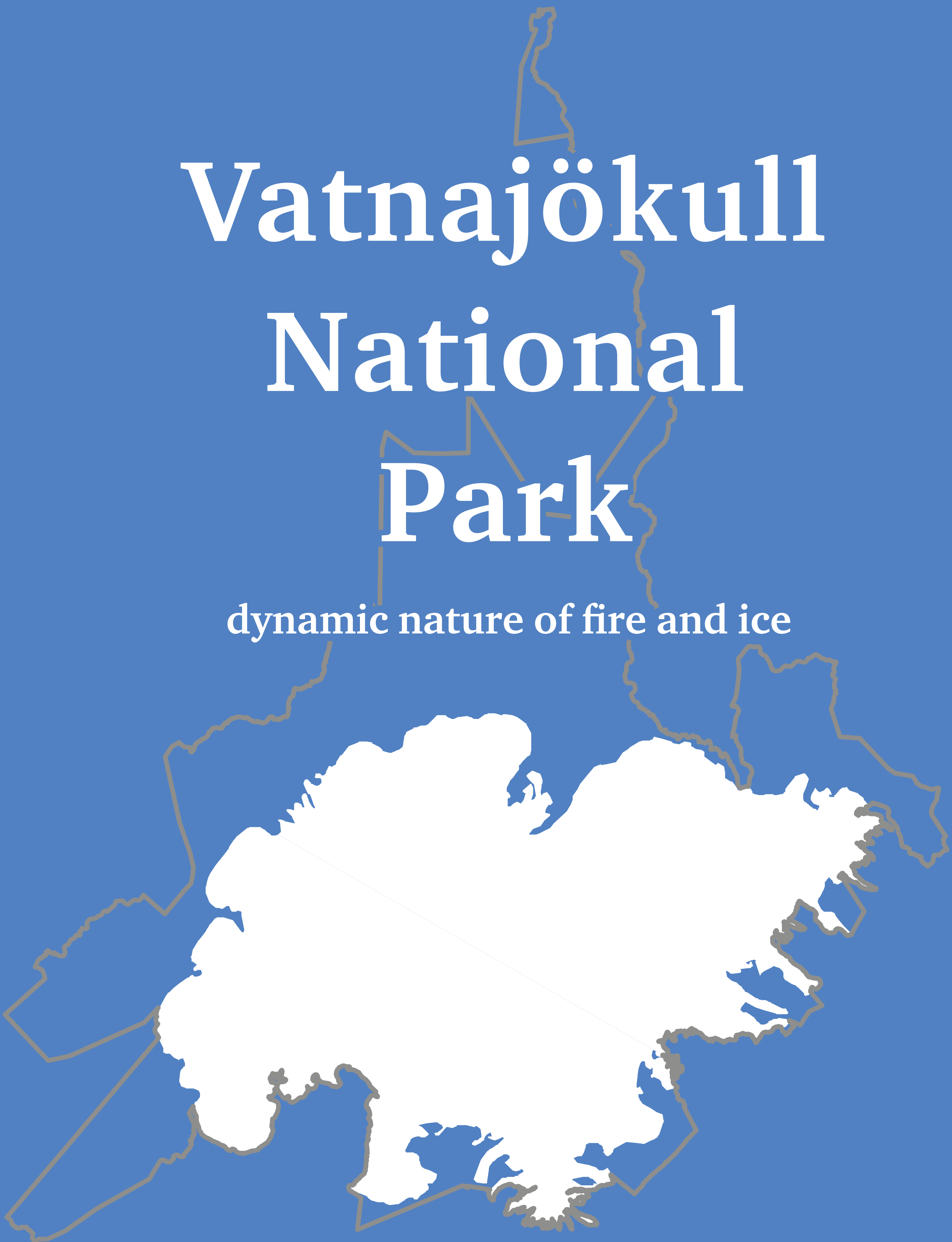
Nomination of

Vatnajökull National Park

dynamic nature of fire and ice



for inclusion in the World Heritage List

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dynamic nature of fire and ice

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Snorri Baldursson, Jónas Guðnason,
Hrafnhildur Hannesdóttir and Þorvaldur Þórðarson

VATNAJÖKULSÞJÓÐGARÐUR
NATIONAL PARK

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Preface

Iceland is one of the most active volcanic areas of the world. It is the only active part of the Mid-Atlantic Ridge above sea level and underneath lies the Icelandic mantle plume. In addition, the country is capped by the largest glacier in Europe, giving it an extremely diverse environment and the most extensive "Fire and Ice interactions" in the world.

The tectonic rift zone within the borders of the nominated property, Vatnajökull National Park, is a remarkable example of geological processes, driven by the geomorphic and physiographic forces that shape and continuously reconstruct the Earth's crust.

The resulting diversity of landforms: volcanoes, lava fields, mountains, ridges, tuyas, tindar, riverbeds, canyons and sands, is unique among volcanic areas, both those on the World Heritage List as well as others.

Vatnajökull National Park is the largest protected area in Iceland. Established in 2008, it includes the entire Vatnajökull glacier along with surrounding land and a few adjacent, previously protected, areas. The park has been enlarged several times to incorporate a variety of geological features created by volcanic activities and glaciovolcanism along the tectonic rift zone.

The Vatnajökull National Park administration was commissioned to prepare the nomination document, to work with the scientific community, government agencies and universities to collect all the latest data, information and maps. In this work it co-operated with a special steering committee which has been responsible for the nomination process and editorial work on behalf of the Ministries involved. The committee consulted with the eight local governments of the nominated area. All the local governments supported the preparation for and establishment of the national park and play an important role in park governance.

The nominated property, Vatnajökull National Park, is an outstanding example of the forces at work and the diversity of features resulting from the interaction of a mantle plume with a major oceanic rift system. The area covers 14% percent of Iceland. It contains natural examples of all the affiliated phenomena and land forms in pristine condition. The presence of the Vatnajökull glacier on top of these system interactions makes this environment and the associated landscapes truly one of a kind.

We are proud to submit, on behalf of the Government of Iceland, this nomination of Vatnajökull National Park for inclusion on the World Heritage List.

Lilja Alfreðsdóttir

Minister of Education, Science and Culture

Guðmundur Ingi Guðbrandsson

Minister for the Environment and Natural Resources

Acknowledgements

This nomination document has been prepared by Vatnajökull National Park as commissioned by the Ministry for the Environment and Natural Resources and the Ministry of Education, Science and Culture. A steering group was set up by the ministries to oversee and manage the nomination process.

Thanks are due to the many experts who contributed text, other background material and advice for various sections of the document:

Agnes Stefánsdóttir, Department Manager, Research and Dissemination Department, The Cultural Heritage Agency of Iceland: Cultural heritage of the nominated property (section 2.a (x)).

Agnes-Katharina Kreiling, PhD Student, Hólar University College: Evolution of fish and invertebrates in groundwater systems (section 2.a (ix)).

Ármann Höskuldsson, Research Scientist, Volcanology, Institute of Earth Sciences, University of Iceland: Geology of Iceland and the nominated property (section 2a (i-ii)).

Bjarni Diðrik Sigurðsson, Professor of Biology, Agricultural University of Iceland, Faculty of Environmental Sciences: Community development on nunataks (section 2a (ix)).

Bjarni Kr. Kristjánsson, Professor, Hólar University College: Evolution of fish and invertebrates in groundwater systems (section 2.a (ix)).

Björn Oddsson, Geophysicist, National Commissioner of the Icelandic Police, Department of Civil Protection and Emergency Management: Risk management and emergency response (section 4.b (iii)).

Christopher Hamilton, Assistant Professor Volcanology and Planetary Surfaces, University of Arizona, Lunar and Planetary Laboratory: Comparison of volcanic processes on Mars and Iceland (section 2.a (ii)).

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David J.A. Evans, Professor of Geography, Durham University, Department of Geography: Glacial geomorphology (section 2a (iv)).

Edwin Baynes, Marie Curie Fellow, University of Rennes, Geosciences Department: The making of Jökulsárgljúfur canyon (section 2a (ii)).

Eric Gaidos, Professor of Geobiology, Department of Geology & Geophysics, University of Hawaii at Manoa: Life in subglacial lakes (section 2a (ix)).

Ester Rut Unnsteinsdóttir, Zoologist, Icelandic Institute of Natural History: Arctic fox (section 2.a (ix)).

Freysteinn Sigmundsson, Professor of Geophysics, Institute of Earth Sciences, University of Iceland: Mantle plume and mid-ocean ridge interactions (section 2b (i)).

Guðbjörg R. Jóhannesdóttir, Adjunct Lecturer, Iceland Academy of the Arts, Department of Art Education: Environmental aesthetics and perception of rapidly evolving landscapes (section 2.a (v)).

Guðrún Gísladóttir, Professor of Geography, University of Iceland, Faculty of Life and Environmental Sciences: Soil formation in proglacial environments (section 2.a (vi)).

Gústaf Ásbjörnsson, Head of department, Soil Conservation Service: Quality management system for sheep grazing (section 4.a).

Halldór Walter Stefánsson, Researcher, East Iceland Nature Research Centre: Pink-footed goose (section 2.a (ix)).

Hrafnhildur Ævarsdóttir, Assistant Park Manager, Vatnajökull National Park: Barnacle goose (section 2.a (ix)).

Jón S. Ólafsson, Research Scientist, Marine and Freshwater Research Institute: Evolution of fish and invertebrates in groundwater systems (section 2.a (ix)).

María Ingimarsdóttir, Researcher, Lund University, Department of Biology: Community development on nunataks (section 2a (ix)).

Oddgeir Isaksen, Project Manager, Research and Dissemination Department, The Cultural Heritage Agency of Iceland: Cultural heritage of the nominated property (section 2.a (x)).

Ólafur Arnalds, Professor of Soil Sciences, Agricultural University of Iceland, Faculty of Environmental Sciences: Soil processes north of the Vatnajökull ice cap, soil map (sections 2a (ii) & (vi)).

Ólafur Nielsen, Ornithologist, Icelandic Institute of Natural History: Gyrfalcon and rock ptarmigan (section 2.a (ix)).

Olga Kolbrún Vilmundardóttir, PostDoc, University of Iceland, Faculty of Life and Environmental Sciences: Soil formation in proglacial environments (section 2a (vi)).

Skarphéðinn Þórisson, Researcher, East Iceland Nature Research Centre: Reindeer (section 2a (ix)).

Skúli Skúlason, Professor, Hólar University College: Evolution of fish and invertebrates in groundwater systems (section 2.a (ix)).

Snæbjörn Pálsson, Professor in Population Biology, University of Iceland, Faculty of Life and Environmental Sciences (section 2.a (ix)).

Snædís Huld Björnsdóttir, PostDoc, University of Iceland, Faculty of Life and Environ-mental Sciences: Microbial life in Vonarskarð geothermal area (section 2a (ix)).

Sólveig Pétursdóttir, Research Scientist, Matís Ltd.: Microbial life in Vonarskarð geothermal area (section 2a (ix)).

Starri Heiðmarsson, Head of Botany Department, Icelandic Institute of Natural History: Community development on nunataks.

Tómas Jóhannesson, Coordinator of Glaciological Research, Icelandic Meteorological Office: Glaciology, glacial lakes and jökulhlaups, climate, hydrology, human resilience in a dynamic environment (sections 2a (iii), (vii), (viii) & (x)).

Trausti Jónsson, Climatologist, Icelandic Meteorological Office: Climate (section 2.a (vii)).

Viggó Marteinsson, Research Group Leader, Matís Ltd: Life in subglacial lakes (section 2a (ix)).

Þóra Ellen Þórhallsdóttir (Thora Ellen Thorhallsdóttir), Professor of Botany, University of Iceland, Faculty of Life and Environmental Sciences: Colonisation and community development on sandur plains proglacial environments (section 2.a (ix)).

