10			
1.5–2.5	200–300: 100	10	0.8–3.0	100–600: 500	23
2.5–4.0	50–200: 150	10	3.0–4.0	100	10
4.0–5.0	50	5	>4.0	10	

glaciations, which no longer were filled by volcanics during interglacial stages. Between 2.5 and 1.5 Ma we estimate down cutting of valleys amounted to 100 m, from 300 to 400 m (Table 1, Fig. 4a and b). Helgason and Duncan (2001) describe somewhat more intense erosion for the Skaftafell area south of Vatnajökull, where local relief increased from 100 m between 4 and 3 Ma, to 200 m (from 400–600 m) between 3 and 0.8 Ma. This estimate is, however, in reasonable agreement with our conclusion from eastern Iceland (Table 1).

The examples from both eastern and southern Iceland suggest that the record of glacial and interglacial intervals is far less complete after 1 Ma than before. This supports the idea that erosional processes exceeded constructive (volcanic) processes in these areas after 1 Ma. Such change is consistent with a westward shift of volcanic activity in eastern Iceland. Glacier deposits older than the last glaciation are also rare in the central highlands, where volcanic processes have exceeded the erosional power of the ice sheets near the ice divides. By comparison, the strata exposed in Tjörnes, located at the rim of the axial rift during the last 3 Myr and within the reach of the major glaciations, provides a nearly continuous history of the competing processes of constructive volcanism and destructive erosion.

Our estimates of erosion during Pliocene glaciations is solely based on down-cutting reflected in valley formation. Lack of field measurements and quantitative data hamper an estimate of erosion rates during both glacial and interglacial intervals. Based on large-scale landform development glacial erosion was concentrated around the ice-sheet margins, producing deep valleys and fjords. Erosion continued across the Icelandic shelf, where a series of broad and relatively deep troughs now extend from the fjords seaward to the shelf break (Fig. 1). The troughs commonly slope seaward and reach depths of between 200 and 650 m. The inferred configuration of the LGM glacier in Iceland implies that flow from an ice divide located in the central highlands was concentrated in a series of outlet glaciers or ice streams (Fig. 6a) (cf. Bourgeois et al., 2000; Geirsdóttir et al., 2002). Although the erosive power of such ice streams is not known, the fjord–trough systems around Iceland suggest that erosion was concentrated in specific regions (e.g., selective linear erosion, Sugden, 1977). The lack of long sediment cores seaward of the shelf break hampers estimates of erosion rates (cf. Andrews and Cartee-Schoofield, 2003).

3.1. Rates of Holocene erosion

Glacial and glaciofluvial processes dominate erosion in Iceland, but eolian and soil erosion are also significant erosive agents (cf. Jennings et al., 2001). Rates of glacial erosion have been estimated from modern process studies and by calculating sediment accumulation rates in depo-centers around Iceland. Published estimates of current denudation rates are highly variable. Velocities of glacier movement are commonly over one meter per day (Björnsson, 1979). Valley glacier erosion is particularly significant around southeastern Vatnajökull, where outlets cut deep into the mountain range (cf. Björnsson, 1996). Based on sediment loads, a rate of denudation of 320 cm ka⁻¹ is estimated for Vatnajökull (Björnsson, 1979; Tomasson, 1976, 1991). Erosion beneath Breidamerkurjökull, a large outlet glacier of Vatnajökull, was very high during the Little Ice Age, averaging 4000–70,000 cm ka⁻¹ for the interval between 1732 and 1890 AD (Björnsson, 1996). Erosion estimates from glacial rivers along southern Iceland range between 100 and 300 cm ka⁻¹ (Boulton, 1979; Boulton et al., 1988; Tomasson, 1976, 1991). However, all of these estimates are based on relatively short intervals, and for areas where erosion is higher than for Iceland as a whole.

The extensive outwash plains near the largest glaciers, particularly Vatnajökull and Mýrdalsjökull in the south, experience extreme floods (jökulhlaups), which reach peak discharges of $50 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ (Guðmundsson et al., 2001).

These jökulhlaups bring abundant sediment to the outwash plains and into the sea. One of these sandurs, Skeiðarásandur south of Vatnajökull, experienced a large jökulhlaup in 1996, which carried a suspended sediment load of approximately 180 million tonnes (Gudmundsson et al., 2001; Smith et al., 2000; Maria et al., 2000; Snorrason et al., 2002). During the 2004 eruption of Grímsvötn about 4 million tonnes of sediment were transported to the same site during the peak of the accompanying jökulhlaup (Hardardóttir et al., 2005). Part of this sediment, often tephra-laden, comes to rest on the vast sandur plains and becomes vulnerable to wind deflation. Iceland also suffers extensive soil erosion today. The soils are mainly of volcanic origin with low organic content owing to a steady flux of eolian and tephra material (Arnalds, 1988; Arnalds et al., 1997). Soils are easily eroded by the prevailing winds and water processes, unless stabilized by vegetation. The areas of the most severe soil erosion today follow the North, East and Western volcanic zones (NVZ, EVZ, WVZ, Fig. 1), where both tephra production and frequent jökulhlaups prevent vegetation from becoming established. Over-grazing and clearing natural vegetation for cultivation probably accelerates erosion or increases the vulnerability of hillslopes to slope erosion and eolian deflation.

An alternative approach to estimating average Holocene denudation rates for Iceland is to capitalize on natural depo-centers that trap eroded sediment, such as lakes or marine basins. Seismic surveys of these basins provide estimates of the volume of sediment stored in the depo-centers. The elapsed time over which sediment accumulated can be defined by radiocarbon dates in sediment cores at key localities. We present the results of two such surveys, one in which we estimate the average denudation rate for all of Iceland during the Holocene based on the volume of sediment stored in shelf basins around the coast of Iceland, and a second, more restricted study, based on the accumulation of sediment in the large lake Hvítárvatn, in central Iceland.

3.2. Estimates of Holocene denudation rates based on sedimentation across the Iceland Shelf

Seismic surveys (3.5 kHz) have been undertaken by the Marine Research Institute (Thors and Helgadóttir, 1991; Thors and Boulton, 1991; Thors and Helgadóttir, 1999), and seismic profiles have been obtained on portions of the W, NW, and N Iceland shelf in 1988, 1993, 1996, 1997, and 1999 (Andrews et al., 2000; Syvitski et al., 1999). These profiles usually were taken along the axis of a trough but in some cases additional lines were run across a trough (Fig. 7).

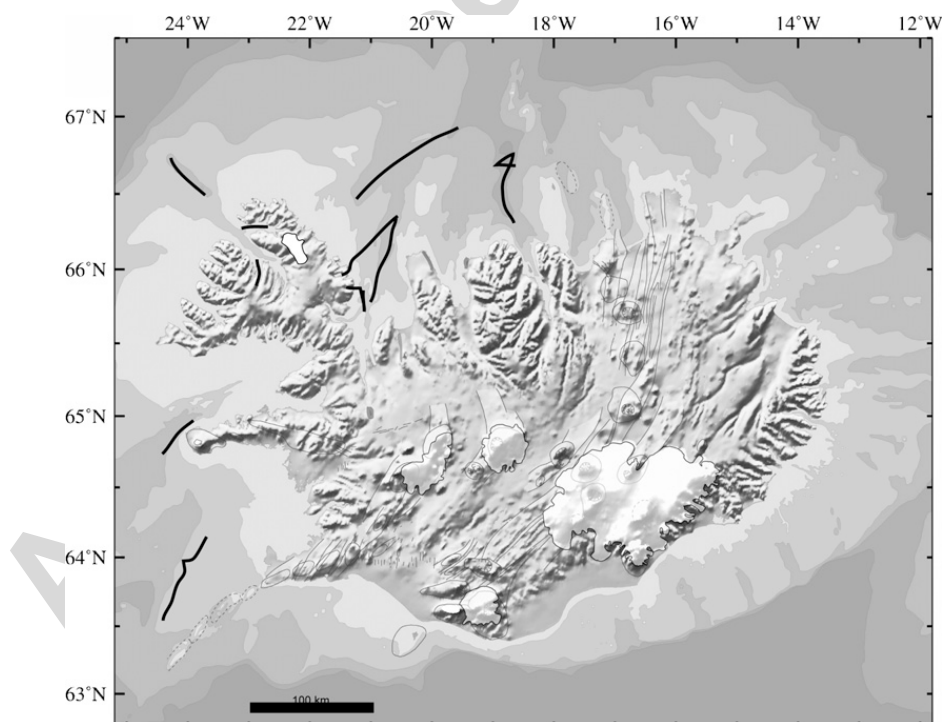


Fig. 7. Seismic surveys (3.5 kHz) referred to in the text were undertaken by the Marine Research Institute (Thors and Helgadóttir, 1991; Thors and Boulton, 1991; Thors and Helgadóttir, 1999), and obtained on portions of the W, NW, and N Iceland shelf in 1988, 1993, 1996, 1997, and 1999 (Andrews et al., 2000; Syvitski et al., 1999).

Seismic surveys on the shelf west of 18°W and north of 63°N (Helgadóttir, 1997) indicate that the inter-trough banks are largely devoid of Holocene sediment. This conclusion is supported by our inability to raise gravity and piston cores from these areas due to “hard ground”. The lack of sediment on banks confirms that the troughs trap the majority of sediment transported from land to the sea as fluvial and glacial-fluvial suspended plumes. In addition, the strong tidal and wave currents on the shelf have reworked sediment on the shallow banks, and even within the troughs, to form a series of drift-like deposits (Geirsdóttir et al., 2002; Andrews et al., 2003). Thus, the volume of sediment accumulated in the troughs represents our best source for deriving a Holocene denudation rate for the SW-N-central sector of Iceland.