Þorsteinn Þorsteinsson (Thorsteinn Thorsteinsson), Glaciologist, Icelandic Meteorological Office: Glacial lakes and jökulhlaups (section 2a (iii)).

Þorvarður Árnason, Director, University of Iceland's Research Centre in Hornafjörður: Landscapes and wilderness within the nominated property (section 2a (v)).

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Next page: Aerial view to Mt. Herðubreið over the geothermal area in Kverkfjöll, 13 August 2017 © Snorri Baldursson.

Left: Silver moss, cf. *Racomitrium canescens*. Right: A patch of pale glaucous thread-moss, *Pholia wahlenbergii*. Below: View over a narrow section of the Laki lava flow to the Skaftá river and Skælingar hiking trail (narrow black band on the other side of the river), 29 July 2010 (c) Snorri Baldursson.

Executive summary

Executive summary

State Party
Iceland

State, Province or Region
Most of the nominated property is located within the southeastern central highlands of Iceland, although it extends onto lowland areas in the north and south. It lies within the boundaries of the following eight municipalities (clockwise from north): Þingeyjarsveit, Skútustaðahreppur, Norðurþing, Fljótsdalshérað, Fljótsdalshreppur, Sveitarfélagið Hornafjörður, Skaftárhreppur and Ásahreppur.

Name of Property
Vatnajökull National Park – dynamic nature of fire and ice.

Geographical Co-ordinates to the Nearest Second
Although considered a single-site nomination, geographic coordinates (mid points) are provided for each of the two discrete parts of the nominated area, the Jökulsárgljúfur canyon in North Iceland, and Vatnajökull and neighbouring areas in south-central Iceland.

Jökulsárgljúfur canyon	N 65° 53' 15.3810"	W 16° 30' 51.4656"
Vatnajökull ice cap and neighbouring areas	N 64° 34' 38.5068"	W 16° 52' 53.5456"

Textual description of the boundaries of the nominated property
The nominated property Vatnajökull National Park comprises the area defined in the Vatnajökull National Park regulation No. 608/2008 and subsequent legislation, in accordance with Act No. 60/2007 on Vatnajökull National Park, and two adjoining nature reserves, Herðubreiðarlindir and Lónsöræfi, that are protected by Decrees 272/1974 and 31/1977, based on the Nature Conservation Act in force at the time.

Criterion under which property is nominated
Vatnajökull National Park is proposed to be inscribed under World Heritage Convention criterion (viii). Thus, the property shall:

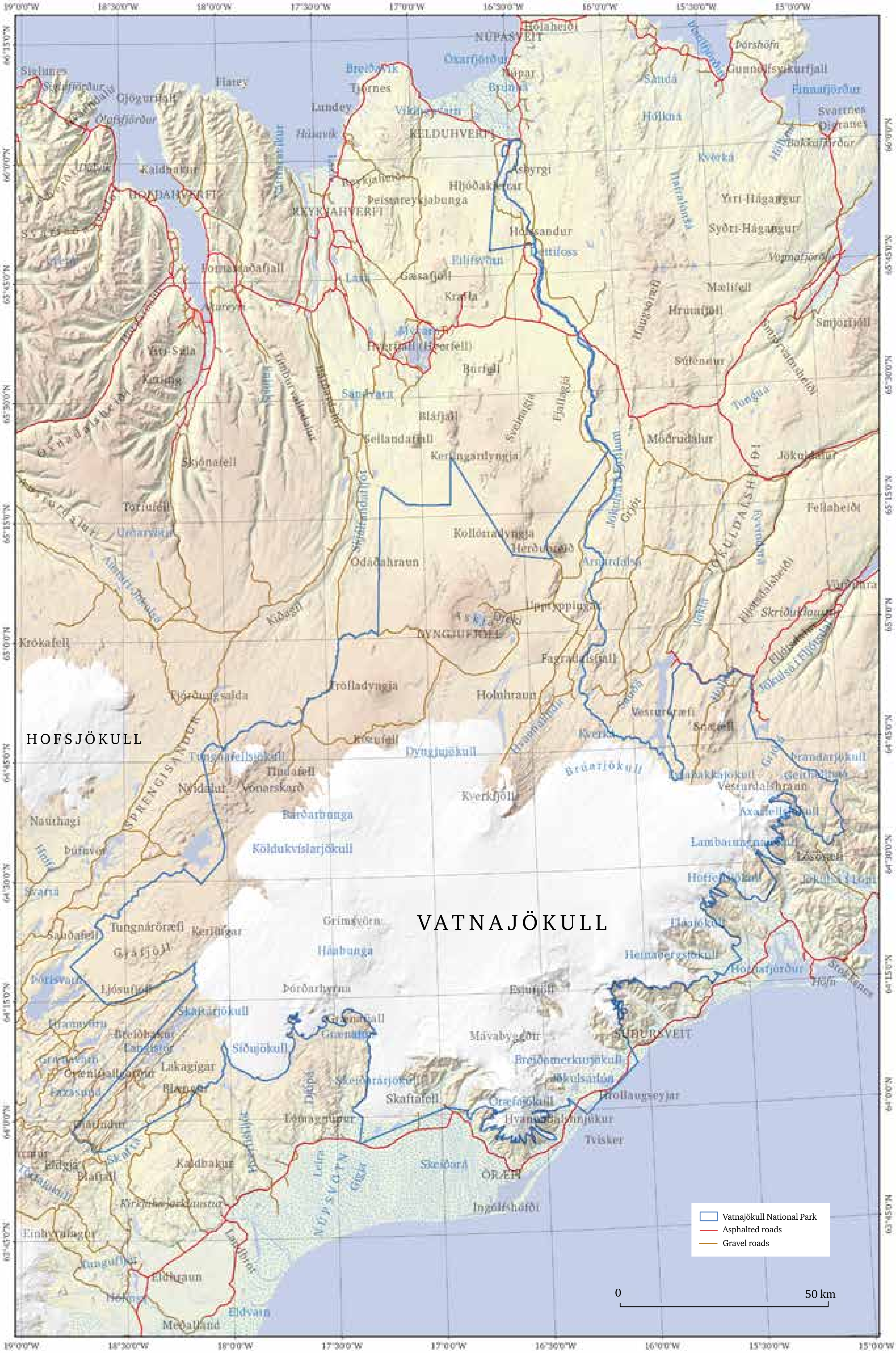
> *Be outstanding examples representing major stages of earth's history, including the record of life, significant ongoing geological processes in the development of landforms, or significant geomorphic or physiogeographic features.*

Draft Statement of Outstanding Universal Value

Brief synthesis
The nominated property, a total of 14,482 km², comprises the whole of Vatnajökull National Park, plus two contiguous protected areas. At its heart lies the 7800 km² Vatnajökull ice cap in southeast Iceland.

Iceland is the only part of the actively spreading Mid-Atlantic Ridge exposed above sea level, with the tectonic plates on either side moving apart by some 19 mm each year. This movement is accommodated in rift zones, two of which, the Eastern and Northern Volcanic Zones, pass through the nominated property. Underneath

Opposite: Topographic map of the nominated property and surrounding areas. Source: National Land Survey of Iceland.


VATNAJÖKULL
HOFSJÖKULL
Vatnajökull National Park
Asphalted roads
Gravel roads
0
50 km
NÚPASVEIT
KELDUHVERFI
REYKJAHVERFI
SUÐURSVEIT
ÖRÆFI
DYNGJUFJÖLL
Ásbyrgi
Dettifoss
Krafla
Búrfell
Bláfjall
Herðubreið
Askja
Odáðahraun
Trölladyngja
Dyngjujökull
Brúarjökull
Kverkfjöll
Bárðarbunga
Köldukvíslarjökull
Grímsvötn
Hábunga
Skaftárjökull
Síðujökull
Skeiðarárjökull
Skaftafell
Öræfajökull
Breiðamerkurjökull
Jökulsárlón
Heinabergsjökull
Hornafjörður
Höfn
Tungnafellsjökull
Nýidalur
Vonarskarð
Laki
Lakagígar
Mývatn
Eyjafjallajökull
Húsavík
Tjörnes
Lundey
Flatey
Siglunes
Kaldbakur
Akureyri
Skjónafell
Krókafell
Fjórðungsalda
Nauthagi
Tungnárörævi
Ljósufjöll
Eldgjá
Kirkjubæjarklaustur
Ingólfshöfði
Hvannadalshnúkur
Þórshöfn
Gunnólfsvíkurfjall
Vopnafjörður
Möðrudalur
Jökuldalur
Snæfell
Vesturöræfi
Eldhraun
Meðalland
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Tvísker
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64°0'0"N
63°45'0"N

their intersection is a mantle plume providing a generous source of magma. The property contains ten central volcanoes, eight of which are subglacial. Two of the latter are among the four most active in Iceland. Most of the property's bedrock is basaltic, the oldest being erupted some 10 million years ago and the most recent in 2015. Outside of the ice cap, the terrain varies from extensive, flat lava flows to mountains, including tuyas and tindar (ridges) of brown hyaloclastites, erupted in fissure eruptions beneath ice age glaciers. The latter occur nowhere else in the world in such numbers.

The nominated property comprises an entire Earth system where magma and the lithosphere are incessantly interacting with the cryosphere, hydrosphere and atmosphere to create extremely dynamic and diverse geological processes and landforms that are currently underrepresented or not found on the World Heritage List. It was here that the phrase "Fire and Ice" was coined.

The Vatnajökull ice cap reached its greatest extent by the end of the 18th century and has on average been retreating since then. Recently, its retreat has accelerated in response to global warming, making the property a prime locality for exploring the impacts of climate change on world glaciers and the landforms left behind when they retreat.

The volcanic zones of the property hold endemic groundwater fauna that has survived the ice age and single-celled organisms prosper in the inhospitable environment of subglacial lakes that may replicate conditions on early Earth and the icy satellites of Jupiter and Saturn.

Justification for criteria

Crietrion (viii). The coexistence and ongoing interaction of an active oceanic rift on land, a mantle plume, the atmosphere and an ice cap, which has varied in size and extent over the past 2.8 million years, make the nominated property unique in a global context.

Earth system interactions are constantly building and reshaping the property, creating remarkably diverse landscapes and a wide variety of tectonic, volcanic and glaciovolcanic features, many of which are not yet represented on the World Heritage List (Wood, 2009). Especially interesting and unique in this regard are the basaltic lava shields (Iceland shields), volcanic fissures and cone rows, vast flood lavas, and features of ice dominant glaciovolcanism, such as tuyas and tindar. Interestingly, the well exposed volcanic features of the property have been used as analogues for similar features on the planet Mars. Geothermal heat and subglacial eruptions produce meltwater and jökulhlaups that maintain globally unique sandur plains, to the north and south of the Vatnajökull ice cap, as well as rapidly evolving canyons.

In addition, the property contains a dynamic array of glacial- and geomorphological features, created by expanding or retreating glaciers responding to changes in climate. These features can be easily accessed and explored at the snouts of Vatnajökull's many outlet glaciers and their forelands, especially in the southern lowlands, making the property a flagship glacial research location.

Statement of integrity

The nominated property covers approximately 25–30% of the central highlands of Iceland and extends onto lowland areas to the

Previous page: Fláajökull, 5 April 2016 © Þorvarður Árnason.

north and south to cover a total of 14% of the country. Most of the property qualifies for IUCN Category II. Its integrity is reflected in the inclusion of entire and intact landscape- and geophysical units, minimal human use and intervention and interest in the property as a scientific subject. The site contains the entire Vatnajökull ice cap, with all its subsidiary glaciers as they stood in 1998. It spans some 200 km of divergent plate boundary and encompasses ten central volcanoes and large parts of the accompanying fissure swarms and subsidiary landforms. The area is intact to a large extent and remote from habituated areas. In fact, some 85 % of the property is classified as wilderness. An intense international scientific interest in the property is evidenced by at least 281 scientific peer reviewed papers, published over the last decade, on various aspects of plate tectonics, volcanism, glaciovolcanism, glaciology, glacial geomorphology and ecology. There has been no destructive human development within the property's boundaries. A few historic farms exist, but today only a few park employees live there on a year-round basis.

Requirements for protection and management
The great majority (98%) of the nominated property is protected as a national park, and the rest as nature reserves by law. Most of the land adjacent to the property is subject to the law on public land, where any invasive use requires approval by the Prime Minister's Office. The property is successfully managed by the government agency, Vatnajökull National Park, which is supported at all levels by the Icelandic government, local municipalities and businesses. A comprehensive management strategy and action plan are in place and there are sufficient financial as well as human resources for its implementation. A long-term monitoring system has been set up, using space- and ground-based observations, for improved evaluation of seismo-tectonic movements and volcanic hazards as well as for glacial flow and fluctuations and key aspects of the property's biota.

Risk management is a major issue in this highly dynamic setting where natural hazards are common. Other management issues include preventing wear and tear of nature at popular visitor destinations within the property, and maintaining adequate infrastructure for educating, managing and guiding the ever-increasing numbers of visitors which were approaching one million in 2017.

Name and contact information of official local institution
The official local institution responsible for the management of the nominated property is the government agency Vatnajökull National Park.

Vatnajökull National Park
Klapparstígur 25-27
101 Reykjavík, Iceland
Tel: +354 575 8400
Email: info@vjp.is
Web Address: www.vjp.is

Table of Contents

Top: Arial view of Hoffellsjökull on 13 July 2006 © Þorvarður Árnason. Bottom: Rock ptarmigan, *Lagopus muta* © Daníel Bergmann.

1. Identification of the Property

1. Identification of the Property

Figure 1.1.
Location of Iceland in the North Atlantic. The red line shows the spreading zone of the Mid-Atlantic Ridge. Direction of the spread is indicated with arrows.

1.a Country
Iceland

1.b State, Province or Region
Most of the property is located within the southeastern central highlands of Iceland, although it extends onto lowland areas in the north and south. It lies within the boundaries the following eight municipalities (clockwise from north): Þingeyjarsveit, Skútustaðahreppur, Norðurþing, Fljótsdalshérað, Fljótsdalshreppur, Sveitarfélagið Hornafjörður, Skaftárhreppur and Ásahreppur.

1.c Name of Property
Vatnajökull National Park – dynamic nature of fire and ice.

Note: The property consists of three separate protected areas, Vatnajökull National Park and two contiguous protected areas, Herðubreiðarlindir and Lónsöræfi Nature Reserves (see Section 5). However, it is managed as one unit and will be referred to hereafter as Vatnajökull National Park.

1.d Geographical Coordinates to the Nearest Second
Although considered a single-site nomination, geographic coordinates (mid points) are provided for each of the two discrete parts of the nominated property, the Jökulsárgljúfur canyon in North Iceland and Vatnajökull ice cap and neighbouring areas in south-central Iceland.

Jökulsárgljúfur canyon	N 65° 53' 15.3810"	W 16° 30' 51.4656"
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1.e Maps and Plans, Showing the Boundaries of the Nominated Property
See Figs 1.2 and 1.3. Full size maps (A1) accompany the nomination report in a rolled format. A buffer zone was not considered necessary for reasons explained in section 5.b.

1.f Area of Nominated Property and Proposed Buffer Zone
The area of the nominated property is 14,482 km² or 1.48 million ha.

Figure 1.2.
Location and outline map of the nominated area, Vatnajökull National Park, within Iceland. The grey areas indicate the active neovolcanic zones.

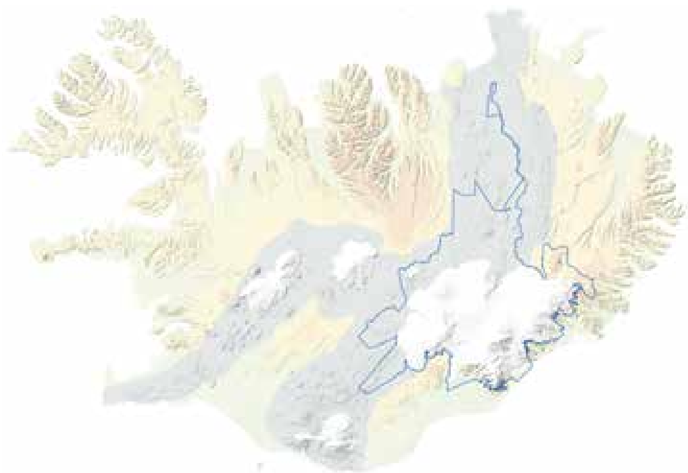
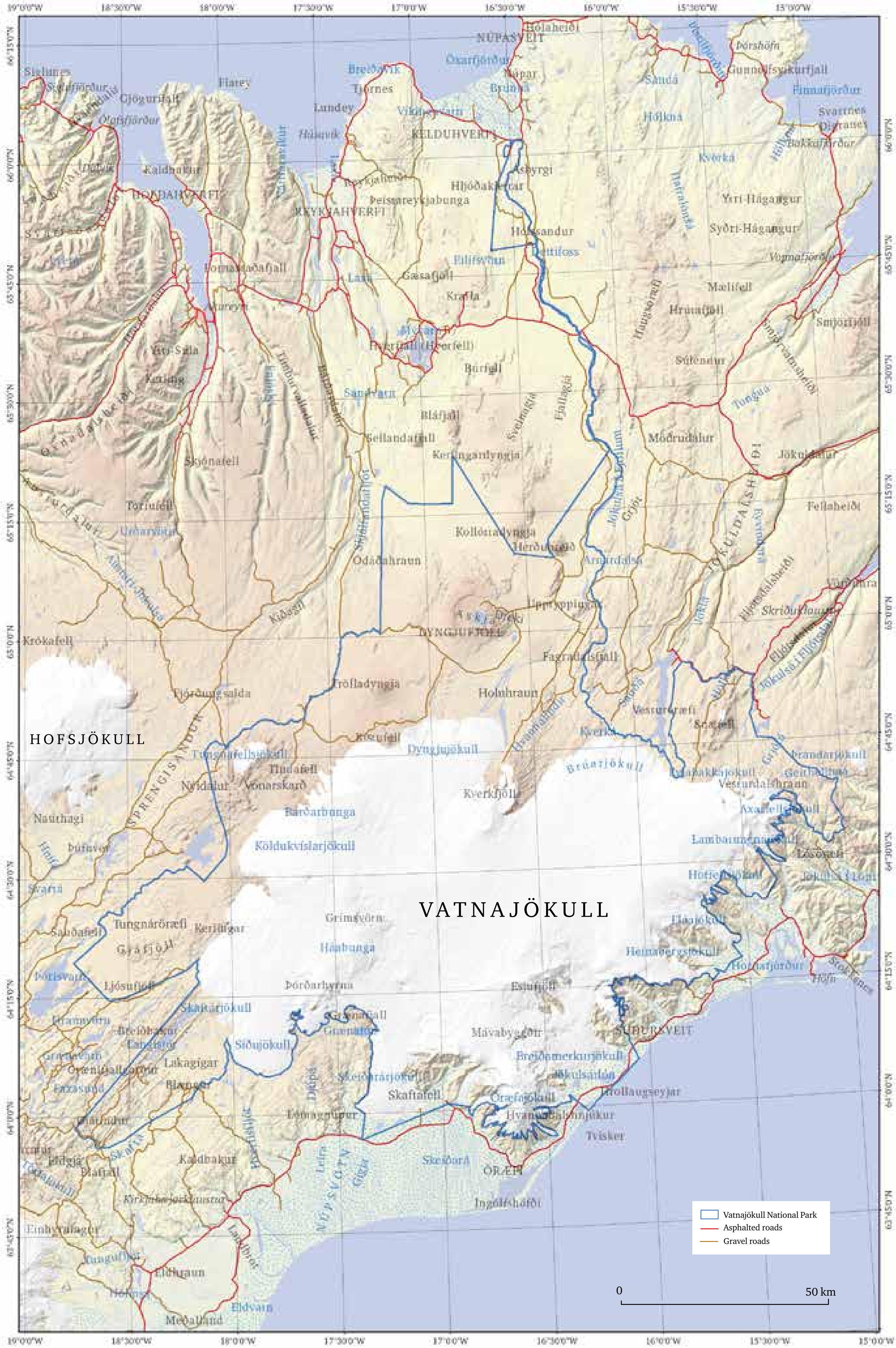


Figure 1.3.
Opposite: Topographic map of the nominated property and surrounding areas. Source: National Land Survey of Iceland.



VATNAJÖKULL
HOFSJÖKULL
Vatnajökull National Park
Asphalted roads
Gravel roads
0
50 km
Akureyri
Ásbyrgi
Dettifoss
Mývatn
Askja
Herðubreið
Kverkfjöll
Skaftafell
Jökulsárlón
Höfn
Kirkjubæjarklaustur
Lakagígar
Eldgjá
Nýidalur
Sprengisandur
Grímsvötn
Öræfajökull
Breiðamerkurjökull
Skeiðarárjökull
Dyngjujökull
Brúarjökull
Snæfell
Jökuldalur
Möðrudalur
Ódáðahraun
Holuhraun
Trölladyngja
Kverká
Tungnaárjökull
Köldukvíslarjökull
Bárðarbunga
Hágöngur
Þórisvatn
Síðujökull
Skaftárjökull
Heinabergsjökull
Hoffellsjökull
Lambatungnajökull
Skeiðarársandur
Þórshöfn
Húsavík
Siglunes
Ólafsfjörður
Eyjafjörður
Tjörnes
Lundey
Flatey
Kelduhverfi
Reykjahverfi
Eyvindará
Skjálfandafljót
Jökulsá á Fjöllum
Núpsvötn
Suðursveit
Öræfi
Ingólfshöfði
Krókafell
Fjórðungsalda
Nauthagi
Þúfuver
Ljósufjöll
Langisjór
Tungnárörævi
Vonarskarð
Tungnafellsjökull
Hvannalindir
Fagradalsfjall
Upptyppingar
Dyngjufjöll
Kollóttadyngja
Bláfjall
Sellandafjall
Búrfell
Krafla
Gæsafjöll
Hljóðaklettar
Hólssandur
Vopnafjörður
Bakkafjörður
Gunnólfsvíkurfjall
Sandá
Hólkná
Selá
Hofsá
Hrúthálsar
Skjóldalsheiði
Hraunfell
Smjörfjöll
Vestur-Öræfi
Jökulsá í Lóni
Stokksnes
Hornafjörður
Trollaugseyjar
Tvísker
Esjufjöll
Mávabyggðir
Þórðarhyrna
Hábunga
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65°15'0"N
65°0'0"N
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Top: Umbrella liverwort, *Marchantia polymorpha*. Middle: Mossy mountain-heather, *Harrimanella hypnoides*. Bottom: Detail of Svartifoss, Skaftafel, 19 july 2010 l © Snorri Baldursson.

2. Description

Iceland traces its human history back over 1100 years, to the time when settlers arrived from Norway and other countries. Just as the early settlers strived to establish a functioning society in a challenging environment, so too have the forces of nature battled to create and shape this land mass in the middle of the North Atlantic. Rifting divides the country in two roughly equal halves and visible fault lines scar the landscape. Volcanic eruptions are still contributing to the growth of the island in opposition to the glaciers, rivers and wind that erode it. All of this is reflected in the nominated property – an area of alarming natural conflict, but also enchanting harmony.