Piston cores at select localities show rapid sedimentation during deglaciation, followed by much slower sediment accumulation rates during the Holocene. To avoid biasing our estimates of Holocene erosion rates by the retreating late Pleistocene ice sheet, we restrict our volume calculations to sediment that accumulated in the past 10 kyr, using the Saksunarvatn tephra, which was erupted $10,200 \pm 60$ cal years BP (Grönvold et al., 1995; Andrews et al., 2002b), as a stratigraphic marker. The Saksunarvatn tephra is visible in many of the seismic profiles as a distinct seismic reflector that occurs from a few meters below the seafloor to >100 m sediment depth. By 10 ka, the Icelandic Ice Sheet had retreated everywhere onto land, and had thinned sufficiently that its erosive power was dramatically reduced. On average, the glacier cover over Iceland during the last 10,000 years was probably not too dissimilar to that of today; the remnant Pleistocene ice sheet was probably gone by 8–9 ka; ice caps were smaller during the Holocene Thermal Maximum (Kaufman et al., 2004) and glaciers expanded over the last 5–6 ka during the Neoglaciation (Gudmundsson, 1997; Stotter et al., 1999). We assume negligible marine erosion during the Holocene; hence, all of the sediment stored on the shelf since 10 ka is derived from terrestrial erosion.

The 3.5 kHz analog data (i.e. paper profiles) were digitized by hand at 1-min time intervals, with measurements made of the total sediment thickness (two-way travel time) to “basement” (often either bedrock or till, although in some cases these were minimum estimates as no clear basal reflector was discernable), and to the Saksunarvatn reflector where it was present. On the banks there was no penetration by the 3.5 kHz system, confirming the concentration of sediment in the shelf troughs. The Saksunarvatn reflector was present in approximately 75% of our available records (totaling over 20 h of survey time). The time to maximum sediment thickness or to the Saksunarvatn reflector was converted to sediment thickness empirically based on the known water depths along the various profiles and the depth of the Saksunarvatn reflector in ms compared to the measured depth of the tephra in the cores (Andrews et al., 2002b).

We use these data to estimate the average sediment accumulation rate (SAR, cm ka^{-1}) for the northwestern sector of Iceland. The mean and median estimates of sediment fill are 5 and 7 m for accumulation since the Saksunarvatn tephra event (Andrews, in press), but with a range of values from 0 to as much as 60 m (Eyjafjardarall, Fig. 1). The distribution is positively skewed reflecting much greater accumulation of sediment in certain areas. The median SAR is 75 cm ka^{-1} .

To convert SAR into rates of terrestrial denudation we change the SAR into mass accumulation rates (MAR, $\text{g cm}^{-2} \text{ a}^{-1}$), and adjust for the ratio of the land area of Iceland to the area of the offshore depo-centers. The average dry bulk density for marine sediment from the Icelandic shelf is $0.8 \pm 0.2 \text{ g cm}^{-3}$ (Andrews et al., 2002c). Hence, our best estimate for the MAR over the last 10 ka is $58 \text{ g cm}^{-2} \text{ ka}^{-1}$, with a 95% probability range between 22 and $86 \text{ g cm}^{-2} \text{ ka}^{-1}$ based on the density variations.

We assume here that the sediment thickness for our seismic coverage is representative of the Icelandic shelf in general. The northwestern sector of Iceland has a surface area of about $52,000 \text{ km}^2$ and the area of the offshore troughs is about $18,000 \text{ km}^2$. This defines a sediment-erosion-area to sediment-deposition-area of about 3.

We convert sediment to source rock assuming a rock density of 2.7 g cm^{-3} . From these data, a MAR in the troughs in the northwestern sector (Andrews, in press) of $58 \text{ g cm}^{-2} \text{ ka}^{-1}$ corresponds to an average denudation rate on the northwestern sector of Iceland during the last 10,200 years of $6.3 \pm 2 \text{ cm ka}^{-1}$.

3.3. Estimates of Holocene denudation rates based on lacustrine sedimentation in central Iceland

Hvítárvatn is a glacier-dominated lake on the eastern margin of Langjökull, the second-largest ice cap on Iceland. The lake has a catchment of 820 km^2 , about a third of which is currently occupied by Langjökull. More than 100 km of seismic profiling across the main depo-centers within the lake allow construction of isopach maps of sediment thickness, which in turn provide constraints on the average Holocene erosion rate across the Hvítárvatn catchment.

Black et al. (2004, 2005) estimate the total sediment volume since regional deglaciation to be $41 \times 10^7 \text{ m}^3$. Based on the presence of diagnostic Saksunarvatn tephra at the base of the sediment pile (Thorvaldur Thordarsson, personal communication, 2005), regional deglaciation is well constrained at 10 ka. The average dry bulk density of the sediment fill in Hvítárvatn is $1.18 \pm 0.33 \text{ g cm}^{-3}$ based on 119 determinations that span the sediment thickness. Dry bulk density is higher than on the marine shelf around Iceland because the lake has coarser sediment and less organic matter. From the dry bulk density the total mass of post-glacial sediment in Hvítárvatn is calculated to be $48 \times 10^{13} \text{ g}$. Hvítárvatn contains substantial suspended sediment that bypasses the lake, and is delivered to the sea via the river Hvítá. To estimate the sediment lost in this manner, Black et al. (2004, 2005) utilized a 25-year monthly sampling of the suspended sediment load in Hvítá taken at the outlet of Hvítárvatn (Pálsson and Vigfússon, 1996). The average mass of sediment lost each year as suspended load is $5.1 \times 10^{10} \text{ g}$; at this rate, the total sediment by-pass over the last 10 kyr is $51 \times 10^{13} \text{ g}$, about the same as the mass of sediment stored in the lake. This figure is considered a maximum estimate, because Langjökull was smaller, and hence less erosive or perhaps absent, in the early Holocene.

The combined sediment mass that is stored in Hvítárvatn or that bypassed as suspended sediment is $99 \times 10^{13} \text{ g}$. Redistributed uniformly over the catchment, assuming a bedrock density of 2.7 g cm^{-3} results in a maximum average denudation rate of $4.5 \pm 1.3 \text{ cm ka}^{-1}$, remarkably similar to the shelf-based estimate above.

4. Conclusions

Estimates for erosion rates during Pliocene glaciations of Iceland are derived solely from down cutting reflected in valley formation. These values are, however, minimum estimates of the average terrestrial erosion rate. In particular, such estimates do not incorporate the impacts of abrupt erosional events, such as jökulhlaups.

- The geological mapping of eastern Iceland shows that the period from 5.0 to 4.0 Ma was characterized by fluvial runoff and accumulation of soil sediments, tephra and lava flows (Geirsdóttir and Eiríksson, 1994). Local glaciation occurred in southeastern Iceland as reported by Helgason and Duncan (2001), but glacial erosional features are not preserved elsewhere in the stratigraphy of Iceland from this time. Estimated erosion rates at this time are around 5 cm/ka^{-1} .
- The first indication of a more widespread glaciation in Iceland dates from ca. 2.9 Ma. A formation of NNE oriented valleys in eastern Iceland and downcutting of ca. 150 m between 4.0 and 2.5 Ma took place due to glacial and fluvial erosion with an estimated erosion rate of ca. 10 cm ka^{-1} (Table 1).
- A change in glacier erosion rate is detected after ca. 2.5 Ma coinciding with the first appearance of hyaloclastite in the stratigraphy and subsequent ice flow changes from NNE to NE in eastern Iceland. Between 2.5 and 0.5 Ma valleys up to 400 m deep were excavated into the Tertiary basalts of eastern Iceland resulting in an average erosion rate of $10\text{--}25 \text{ cm ka}^{-1}$ (Table 1).
- During the last 0.5 million years the valleys have been excavated down to more than 600 m with a much increased erosion rate of $50\text{--}175 \text{ cm ka}^{-1}$ (Table 1). This increasing trend in erosion rate through time reflects amplified glaciations in Iceland with a marked increase at around 2.5 Ma and again around 0.5 Ma, very similar to changes in ice-rafted detritus and increased amplitude of oxygen isotope excursions found in the marine sediment record.

Our two independent estimates of average late Quaternary landscape denudation for Iceland produce similar erosion rates of about 6 cm ka^{-1} , well below the estimates previously reported in the literature that are locally $10\text{--}10^5$ higher (Table 2), but similar to the estimate for strata older than 4 Ma that has not been affected by regional glaciation. The

Table 2
Modern and Holocene erosion rates estimates

Basis	Erosion rates (cm ka^{-1})	Reference
Modern valley glacier erosion, Vatnajökull	320	Björnsson (1979)
LIA valley glacier erosion, Vatnajökull	4000–70,000	Björnsson (1996)
Glacier rivers, south Iceland	100–300	Boulton (1979) and Tomasson (1976, 1991)
Last 10 kyr, sediment on the Iceland shelf	6.3 ± 2	This study, Andrews in press
Last 10 kyr, lake sediment, central Iceland	4.5 ± 1.3	Black et al. (2004, 2005)

mismatch between our erosion rates based on long-term sediment accumulation rates in depositional centers, and the shorter-term, direct measurements of erosion is substantial. Possible reasons for this large discrepancy include:

- Estimates of land denudation are biased toward the high side because they are based on the large, but geographically restricted, glacially fed rivers of southern Iceland, or for specific outlet glaciers.
- Marine data come mostly from the northern and western shelves that are fed by relatively small rivers; whereas most of the rivers draining large ice caps drain to the south. We do not include estimates for the sedimentation in the troughs off Vatnajökull (Maria et al., 2000).
- We do not account for any sediment bypassing of the shelf depo-centers in the marine study. Seismic surveys do show that canyons draining shelf troughs have depositional fans at the juncture of the canyons and abyssal plain, but these fans have not been cored and we cannot at this point estimate how much of that sediment is of Holocene age, and how much is restricted to rapid sedimentation at the margin of the ice sheet that terminated at the shelf break during peak glacial episodes.

In none of these estimations is the effect of eolian erosion taken into account. It would be assumed, based on the amount of soil erosion today, that this would be a considerable part of the terrestrial erosion during glaciations and particularly during the early interglaciations before colonizing vegetation stabilized the freshly deglaciated landscape.