2. Description

2.a Description of Property

The nominated property encompasses one of Iceland's most dynamic and rugged regions with world-class examples of geological and geographical processes along with examples of arctic biota. At its heart is the vast Vatnajökull ice cap, and the property includes pristine and barren wilderness as well as fertile coastal valleys.

2.a (i) Geology – overview

The Mid-Atlantic Ridge and the Iceland Plume

The surface of the Earth is a mosaic of tectonic plates in continuous motion producing earthquakes and volcanic eruptions at its boundaries. The Mid-Atlantic Ridge marks the divergent plate boundary between South American and African plates in the south and North American and Eurasian plates in the north (Fig 1.2). At the latitude of Iceland, the rate of separation is about 19 mm/year in the directions of 104°E and 284°W (e.g. Sigmundsson, 2006).

Most of the Mid-Atlantic Ridge is below sea level, at a depth of 2000–3000 m. However, in Iceland it rises out of the ocean to heights of some 2000 m, generating a major anomaly along the Mid-Atlantic Ridge. Its existence above sea level is most commonly attributed to the presence of a mantle plume beneath Iceland that has elevated the region due to excess buoyancy and magma generation. As such, it is a hot spot and currently the only one on Earth where a mantle plume is interacting with a major oceanic rift system (see section 2.b). The present-day centre of the hot spot is within the nominated property.

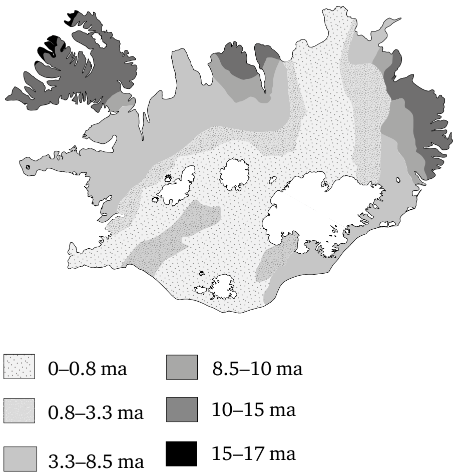


Figure 2.1.
The age of surface rocks in Iceland in millions of years. The rock series become progressively older to the west and east of the spreading plate boundary.

The bedrock of Iceland

Iceland is an integral part of the oceanic crust, formed by seafloor spreading and excess magma generation. It is predominantly built up of igneous rocks (90%) whereas sediments make up about 10% of Iceland's overall volume (Thórðarson & Höskuldsson, 2014). The oldest volcanic rocks exposed at the surface in Iceland were formed about 17 Ma (million years ago). Therefore, in geological terms Iceland is a young country, formed during the upper Cenozoic era or from the late Neogene to the Quaternary period (Fig 2.1) and spans four geological epochs (Table 2.1).

<u>The Neogene era</u>

The Neogene era is the oldest stratigraphic formation in Iceland and spans the mid to upper Miocene and the Pliocene epochs (Table 2.1; Fig 2.2; e.g. Sæmundsson, 1979; Harðarson et al., 2008; Grímsson & Símonarson, 2008). It mainly appears in two large regions on either side of the active rift zones. In the east, the Neogene Basalt Formation extends from the Skaftafell mountains within the nominated property across the eastern fjords to Bakkaflói in Northeast Iceland. In the west, it stretches from Hvalfjörður in the southwest, across Snæfellsnes and the western fjords, to Bárðardalur in North Iceland. Its cumulative thickness is about 10,000 m, but its true thickness at any location does not exceed 3000 m, because the vertical accumulation of volcanic and sedimentary rocks is coupled with

Table 2.1.
Stratigraphic formations in Iceland compared to IUGS (International Union of Geological Sciences) stratigraphic division (Cohen et al., 2013). Rock facies, geomagnetic time scale and radiometric dating determine the division in Iceland due to lack of radiometric dating. Numbers are in millions of years.

IUGS Stratigraphic Divisions			Stratigraphic Formations in Iceland
Quaternary (2.588–Present)	Holocene (0.0117–present)		Holocene Formation (0.01 Ma–present)
	Pleisto-cene (2.588–0.0117)	Upper Pleistocene (0.781–0.0117)	Upper Pleistocene (Móberg) Formation (0.8–0.01)
		Lower Pleistocene (2.588–0.781)	
Neogene (23.03–2.588)	Pliocene (5.332–2.58)	Upper Pliocene (3.6–2.588)	Upper Pliocene to Lower Pleistocene (Plio-Pleistocene) Formation (3.3–0.8)
		Lower Pliocene (5.332–36)	
	Miocene (23.03–5.332)		Upper Miocene to Lower Pliocene (Tertiary) Formation (17–3.3)

outward spreading of the pile. The original Neogene landscape, which is not readily visible today, featured scattered central volcanoes, 300 m to more than 1000 m high, towering over broad and flat lying lava plains. These plains were spotted with wetlands and dissected by the occasional gorge or river valley. Excellent cross sectional views through the Neogene succession are preserved within the south and southeast domains of the nominated property.

The most distinctive outcrop feature of the Neogene pile is its layer-cake stratigraphy, where one basaltic lava flow is stacked onto another, forming gently dipping successions hundreds to thousands of metres thick. It consists mainly of volcanic rocks, or 90% (81% basaltic, 9% silicic). Sediments make up 10% (Thórðarson & Höskuldsson, 2008). The succession is cut by many thin (1– >10 m wide) dykes that strike parallel to the long axis of the systems and, in places the density of the dykes is such that it is effectively a swarm. These dyke swarms are the subsurface component of the fissure swarms that we see presently in active volcanic systems.

<u>The Quaternary era</u>

The oldest glaciogenic deposits in Iceland are considered to be in the age range of 4–5 Ma (e.g. Geirsdóttir, 2011), although a single occurrence of glacial deposits has been reported within a 7 Ma succession in southeast Iceland (Friðleifsson, 1995). This occurrence is within the nominated property. These early glacier occurrences where of limited extent and were confined to the higher peaks, often central volcanoes, within the mountainous and humid southeastern part of the country, i.e. the nominated property (e.g. Eiríksson, 2008; Geirsdóttir 2011).

Extensive glaciation becomes evident from about 2.8 Ma and onwards. Although the ice age is referred to in the singular, it was comprised of multiple glacial and interglacial stages. Up to 20 alternating glacial and interglacial stages have been identified in Iceland. During the glacial stages the glaciers grew to form a coherent ice sheet that covered most or all of Iceland and thus dominated the landscape. During the interglacial periods Iceland was mostly ice-free (e.g. Geirsdóttir et al., 2009; Geirsdóttir, 2011).

The Quaternary era in Iceland is subdivided into three main periods, the 2.8 to 0.774 Ma Grey Basalt (Lower Pleistocene) period, the 0.774 to 0.0117 Ma Móberg period and the 0.0117 to present day Holocene period (Thórðarson & Höskuldsson, 2014; Table 2.1). The division between the Grey Basalt and Móberg formations is based on the geomagnetic timescale, more specifically the division between Matuyama and Brunhes geochrons dated at 0.774 Ma. Both periods are characterised by alternation of glaciogenic deposits and subglacial and subaerial volcanics. The Grey Basalt formations are primarily exposed in stratigraphic sections, while the subglacial and subaerial volcanic formations of the Móberg period are prominent at the surface and form some of the most spectacular volcano-glacial landforms preserved on Earth. The Móberg formation covers about 11,200 km² of Iceland and just under one third of it is within the nominated property. The ice age had major effects on the morphology of Iceland, firstly through construction of landforms by glaciovolcanism (i.e. subglacial eruptions) and secondly, through glacial erosion, which greatly increased formation of sediments as well as rates of sedimentation.

The Holocene era

Volcanism during the Holocene period is dominated by the formation of subaerial lava flows in the ice-free parts of the neovolcanic zones and by subglacial tephra and lava formations in the glacier-covered parts (Thórðarson & Höskuldsson, 2008).

Neovolcanic zones and volcanic systems

Current volcanism in Iceland is confined to regions referred to as the neovolcanic zones (Fig 2.3). The position of the neovolcanic zones is a reflection of the interplay between the tectonic activity and magmatism of the active Mid-Atlantic Ridge spreading system and the underlying mantle plume (Einarsson, 2008; section 2.b). Segmentation of the plate boundary across Iceland is threefold (Macdonald et al., 1991; Fig 2.3). The first order segmentation is defined by two distinct continuities; (i) the Reykjanes – Langjökull (RLC) and (ii) the Vestmannaeyjar – Skjálfandi (VSC) volcano-tectonic continuities. These continuities are linked by two first order discontinuities, the South Iceland Seismic Zone and the Tjörnes Fracture Zone. The second order segmentation is referred to as volcanic zones, where the RLC is divided into the Reykjanes Volcanic Belt and the Western Volcanic Zone and the VSC is divided into the Eastern and Northern Volcanic Zones. In addition to these principal elements, Iceland features two intraplate volcanic belts, the Snæfellsnes and Öræfajökull Volcanic Belts. The third order segmentation is the volcanic systems, which define the principal geological unit of the volcanic zones or belts. Each system is between 7–200 km long and 7–30 km wide. In total 30 active volcanic systems are identified in Iceland.

Each volcanic system consists of a central volcano or fissure swarm or both (Fig 2.3) and the fissure