References

- Albertsson, K., Eiríksson, J., 1989. K/Ar ages of rocks from the Flatey borehole in the offshore Skjálfandi Basin, North Iceland. *Jökull* 13, 55–68.
- Andrews, J.T., in press. Holocene denudation of the northwest sector of Iceland as determined from accumulation of sediments on the continental margin, Boreas.
- Andrews, J.T., 2005. Late Quaternary marine sediment studies of the Iceland shelf, Paleooceanography and land/ice sheet/ocean interactions. In: Caseldine, C., Ruseell, A., Hardardóttir, J., Knudsen, O. (Eds.), *Iceland-Modern Processes and Past Environments*. Elsevier, London, pp. 5–24.
- Andrews, J.T., Cartee-Schoofield, S., 2003. Late Quaternary lithofacies, provenance, and depositional environments (~12–30 cal ka), north and south of the Denmark Strait. *Mar. Geol.* 199, 65–82.
- Andrews, J.T., Geirsdóttir, A., Hardardóttir, J., Principato, S.M., Kristjansdóttir, G.B., Helgadóttir, G., Sveinsbjornsdóttir, A., Grönvold, K., Drexler, J., 2002b. Distribution, age, and geochemistry of the Saksunarvatn ($10.18 \pm$ cal ka) ash in marine, lake, and terrestrial sediments, NW Iceland. *J. Quaternary Sci.* 17, 731–745.
- Andrews, J.T., Hardardóttir, J., Geirsdóttir, A., Helgadóttir, G., 2002a. Late Quaternary ice extent and glacial history from the Djúpáll trough, off Vestfirðir peninsula, northwest Iceland: a stacked 36 cal kyr environmental record. *Polar Res.* 21, 211–226.
- Andrews, J.T., Hardardóttir, J., Stoner, J.S., Mann, M., Kristjansdóttir, G.B., Koc, N., 2003. Decadal to millennial-scale periodicities in North Iceland shelf sediments over the last 12,000 cal year: long term North Atlantic oceanographic variability and solar forcing. *Earth Planet. Sci. Lett.* 210, 453–465.
- 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., Syvitski, J.P.M., 2000. The N and W Iceland Shelf: Insights into Last Glacial Maximum Ice Extent and Deglaciation based on Acoustic Stratigraphy and Basal Radiocarbon AMS dates. *Quaternary Sci. Rev.* 19, 619–631.
- Andrews, J.T., Helgadóttir, G., 2003. Late Quaternary ice extent and deglaciation of Hunafloaall, north Iceland: evidence from marine cores. *Arct. Antarct. Alp. Res.* 35, 218–232.
- Andrews, J.T., Kihl, R., Kristjansdóttir, G.B., Smith, L.M., Helgadóttir, G., Geirsdóttir, Á., Jennings, A.E., 2002c. Holocene sediment properties of the East Greenland and Iceland continental shelves bordering Denmark Strait (64° – 68° N), North Atlantic. *Sedimentology* 49, 5–24.
- Arnalds, Ó., 1988. Jarðvegur á ógrónu landi. Náttúrufræðingurinn 58, 101–116 (In Icelandic: Soils of denudated areas in Iceland).
- Arnalds, Ó., Þórarinsdóttir, E.F., Metúsalemsson, S., Jónsson, Á., Grétarsson, E., Árnason, A., 1997. Jarðvegsrof á Íslandi (Soil erosion in Iceland). Soil Conservation Service & Agricultural Research Institute.
- Aronson, J.L., Sæmundsson, K., 1975. Relatively old basalts from structurally high area in central Iceland. *Earth Planet. Sci. Lett.* 28, 83–97.
- Björnsson, H., 1979. Glaciers in Iceland. *Jökull* 29, 74–80.
- Björnsson, H., 1996. Scales and rates of glacial sediment removal: a 20 km long and 300 m deep trench created beneath Breidamerkurjökull during the Little Ice Age. *Ann. Glaciol.* 22, 141–146.
- Black, J., Miller, G.H., Geirsdóttir, Á., Manley, W., Björnsson, H., 2004. Sediment thickness and Holocene erosion rates derived from a seismic survey of Hvítárvatn, central Iceland. *Jökull* 54, 37–56.
- Black, J., Miller, G.H., Geirsdóttir, Á., Manley, W., Björnsson, H., 2005. Erratum: sediment thickness and Holocene erosion rates derived from a seismic survey of Hvítárvatn, central Iceland. *Jökull* 55, 120.
- Boulton, G.S., 1979. Processes of glacier erosion on different substrata. *J. Glaciol.* 23, 15–38.
- Boulton, G.S., Thors, K., 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. *Mar. Geol.* 83, 193–223.
- Bourgeois, O., Dauteil, O., van Viet-Lanoe, B., 2000. Geothermal control on ice stream formation: flow patterns of the Icelandic Ice Sheet at the Last Glacial Maximum. *Earth Surf. Process. Land.* 25, 59–76.