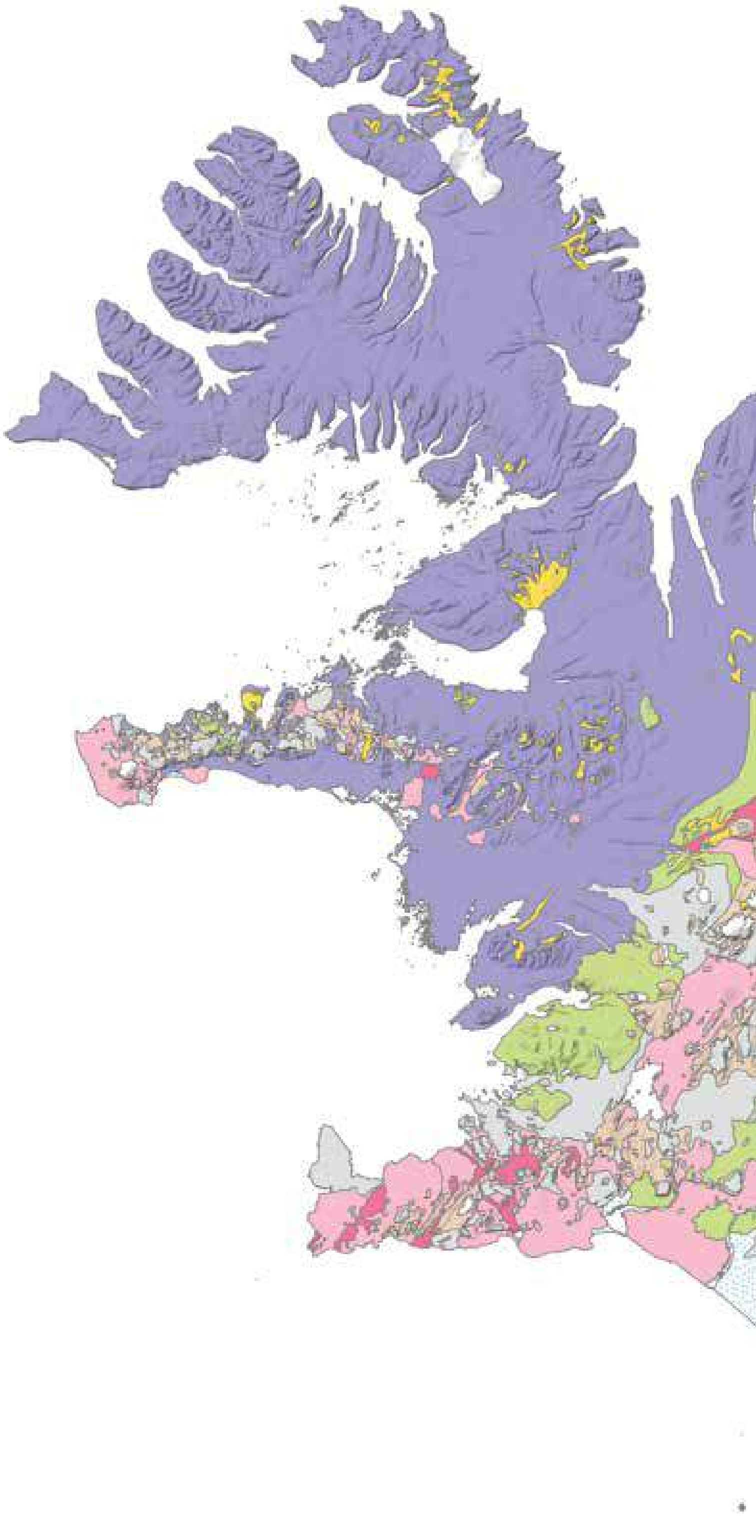
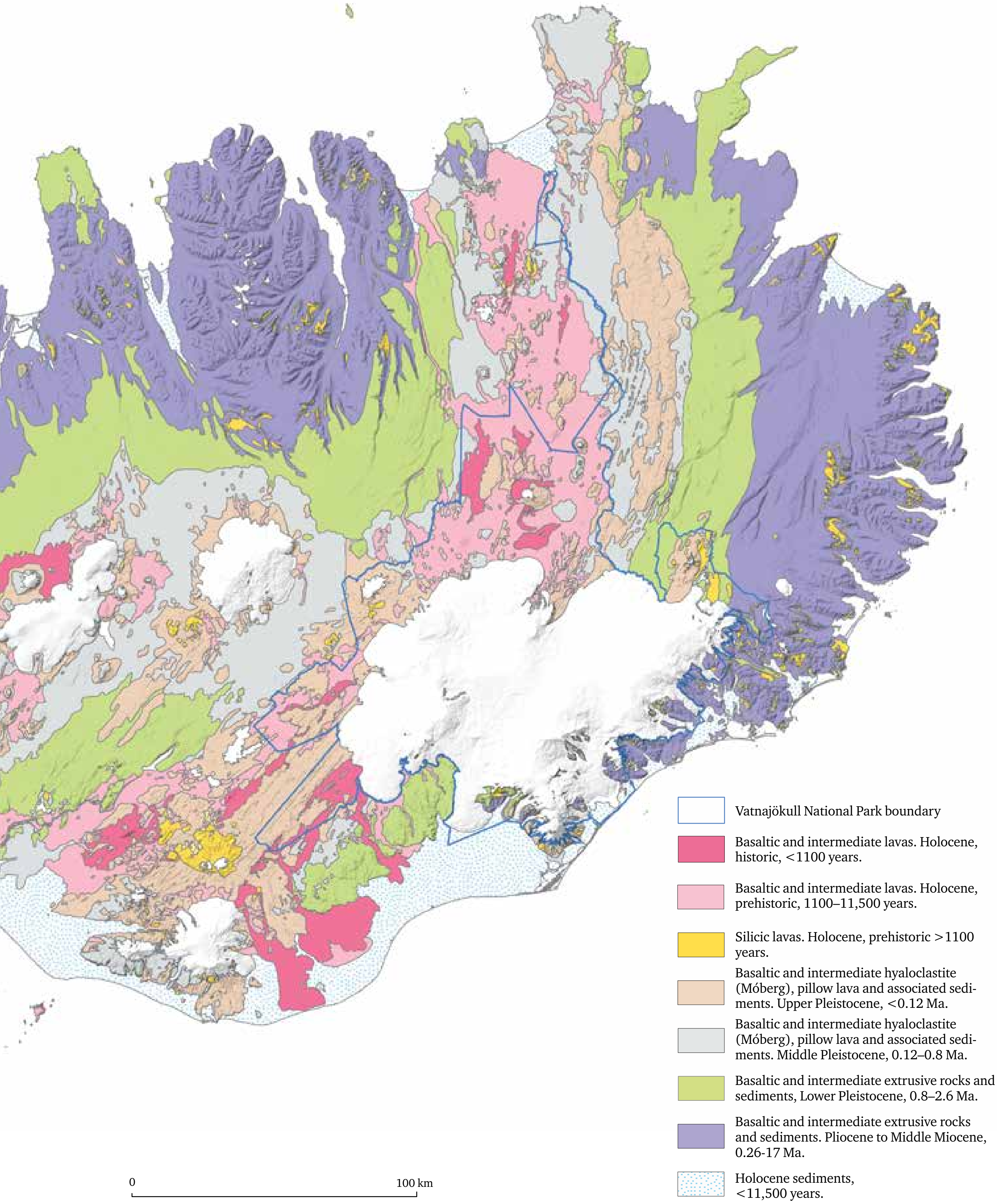


Figure 2.2.
Simplified geological map of Iceland, displaying the principal geological formations. Modified after Jóhannesson (2014).



Vatnajökull National Park boundary
Basaltic and intermediate lavas. Holocene, historic, <1100 years.
Basaltic and intermediate lavas. Holocene, prehistoric, 1100–11,500 years.
Silicic lavas. Holocene, prehistoric >1100 years.
Basaltic and intermediate hyaloclastite (Móberg), pillow lava and associated sediments. Upper Pleistocene, <0.12 Ma.
Basaltic and intermediate hyaloclastite (Móberg), pillow lava and associated sediments. Middle Pleistocene, 0.12–0.8 Ma.
Basaltic and intermediate extrusive rocks and sediments, Lower Pleistocene, 0.8–2.6 Ma.
Basaltic and intermediate extrusive rocks and sediments. Pliocene to Middle Miocene, 0.26-17 Ma.
Holocene sediments, <11,500 years.
0
100 km

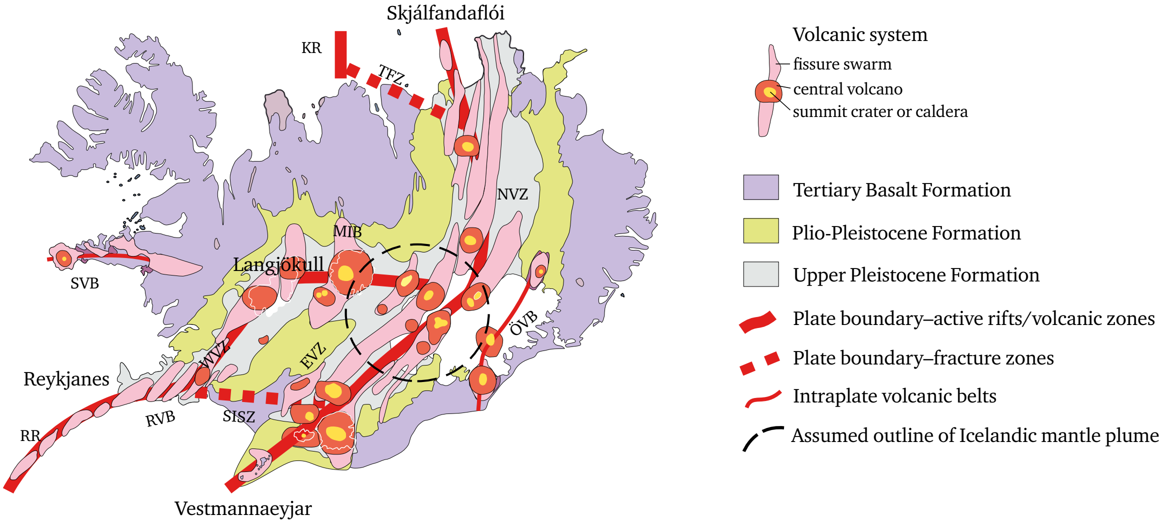


Figure 2.3.
Simplified geological map of Iceland, emphasising segmentation of the plate boundary, volcanic zones and volcanic systems. RR, Reykjanes Ridge; RVB, Reykjanes Volcanic Belt; WVZ, Western Volcanic Zone; MIB, Mid-Iceland Belt; EVZ, Eastern Volcanic Zone; NVZ, Northern Volcanic Zone; TFZ, Tjörnes Fracture Zone; KR, Kolbeinsey Ridge; ÖVB, Öræfi Volcanic Belt; SVB, Snæfellsnes Volcanic Belt. Modified after Thórðarson Hörkuldsson, 2014.

swarms typically feature numerous monogenetic cones and cone rows (Jóhanesson & Sæmundsson, 2009). Similar configuration is observed within the Neogene formation, i.e. a central volcano and associated dyke swarm where the dykes are the subsurface representation of the surface fissures. This realisation suggests that the volcanic system segmentation is prevalent throughout Iceland's geological history (e.g. Sæmundsson, 1979). The eruption frequency is highest within the central volcanoes, yet they account for <25% of magma erupted by individual systems because the vast majority of these eruptive events are small in terms of magma volume. Fissure swarms, when present, account for >75% of the magma production on individual systems, mostly in large-volume flood lava (one to 100 km³) events. The central volcanoes erupt basaltic (low SiO_2) to rhyolitic (high SiO_2) magmas, while magma production on the fissure swarms is entirely basaltic. Both components produce effusive and explosive eruptions, although the latter is more common within the central volcanoes. The size, magnitude and frequency of eruptions, make Iceland one of the most active and productive volcanic regions on Earth (Thórðarson & Höskuldsson, 2008).

Tindar landscape of Kverkfjallarani from air, 13 August 2017. Mt. Herðubreið in the distance © Snorri Baldursson

2.a (ii) Geology of the Nominated Property

Geological formations from all four epochs exposed in Iceland are found within the nominated property. However, as the property covers large parts of the active rift and one of the intraplate volcanic belts, the volcanic landscape is dominated by Móberg and Holocene epoch geological formations, along with the Vatnajökull ice cap (Fig 2.2). Some of the best examples of upper Miocene rock formations in Iceland are found in the south and southeast parts of the property. There, hundreds of metres of the volcanic successions are exposed through glacial erosion, providing a window into the geological past of Iceland. A continuum from upper Miocene to Holocene can then be followed from the southeastern edge of the property towards the currently active volcanic zones.

The western and northern regions of the property feature young volcanics and active glacial processes. The interplay in time and space between volcanism and the glacier is evident. The stratigraphic succession spans the Móberg formation to the Holocene, and the surface geology is typified by subaerial Holocene lava flows filling the low-lying areas between the subglacial Móberg formation ridges and mountains, giving the impression that the subglacial pillow lava and hyaloclastite formations are “islands” in a vast sea of lava. Spectacular illustrations of this interplay are present in the Langisjór-Laki area to the west of Vatnajökull and in the Kverkfjallarani mountain range and around Mt. Herðubreið to the north of Vatnajökull.

In the region of Skaftafell and Öræfajökull, in the southcentral part of the property, stratigraphic sequences of the Grey Basalt formation feature increasing proportions of thicker, valley-confined lava flows and sediments: a manifestation of the gradually declining global climate towards the end of the Neogene. In the upper part of the sequence, hyaloclastites and glaciogenic sediments become more abundant, representing recurrences of glaciations and subglacial volcanic activity, documenting the onset of the ice age. Altogether 16 glacial and interglacial intervals have been identified in the stratigraphic succession of Öræfi and Skaftafell (Helgason & Duncan, 2001).

The lava shield Mt. Trölladyngja, 9 September 2014 © Snorri Baldursson.

Volcanic systems of the nominated property

The first order VSC segment cuts across the nominated property, including about one third of the Eastern Volcanic Zone and a large part of the Northern Volcanic Zone, as well as the entire Öræfajökull Volcanic Belt. Collectively, this means that nine volcanic systems are entirely or partly contained within the nominated property. Belonging to these volcanic systems are 10 central volcanoes and associated fissure swarms. These are from north to south Askja, Kverkfjöll, Snæfell, Tungnafellsjökull, Bárðarbunga, Grímsvötn, Esjufjöll, Þórðarhyrna and Öræfajökull (Fig 2.4; Table 2.2). In addition, the fissure swarms of two other volcanic systems extend into the property. The 934–939 Eldgjá vent system of the Katla volcanic system extends into the property's southwestern part and the Fremrinámar fissure swarm reaches into its far northwestern part.

Volcanic activity in individual systems has its own characteristics when it comes to the frequency and style of the eruption. The systems that are centrally located within the neovolcanic zones, such as Askja, Bárðarbunga and Grímsvötn, are very active, with tens to hundreds of events during the Holocene. However, the systems within the Öræfajökull Volcanic Belt, i.e. Öræfajökull, Esjufjöll and Snæfell, are farther away from the active rift and less active.

The volcanic systems of the nominated property are the source

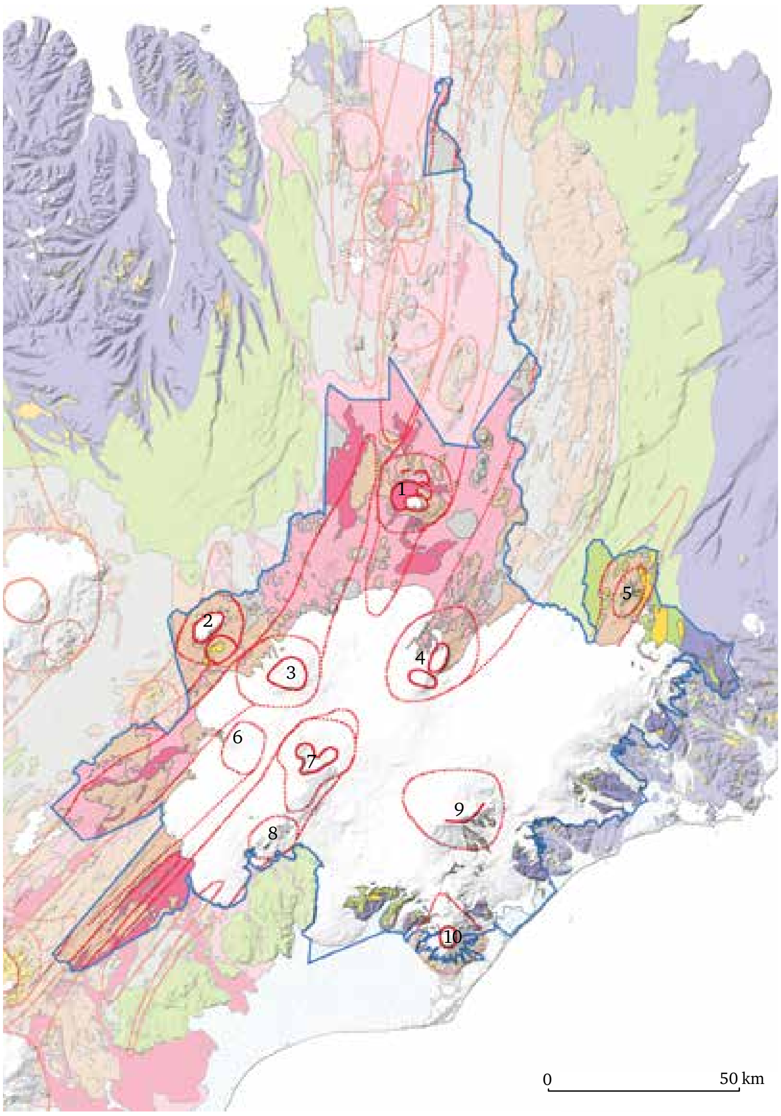


Figure 2.4.
The volcanic systems and central volcanoes of the nominated property. Modified after Jóhannesson & Sæmundsson (2009). See larger map in Appendix 1.1.

1. Askja
2. Tunnafellsjökull
3. Barðarbunga
4. Kverkjöll
5. Snæfell
6. Hamarinn
7. Grímsvötn
8. Þórðarhyrna
9. Esjufjöll
10. Öræfajökull

Vatnajökull National Park boundary
Central volcanoes and fissure swarms
Calderas
Historic lavas, <1100 years.
Prehistoric lavas, 1100–11,500 years.
Silicic prehistoric lavas, >1100 years.
Hyaloclastite (Móberg). Upper Pleistocene, <0.12 Ma.
Hyaloclastite (Móberg). Middle Pleistocene, 0.12–0.8 Ma.
Basaltic rocks, Lower Pleistocene, 0.8–2.6 Ma.
Basaltic rocks. Pliocene to Middle Miocene, 0.26-17 Ma.
Holocene sediments, <11,500 years.

Öræfajökull central volcano and Iceland's highest peak, Hvannadalshnjúkur, 21 February 2015 © Þorvarður Árnason.

of some of the largest Holocene volcanic events in Iceland as well as on Earth. Most notable prehistoric events are: (i) the Grímsvötn eruption series, ca. 10,400 to 9900, which sent tephra across the North Atlantic during an intense period of activity, spanning some 500 years, that may have produced as much as 100 km³ of tephra; (ii) the ca. 8600 Þjórsá lava (25 km³), and (iii) the ca. 7000 Trölladyngja lava shield (15 km³), of the Bárðarbunga system. In historic time, i.e. the last 1140 years, the list includes events like the 871 Vatnaöldur (5 km³; Bárðarbunga), 934–939 Eldgjá (20 km³; Katla), 1362 Öræfajökull (10 km³), 1477 Veiðivötn (11 km³; Bárðarbunga), the 1783–1784 Laki (15 km³; Grímsvötn) and the 1875 Askja (1 km³) eruptions (e.g. Tórðarson & Höskuldsson, 2008; Table 2.2).

Table 2.2.
Central volcanoes influencing the nominated property. The presence of ice cover and the last known activity are indicated.

Volanic system	Ice covered Central volcano	Last subglacial volcanic activity	Last subaerial activity	Size (l x w in km)
Fremrinámar	No	>10,000 BP	Ca. 3000 BP	150 x 15
Askja	No	>10,000 BP	1961	190 x 20
Kverkfjöll	Yes	Ca. 1400 BP	Ca. -4500 BP	130 x 20
Snæfell	Partly	>10,000 BP	>10,000 BP	27 x 12
Tungnafellsjökull	Yes	>10,000 BP	<10,000 BP	55 x 15
Bárðarbunga	Yes	2014–2015	2014–2015	190 x 25
Grímsvötn	Yes	2011	1783–1784	100 x 18
Esjufjöll	Yes	1927 (inferred)	1927	20 x 20
Hamarinn	Yes	18th century	1477	80 x 10
Þórðarhyrna	Yes	1903	6000 BP	80 x 10
Katla	Yes	1918	934–939	110 x 30
Öræfajökull	Yes	1727	1727	20 x 20

Previous page: Askja caldera lake, 13 August 2017 © Snorri Baldursson.

Geological description of the property by regions

Although the administrative regions of Vatnajökull National Park (see section 5.c) were not delineated on the basis of physiogeography, they provide a useful framework for describing the diverse geology exposed outside the ice cap. Each region has its special geological features, from the old bedrock in the southeast to the active spreading and volcanism in the west and north.

Northern region

The northern region of the nominated property (Figs 1.3, 2.5) is framed by two major glacial rivers, Skjálfandafljót, carrying meltwater from the Bárðarbunga, Rjúpnabrekkujökull region, and Jökulsá á Fjöllum, flowing from the Dyngjujökull, Kverkjökull and Brúarjökull outlet glaciers. The area is largely confined within the junction of the highly active Eastern Volcanic Zone and the Northern Volcanic Zone. The northern region has the most extensive ice-free land of all of the park's regions. Constructive forces mostly shape the surface morphology of the region, where extensive subaerially erupted lava flows, often torn apart by fissures and faults, fill the valleys between the subglacially formed volcanic ridges and central edifices.

Volcanic activity of the northern region spans two volcanic systems. These are the partly subglacial Bárðarbunga and the fully

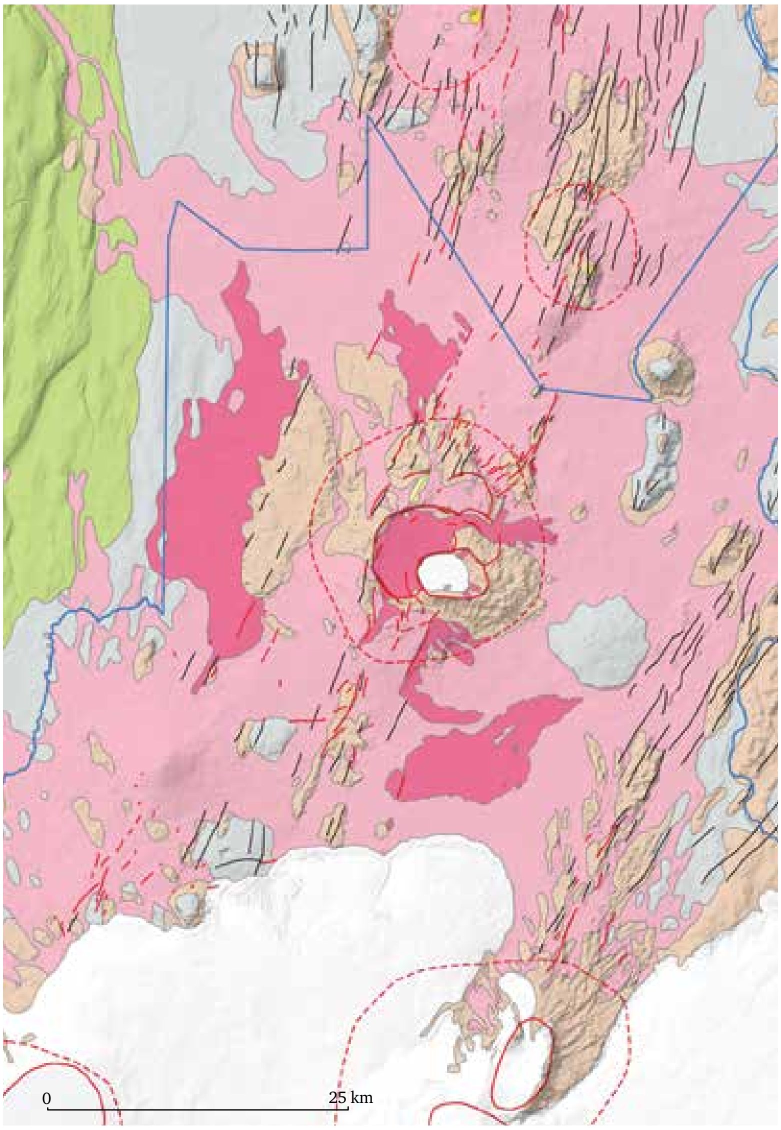
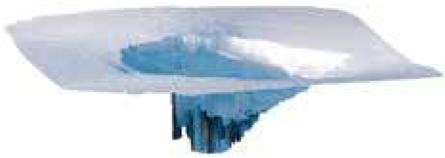


Figure 2.5.
Simplified geological map of the northern region of the nominated property, displaying the main geological features. Modified after Hjartarson & Sæmundsson (2014). See larger map in Appendix 1.1.