- Cande, S.C., Kent, D.V., 1995. Revised calibration of the geomagnetic polarity timescale for the late Cretaceous and Cenozoic. *J. Geophys. Res.* 100, 6093–6095.
- Einarsson, T., Albertsson, K.J., 1988. The glacial history in Iceland during the past three million years. *Philos. Trans. R. Soc. Lond. B* 318, 637–644.
- Einarsson, Th., 1994. *Geology of Iceland. Rocks and Landscape*. Mál & Menning, Reykjavík, 309 p.
- Eiríksson, J., 1985. Facies analysis of the Breidavík Group sediments on Tjörnes. *Acta Nat. Islandica* 31, 56.
- Fronval, T., Jansen, E., 1996. Late Neogene Paleoclimate and Paleoceanography in the Iceland-Norwegian Sea. In: Thiede, J., Myhre, A.M., Futh, J.V., Johnson, G.L., Ruddiman, W. (Eds.), *Proceedings of the ODP, Sci Rept. 151*. College Station, TX (Ocean Drilling Project), pp. 455–468.
- Geirsdóttir, Á., 1990. Diamicrites of late Pliocene age in western Iceland. *Jökull* 40, 3–25.
- Geirsdóttir, Á., 2004. Extent and chronology of Glaciations in Iceland. In: Ehlers, J., Gibbard, P. (Eds.), *Quaternary Glaciations—Extent and Chronology of Glaciations. Part 1. Europe*. INQUA Commission on Glaciation 2004, Work Group 5, Elsevier B.V., pp. 175–182.
- Geirsdóttir, A., Andrews, J.T., Olafsdóttir, S., Helgadóttir, G., Hardardóttir, J., 2002. A 36 ky record of iceberg rafting and sedimentation from north-west Iceland. *Polar Res.* 21, 291–298.
- Geirsdóttir, Á., Eiríksson, J., 1994. Growth of an intermittent ice sheet in Iceland during the late Pliocene and early Pleistocene. *Quaternary Res.* 42, 115–130.
- Geirsdóttir, Á., Eiríksson, J., 1996. A review of studies of the earliest glaciations in Iceland. *Terra Nova* 8, 400–414.
- Geirsdóttir, A., Hardardóttir, J., Eiríksson, J., 1997. Depositional history of the Younger Dryas(?)—Preboreal sediments, South Central Iceland. *Arct. Alp. Res.* 29, 13–23.
- Geirsdóttir, A., Hardardóttir, J., Sveinbjörnsdóttir, A.E., 2000. Glacial extent and catastrophic meltwater events during the deglaciation of Southern Iceland. *Quaternary Sci. Rev.* 19, 1749–1761.
- Geirsdóttir, Á., Thordarson, Th., Kristjánsson, L., 1993. The interactive impact of climatic deteriorations and volcanic activity on facies assemblages in late Pliocene to early Pleistocene strata of the Hreppar Formation, South Central Iceland. *EOS* 74 (43), 131.
- Grönvold, K., Oskarsson, N., Johnsen, S.J., Clausen, H.B., Hammer, C.U., Bond, G., Bard, E., 1995. Ash layers from Iceland in the Greenland GRIP ice core correlated with oceanic and land sediments. *Earth Planet. Sci. Lett.* 135, 149–155.
- Gudmundsson, Á., 1978. Austurlandsvirkjun, Múlavirkjun. Frumkönnun á jarðfræði Mula og umhverfis. Orkusöfnun, OS-ROD-7818. Reykjavík.
- Gudmundsson, H., 1997. A review of the Holocene environmental history of Iceland. *Quaternary Rev.* 16, 81–92.
- Gudmundsson, M.T., Bonnel, A., Gunnarsson, K., 2001. Seismic soundings of sediment thickness on Skeidarársundur, SE-Iceland. *Jökull* 51, 53–64.
- Hardardóttir, J., Geirsdóttir, A., Sveinbjörnsdóttir, A.E., 2001. Seismostratigraphy and sediment studies of Lake Hestvatn, south Iceland; Implication for the deglacial history of the region. *J. Quaternary Sci.* 16 (2), 167–179.
- Hardardóttir, J., Jonsson, P., Sigurdsson, G., Elefsen, S.O., Sigfusson, B., Gislason, S.R., 2005. Discharge and Sediment Monitoring of the 2004 glacial Outburst Flood Event (Jökulhlaup) on Skeidara Sandur Plain, South Iceland, *Geophys. Res. Abstr.*, vol. 7, EGU05-A-08854.