Vatnajökull National Park boundary
Central volcanoes
Calderas
Fault
Historic lavas, <1100 years.
Prehistoric lavas, 1100–11,500 years.
Silicic prehistoric lavas, >1100 years.
Hyaloclastite (Móberg). Upper Pleistocene, <0.12 Ma.
Hyaloclastite (Móberg). Middle Pleistocene, 0.12–0.8 Ma.
Basaltic rocks, Lower Pleistocene, 0.8–2.6 Ma.
Basaltic rocks. Pliocene to Middle Miocene, 0.26-17 Ma.
Holocene sediments, <11,500 years.



Bottom: Ice cauldrons on the Bárðarbunga caldera rim on 28 November 2017 © Ragnar Axelsson (RAX). Top: Model of the larger cauldron from different angles. Source: Ingibjörg Jónsdóttir.

subaerial Askja systems. The Bárðarbunga system covers 3130 km². It is 193 km long and has a maximum width of 28 km, while the Askja system covers ca. 2400 km² and is ca. 200 km long and up to 20 km wide (e.g. Jóhanneson & Sæmundsson, 2009). The systems take their name after their highly active central volcanoes, which are prominent on the horizon in the northern region.

Bárðarbunga central volcano sits directly above the assumed centre of the Icelandic mantle plume. It rises to an altitude of 2010 m above sea level and 600–700 m above its surroundings. It is surprisingly small – basal diameters are 21 and 18 km and the total volume is 98 km³ – considering that it is one of Iceland's most active central volcanoes (Jóhanneson & Sæmundsson, 2009). The ice-filled caldera is 8 x 11 km wide and 700 m deep (Guðmundsson, 2001; Guðmundsson et al., 2016). It has produced at least 20 explosive basaltic eruptions in historic time and >330 events during the Holocene (e.g. Larsen et al., 1998; Thórðarson & Larsen, 2007; Óladóttir et al., 2011; section 2.b). The northern arm of the Bárðarbunga fissure swarm, often referred to as Dyngjuháls, is contained within the northern region. It has produced numerous, small to very large effusive fissure and circular vent eruptions, including the ca. 9000 Bárðardalur lava (8 km³), which reached the north coast at Skjálfandi, the Trölladyngja lava shield (see above) and the 14th century Frambruni lava (4 km³). The latest fissure eruption in Iceland at Holuhraun 2014–2015 took place within the northern region on the sandur plains of Dyngjujökull (Box p. 36–37).

Further north is the Askja central volcano, situated between the Frambruni lava field in the west and the river Jökulsá á Fjöllum in the east. The volcanic massif, termed Dyngjufjöll, dominates the

Holuhraun 2014–2015

The unrest on 16 August 2014 began with seismic activity beneath the northern foothills of the Bárðarbunga volcano and Mt. Kistufell, as well as with a seismic swarm at depths of 3–5 km beneath the rim of the Bárðarbunga caldera, propagating about 5 km to the southeast. This was followed by a seismic swarm originating at 2–6 km depth, ca. 5 km to the northeast of the aforementioned swarm. Over a period of 10 days this swarm migrated 42 km northwards at a depth interval of 5–8 km, reaching deeper with increasing distance. On 29 and 31 August this activity culminated in eruptions on the pre-existing 1797 Holuhraun cone row (Guðmundsson et al., 2016a; Pedersen et al., 2017). The seismic unrest has been interpreted as indicating lateral dyke emplacement originating at Bárðarbunga and migrating 48 km at depths of 5–7 km at a rate of 0.08-1.3 m/s (Fig 2.6; Sigmundsson et al., 2014; Ágústsdóttir et al., 2016). An alternative interpretation was put forth by Guðmundsson et al. (2014) where the migrating seismic swarm is taken to represent the unzipping of the roof of an elongate mid-crustal reservoir followed by a subsequent vertical rise of the magma filling the opening fissure and reaching the surface in the form of an eruption at four locations.

The 2014–2015 eruption in Holuhraun was the largest effusive volcanic eruption in Iceland (or Europe) since the Laki event in 1783–1784. The lava field covers 84 km² and has a volume of 1.45 km³. The average discharge rate was 90 m^3s^{-1}, with a peak intensity of ca. 570 m^3s^{-1} (Bonny & Wright, in press). Not only was the eruption unique for Iceland's recent volcanic past, but also the precursors were unique. This was the first observed propagation of an earthquake swarm under ice, inferred to indicate the emplacement of the feeder dyke (Sigmundsson et al., 2015) and an exceptionally well-monitored caldera subsidence at Bárðarbunga caldera, perhaps the best recorded event of its kind (e.g. Guðmundsson et al., 2016).

Left and opposite page: The Holuhraun eruption on 2 September 2014 © Walter Huber. Right: The main crater, Baugur, of the 2014 – 205 Holuhraun eruption, 13 August 2017 © Snorri Baldursson.

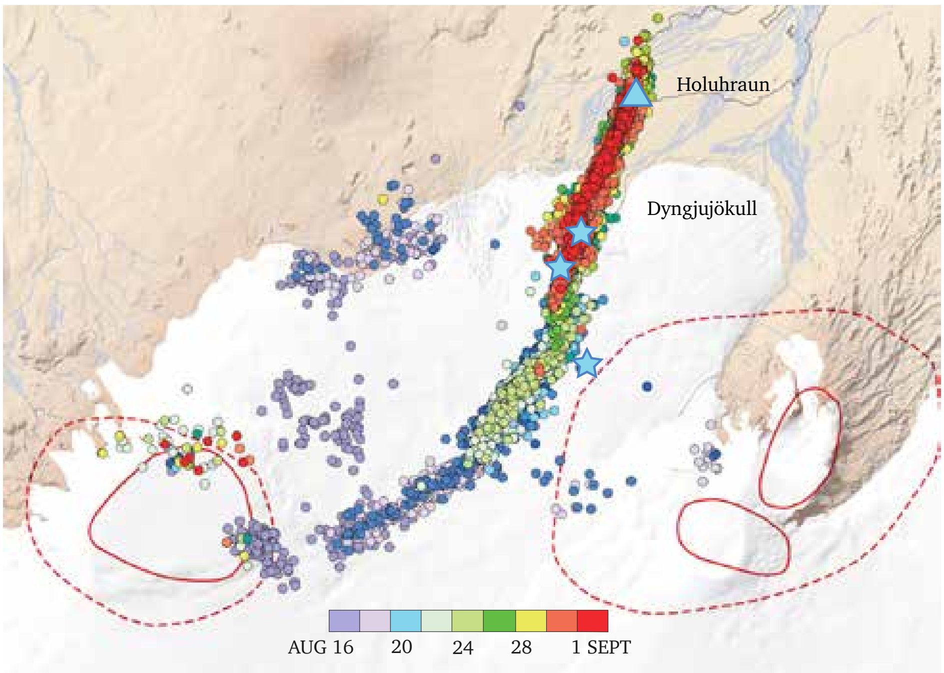
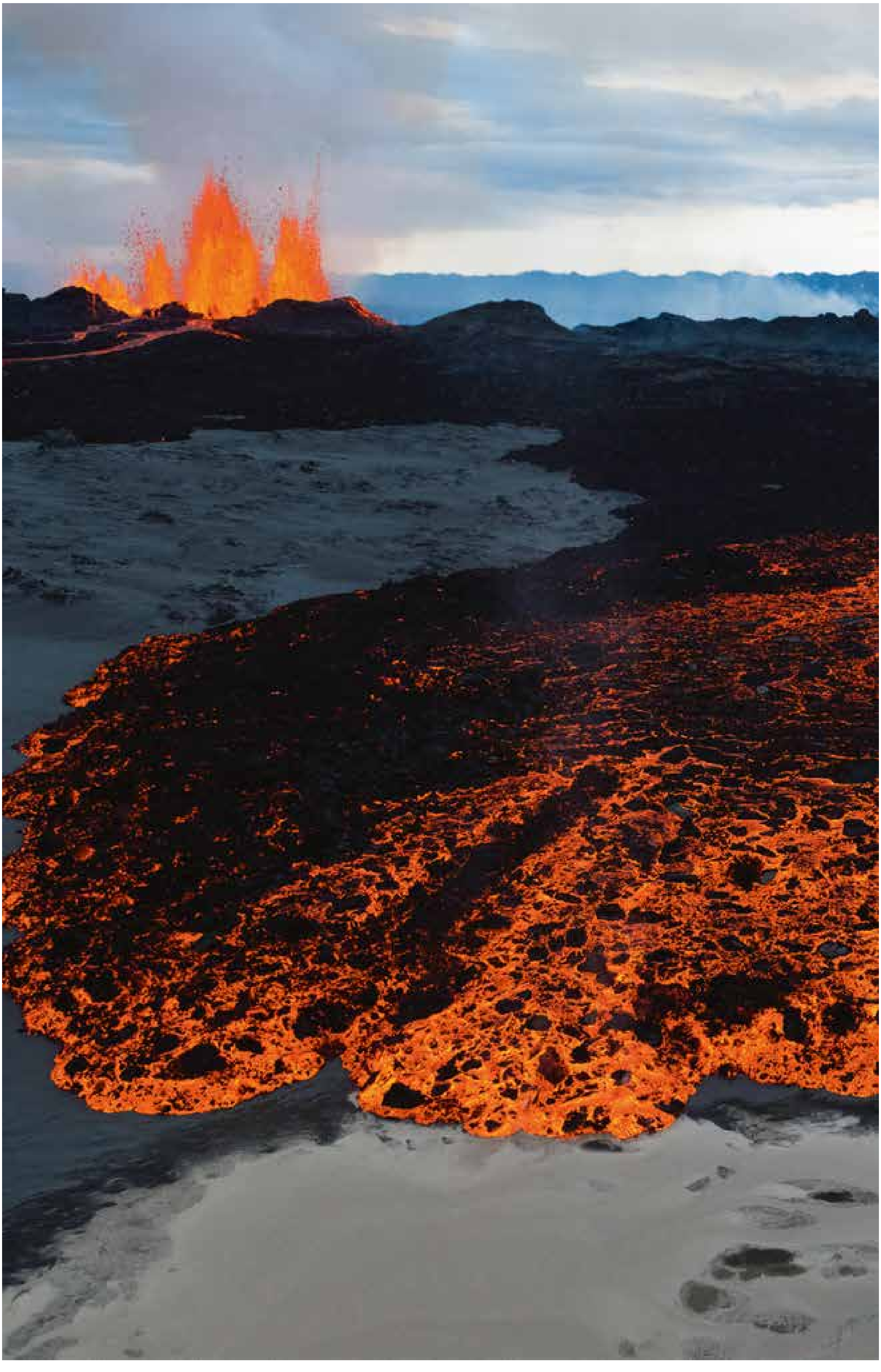


Figure 2.6.
The seismic swarm of 16–31 August 2014, coloured by date in map view. Red lines delineate central volcanoes and calderas, blue triangle the eruption site and blue stars depressions in the ice surface. Modified after Ágústsdóttir et al. (2016).



Northern region. Top: The crater Víti (1875) in the foreground with clouds reflecting in Öskjuvatn caldera lake in the back, 13 August 2017. Middle: Horizontal basalt columns at Hljóðaklettar, Jökulsárgljúfur canyon, 17 July 2013. Bottom: Jökulsá á Fjöllum and Mt. Herðubreið, 13 August 2017 © Snorri Baldursson.

Northern region, cont.: Top: Dettifoss on 19 February 2013 © Walter Huber. Middle: The light brown tephra of the 1975 Askja eruption, Dyngjufjöll massif in the back, 17 August 2016 © Snorri Baldursson. Bottom: Bárðarbunga central volcano, 10 March 2010 © Oddur Sigurðsson.

ice-free area to the north of Vatnajökull. Its highest peak, Þorvaldstindur, reaches 1510 m above sea level and 750 m above its surroundings. The volcano covers about 380 km^2 and has a volume of about 135 km^3. It is comprised of Móberg formation hyaloclastites as well as Holocene lava flows and domes, which fill the calderas and cover parts of the volcano flanks (Sigvaldason, 2002; Hartley & Thórðarson, 2013; Grattinger et al., 2013).