- Helgadottir, G., 1997. Paleoclimate (0 to >14 ka) of W. and NW Iceland: an Iceland/USA Contribution to P.A.L.E., Cruise Report B9-97, Rep. Hafrannsóknastofnun Fjölrit No. 62, Marine Research Institute of Iceland, Reykjavík.
- Helgadottir, G., Brandsdottir, B., Geirsdottir, Á., Björnsson, H. 2005. Offshore Extent of the Iceland Ice Sheet During the Last Glacial Maximum Inferred from Multibeam Bathymetric Data and Sediment Cores. American Geophysical Union (AGU) Fall Meeting, San Francisco, Dec 2005. *Eos Trans. AGU*, 86(52), Fall Meet. Suppl., Abstract H51G-0449.
- Helgason, J., Duncan, R.A., 2001. Glacial–interglacial history of the Skaftafell region, southeast Iceland, 0–5 Ma. *Geology* 29, 179–182.
- Hjartarson, Á., Ingólfsson, Ó., 1988. Preboreal glaciation of southern Iceland. *Jökull* 38, 1–16.
- Hjort, C., Hreggvidur, N., 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.
- Ingólfsson, O., 1991. A Review of the Late Weichselian and Early Holocene Glacial and Environmental History of Iceland. In: Caseldine, C., Maizels, J.K. (Eds.), *Environmental Change in Iceland: Past and Present*. Kluwer Academic Publishers, Netherlands, pp. 13–29.
- Ingólfsson, O., Norddahl, H., 1994. A review of the environmental history of Iceland, 13,000–9000 year BP. *J. Quaternary Sci.* 9, 147–150.
- Ingólfsson, O., Björck, S., Hafliðason, H., Rundgren, M., 1997. Glacial and climatic events in Iceland reflecting regional North Atlantic climatic shifts during the Pleistocene–Holocene transition. *Quaternary Sci. Rev.* 16, 1135–1144.
- Jancin, M., Young, K.D., Voight, B., 1985. Stratigraphy and K&Ar ages across the West flank of the Northeast Iceland axial rift zone, in relation to the 7 Ma volcano-Tectonic reorganization of Iceland. *J. Geophys. Res.* 90, 9961–9985.
- Jansen, E., Fronval, T., Rack, F., Channell, E.T., 2000. Pliocene–Pleistocene ice rafting history and cyclicity in the Nordic Seas during the last 3.5 Myr. *Paleoceanography* 15, 709–721.
- Jansen, E., Sjöholm, J., 1991. Reconstruction of glaciation over the past 6 Myr from ice-borne deposits in the Norwegian Sea. *Nature* 349, 600–603.
- Jansen, E., Sjöholm, J., Bleil, U., Erichsen, J.A., 1990. Neogene and Pleistocene glaciations in the Northern Hemisphere and late Miocene–Pliocene global ice volume fluctuations: evidence from the Norwegian Sea. In: Bleil, U., Thiede, J. (Eds.), *Geological History of the Polar Oceans: Arctic versus Antarctic*. Kluwer Academic, Dordrecht, pp. 677–705.
- Jennings, A.E., Hagen, S., Hardardottir, J., Stein, R., Ogilvie, A.E.J., Jonsdottir, I., 2001. Oceanographic Change and Terrestrial Human Impacts in a post 1400 AD record from the Southwest Iceland Shelf. *Climatic Change* 48, 83–100.
- Jóhannesson, H., Saemundsson, K., 1998. Jarðfræðikort af Íslandi. Höggun 1:500,000. Náttúrufarskort. Geological Map of Iceland 1:500,000. Tectonics. Reykjavík: Náttúrufræðistofnun Íslands.
- Kaldal, I., Víkingsson, S., 1990. Early Holocene deglaciation in Central Iceland. *Jökull* 40, 31–66.
- Kaufman, D.S., Ager, T.A., Anderson, N.J., Anderson, P.M., Andrews, J.T., Bartlein, P.J., Brubaker, L.B., Coats, L.L., Cwynar, L.C., Duvall, M.L., Dyke, A.S., Edwards, M.E., Eisner, W.R., Gajewski, K., Geirsdóttir, A., Hu, F.S., Jennings, A.E., Kaplan, M.R., Kerwin, M.W., Lozhkin, A.V., MacDonald, G.M., Miller, G.H., Mock, C.J., Oswald, W.W., Otto-Bliessner, B.L., Porinchu, D.F., Rühland, K., Smol, J.P., Steig, E.J., Wolfe, B.B., 2004. Holocene thermal maximum in the western Arctic (0–180°W). *Quaternary Sci. Rev.* 23, 529–560.

- Leifsdóttir, Ó.E., 1999. Ísaldarlög á norðanverðu Snæfellsnesi. Setlög og skeldýrafánur. Unpublished MS Thesis. University of Iceland, 101 pp.
- Maria, A., Carey, S., Sigurdsson, H., Kincaid, C., Helgadóttir, G., 2000. Source and dispersal of jökulhaup sediments discharged to the sea following the 1996 Vatnajökull eruption. *Geol. Soc. Am. Bull.* 112, 1507–1521.
- Maslin, M.A., Li, X.S., Loutre, M.-F., Berger, A., 1998. The contribution of orbital forcing to the progressive intensification of northern hemisphere glaciation. *Quaternary Sci. Rev.* 17, 411–426.
- McDougall, I., Sæmundsson, K., Johannesson, H., Watkins, N.D., Kristjánsson, L., 1977. Extension of the geomagnetic polarity time scale to 6.5 m.y.: K–Ar dating and geological and paleomagnetic study of a 3500 m lava succession in western Iceland. *Bull. Geol. Soc. Am.* 88, 1–15.
- Mix, A.C., Pisias, N.G., Rugh, W., Wilson, J., Morey, A., Hagelberg, T., 1995a. Benthic foraminifera stable isotope record from Site 849: 0–5 Ma: local and global climate changes. In: Pisias, N.G., Mayer, L., Janecek, T., Palmer-Julson, A., vanAndel, T.H. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 138. College Station, TX, USA, pp. 371–412.
- Mix, A.C., Le, J., Shackleton, N.J., 1995b. Benthic foraminiferal stable isotope stratigraphy of Site 846: 0–1.8 Ma. In: Pisias, N.G., Mayer, L., Janecek, T., Palmer-Julson, A., vanAndel, T.H. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 138. College Station, TX, USA, pp. 839–854.
- Norddahl, H., 1990. Late Weichselian and early Holocene deglaciation history of Iceland. *Jökull* 40, 27–50.
- Norddahl, H., Hafliðason, H., 1992. The Skogar tephra, a Younger Dryas marker in North Iceland. *Boreas* 21, 23–41.
- ODP leg 151 Scientific Party, 1994. Exploring Arctic history through scientific drilling. *EOS* 75 (25), 281–286.
- Pálsson, S., Vigfússon, G.H., 1996. Gagnasafn aurburðarmælinga 1963–1995. Orkustofnun OS-96032/VOD-05 B 270 pp (in Icelandic).
- Principato, S.M., 2003. The Late Quaternary History of Eastern Vestfirðir, NW Iceland. Unpublished Ph.D. Dissertation. University of Colorado, 258 pp.
- Principato, S.M., Geirsdóttir, Á., Jóhannsdóttir, G.E., Andrews, J.T., 2006. Late Quaternary glacial and deglacial history of eastern Vestfirðir. *J. Quaternary Sci.* 21 (3), 271–285.
- Raymo, M.F., Ruddiman, W.F., Clement, B.M., 1986. Pliocene–Pleistocene paleoceanography of the North Atlantic DSDP Site 609. In: Kidd, R.B., Ruddiman, W.F., Thomas, E., et al. (Eds.), *Initial Reports of the Deep Sea Drilling Project 94*. U.S. Government Printing Office, Washington, DC, pp. 895–902.
- Rundgren, M., Ingólfsson, O., 1999. Plant survival in Iceland during periods of glaciation? *J. Biogeogr.* 26, 387–396.
- Sæmundsson, K., 1979. Outline of the geology of Iceland. *Jökull* 29, 7–28.
- Sæmundsson, K., Noll, H., 1974. K/Ar ages of rocks from Husafell, Western Iceland, and the development of the Husafell Central Volcano. *Jökull* 24, 40–59.
- Shackleton, N.J., Berger, A., Peltier, W.R., 1990. An alternative astronomical calibration of the lower Pleistocene time based on ODP Site 677. *Trans. R. Soc. Edinburgh Earth Sci.* 81, 251–261.
- Smith, L.C., Magillian, F.J., Gomez, B., Martes, L.A.K., Smith, N.D., Garvin, J.B., 2000. Estimation of erosion, deposition, and net volumetric change caused by the 1996 Skeidarársandur jökulhlaup, Iceland, from synthetic aperture radar interferometry. *Water Resour. Res.* 36, 1583–1594.
- Snorrason, Á., Jónsson, P., Sigurdsson, O., Pálsson, S., Árnason, S., Víkingsson, S., Kaldal, I., 2002. November 1996 jökulhlaup on Skeidarársandur outwash plain, Iceland. *Special Publication of the International Association of Sedimentologists* 32, 55–65.
- Stokes, C.R., Clark, C.D., 2001. Palaeo-ice streams. *Quaternary Sci. Rev.* 20, 1437–1457.
- Stotter, J., Wastl, M., Caseldine, C., Haberle, T., 1999. Holocene paleoclimatic reconstructions in Northern Iceland: approaches and results. *Quaternary Sci. Rev.* 18, 457–474.
- Sugden, D.E., 1977. Reconstruction of the morphology, dynamics and thermal characteristics of the Laurentide Ice Sheet. *Arct. Alp. Res.* 9, 21–47.
- Syvitski, J.P.M., Jennings, A.E., Andrews, J.T., 1999. High-resolution seismic evidence for multiple glaciation across the southwest Iceland shelf. *Arct. Antarct. Alp. Res.* 31, 50–57.
- Tomasson, H., 1991. Glaciofluvial sediment transport and erosion. In: Paper presented at Arctic Hydrology-Present and Future Tasks. Proceedings of the Seminar Longyearbyen, Svalbard, Norway, September 1990.
- Tomasson, H., 1976. The sediment load of Icelandic rivers. Paper Presented at Proceedings of the Nordic Hydrological Conference, Reykjavik.
- Thors, K., Boulton, G.S., 1991. Deltas, spits and littoral terraces associated with rising sea level: late Quaternary examples from northern Iceland. *Mar. Geol.* 98, 99–112.
- Thors, K., Helgadóttir, G., 1991. Evidence from southwest Iceland of low sea level in early Flandrian times. In: Maizels, J.K., Caseldine, C. (Eds.), *Environmental Change in Iceland: Past and Present*. Kluwer, Dordrecht, pp. 93–104.
- Thors, K., Helgadóttir, G., 1999. Seismic reflection profiles from Ísafjardardjúp, Jökulfirðir, and Djúpáll, NW Iceland. *Geol. Soc. Am. Abstract Volume* 31 (7), A74.
- Watkins, N.D., Walker, G.P.L., 1977. Magnetostratigraphy of eastern Iceland. *Am. J. Sci.* 277, 513–584.
- Wolf, T.C.W., Thiede, J., 1991. History of terrigenous sedimentation during the past 10 my in the North Atlantic (ODP-leg's 104, 105 and DSDP-Leg 81. *Mar. Geol.* 101, 83–102.