The heart of the Askja central volcano is an 8–10 km wide caldera from which the volcano and the volcanic system take their names. At least four calderas have been identified within the Askja central volcano. The youngest one is occupied by the Öskjuvatn lake, formed over a period of 50 years following a major Plinian (i.e. explosive) silicic eruption on 28–29 March 1875. The three older calderas have all been progressively filled with Holocene lavas since their formation (Sigvaldason, 2002; Hartley & Thórðarson, 2013).

The lower-elevation regions around Askja are covered by Holocene lava flows from circular vent and fissure eruptions originating from Askja, Kverkfjöll and Bárðarbunga volcanic systems. Many of these events took place on the fissure swarms of these systems, including eight events that lead to the formation of a spectacular cluster of interglacial to Holocene lava shields; which, from south to north, are Urðarháls, Trölladyngja, Hrímalda, Vaðalda, Svartadyngja, Fjárhóladyngja and Flatadyngja (Hjartardóttir & Einarsson, 2015). These monogenetic lava shields are only present in the northern region of the nominated property and their age extends over at least 100 thousand years, with the youngest shield possibly as young as 1000 years old (Hartley et al., 2016).

Two types of lava shields are observed, subaerial and subglacial. Of the subaerial ones, the lava shield of Trölladyngja and Kollóttadyngja (just outside the property) are the most prominent and among the largest in Iceland, with basal diameters of 13 and 8 km and rising 500–600 m above their surroundings. The interglacial lava shields Urðarháls, Hrímalda and Vaðalda are a good demonstration of how these shield-like volcanic edifices withstand glacial erosion as they have maintained their original form remarkably well. Two subglacial lava shields are present, Kistufell and Herðubreið. These table-like landforms are referred to as “tuyas” (Box p. 41) in the scientific literature and were formed in a prolonged subglacial circular-vent eruption during the last (Weichselian) glaciation. The northern area, thus offers ample opportunity to examine and compare effects of vastly different geological environments, subaerial and subglacial, on volcanism and the landform it produces, the latter simulating landforms on subaquatic mid-oceanic ridges.

Mostly constructive forces have moulded the landscape of the northern region, but there are also significant erosional features. Between the Dyngjujökull outlet glacier and the Dyngjufjöll mountain massif is Dyngjusandur or Flæður, a 140 km^2 sandur (outwash) plain created by the glacial discharge of Jökulsá á Fjöllum. This sandur plain is now partly covered by the 2014–2015 Holuhraun lava field. Dyngjusandur is the most productive dust source in Iceland and among the most productive on Earth (Box p. 42).

The products of Askja volcanic system – subglacial and subaerial

Northeast of Askja is Mt. Herðubreið (1682 m), a tuya formed during the Weichselian glaciation and rising more than 1000 m above its surroundings. Mt. Herðubreið is an example of a lava shield forming eruption that erupted up through more than 1000 m thick ice sheet. The stratigraphy of the mountain goes from pillow lavas at its base to hyaloclastites midway and finally it is capped by subaerial lava. The facies changes in the eruptive products reflect water pressure at the time of eruption. Pillow lavas are formed under the deepest water column, i.e. the highest pressure, resulting in a relatively quiet effusion of the magma and a minimal exsolution of magmatic volatiles. The hyaloclastite represents the stage when the edifice has built up to reduce the water depth such that the pressure is low enough to exolve magmatic volatiles plus interact with surrounding meltwater to produce an explosive eruption, first through the water column and later through a subaerial vent. The lava cap represents the final stage of activity, were the vent is fully emerged and dry eruption ensues with fountaining and lava formation (Fig 2.7).

Herðubreið is a classic example of a tuya, demonstrating how the eruption, and the architecture of the volcanic edifice, changes as it builds up through a relatively deep water column and fully emerges to become an island in the ice. As such, it is a volcanic landform that is very comparable to seamounts on the ocean floor.

Directly south of Herðubreið is a linear group of peaks named Herðubreiðartögl, defining a ridge-like landform. These landforms are referred to as tindar in the scientific literature. Tindar, also known as móberg or hyaloclastite ridges, are linear structures erupted under ice with a width to length ratio of at least 1:2 (Jakobsson & Guðmundsson, 2008). They often occur as a row of peaks at semi-regular intervals, reflecting a subglacial fissure eruption where the volcanic activity quickly concentrated along a row of vents, like the subaerial Laki fissure eruption and its cone row. Herðubreið and Herðubreiðartögl are classic examples of subglacial (subaquatic) volcanic formations of different shapes, as determined by the geometry of the eruptive vents, circular versus linear, respectively.

Tuyas and tindar can be described simply in terms of their volcanic components, but in the field, they are complicated structures, formed in very dynamic environments. The fact that they were erupted under thick ice makes it difficult to observe their formation, even in Iceland. The 1996 eruption of Gjálp (Box p. 64) provided a very rare opportunity to observe and monitor a subglacial eruption resulting in the formation of a tindar landform and the associated post-eruption evolution of its edifice (Jakobsson & Johnson, 2012).

Some 10 km to the west-northwest of Herðubreið is the 14 km² Kollóttadyngja (just outside the property), an early Holocene lava shield that rises to 1178 m and 500 m above the surrounding plains (Sigvaldason, 2002; Hartley et al, 2016). The formation of a tuya and a lava shield have often been inferred to be intrinsically the same, or constructed by prolonged circular-vent events, but taking place in different eruptive environments, subglacial versus subaerial. In the nominated property these contrasting volcanic landforms can, literally speaking, be observed and examined side by side. Another similar set of subglacial and subaerial edifices, both formed by fissure eruptions, are the Herðubreiðartögl tindar formation and the Holocene crater row of Fjallsendagígar, the vent system for the extensive 14th century Frambruni lava field.

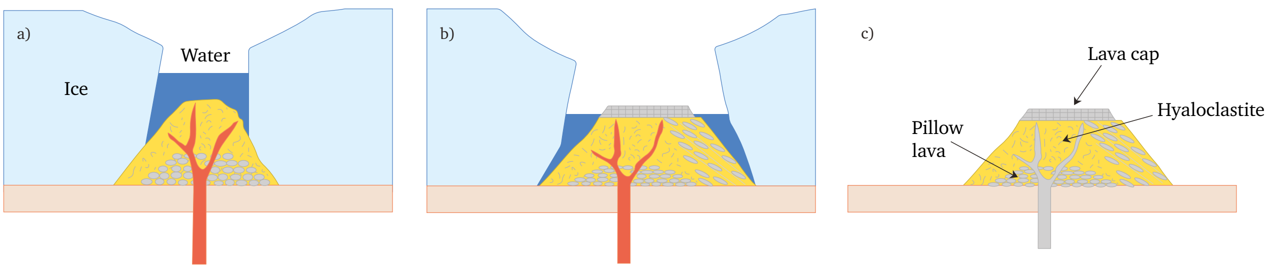


Figure 2.7.
Schematic diagram illustrating the formation of a tuya and the facies changes in the eruptive products.

The dust bowl of Dyngjusandur – a dynamic arena of aeolian processes

There are certain areas on Earth where conditions lead to an unusual amount of dust production. The most productive area of this kind in the world is the Bodelé depression in Chad, which is responsible for a great deal of the >200 million metric tons of dust produced in North Africa each year (Engelstaedter et al., 2006). The Dyngjusandur area, north of Dyngjujökull (northwest of Vatnajökull), is rated as the most productive dust source in Iceland (Dagsson-Waldhauserova et al., 2013a, 2013b) and among the most productive on Earth.

The Dyngjusandur dust source, together with most other Icelandic dust spots, is unique in that it emits poorly crystallised basalt grains, in contrast to quartz and other silica- and carbonate-rich dust sources on Earth. Other dust spots within the nominated property are Vonarskarð, northwest of Vatnajökull, and Skeiðarársandur (south of the ice cap, but only partly included), together with several other smaller areas, especially along glacial rivers.

The dust from these and other sources in Iceland has a dominant influence on ecosystem development, as the sediments control soil formation processes and soil properties in most of the country. The poorly crystallised basalt (glass) weathers rapidly to release a suite of cations and form fertile volcanic soil, Andosols. The amount of dust greatly influences the fertility of ecosystems, as reflected by bird nest abundance for example (Gunnarsson, 2015). Dyngjusandur dust production dominates the dust deposition in a semi-circular area running from southeast Iceland to north Iceland, or about 33% of the Icelandic land mass (Arnalds, 2010). The area has been a subject of several studies, including a study comparing the area to conditions on Mars and other planets (Baratoux et al., 2011).

The amount emitted from the Dyngjusandur dust spot can exceed 200,000 metric tons in the most intense events, which is phenomenal in relation to the size of the area. In comparison, the production in Bodelé in Chad is often around 700,000 tons in major storms, but the latter area is several hundred thousand km² in size. However, most of the events at Dyngjusandur are much smaller, or a few thousand to 30 thousand tons per event (Arnalds et al., 2015).

The 2014–2015 Holuhraun lava covered about 84 km² and reduced the size of the main dust source by >50%. This is, however, temporary, as the lava will slowly be filled by sand. The Holuhraun eruption provided a unique opportunity to study several processes related to the evolution of dust sources. The area is being researched and monitored by the Agricultural University of Iceland, using surveillance cameras and other methods.

Opposite: Aerial view of a detail in the Dyngjujökull outlet glacier, 13 August 2017 © Walter Huber.

Above: Aerial view of the Flæður dust source at Dyngjusandur, 13 August 2017. Right: Dust cloud forming at Flæður on 19 September 2014 © Snorri Baldursson.

Herðubreiðarlindir is a lush refuge of vegetation east-northeast of Mt. Herðubreið, in the otherwise vast and barren Ódáðahraun lava field. Herðubreiðarlindir owes its luxurious flora to cold water springs that emerge at the front of the lava flow of the Holocene lava shield, Flatadyngja. The springs move forth in small streams and ponds and finally gather into the Lindá river, that rolls along the lava flow edge until it joins Jökulsá á Fjöllum.

Herðubreiðarlindir used to be a very popular recreational and camping area among Icelanders. Nowadays, however, most travellers only spend a few hours there on their journey to Askja. Ruins of a humble hut made of lava blocks are found at the edge of the Flatadyngja lava flow, close to the camping area. A small stream runs through the hut and the remains of animal bones are found in the area. It is believed that the famous outlaw Fjalla-Eyvindur (see pp. 49 & 152) lived there for a while in the 18th century.

Herðubreiðarlindir was protected as a nature reserve in 1974. Since 2008, Vatnajökull National Park (the agency) has managed the area, as per contract with the Environment Agency of Iceland. The Icelandic Travel Association has run a campground and an overnight hut in the area since the mid-20th century, now in collaboration with Vatnajökull National Park. Several hiking routes begin here, including the hiking trail to Askja.

Flash floods, commonly referred to as jökulhlaups, to the north from Vatnajökull ice cap are thought to originate either from within the glacier-covered parts of the Bárðarbunga or Kverkfjöll volcanic systems. These include the cataclysmic jökulhlaups that created the Jökulsárgljúfur canyon and the horseshoe-shaped chasm of Ásbyrgi, which is an outstanding example of the erosional might of these floods (Box p 90). Jökulsá á Fjöllum flows from Dyngjujökull in the south to Öxarfjörður bay in the north. The lower part of it, Jökulsárgljúfur canyon, with its three waterfalls, Hafragilsfoss, Dettifoss and Selfoss, was first protected as a national park in 1973, and incorporated into Vatnajökull National Park in 2008. The thunderous Dettifoss waterfall is the major showpiece of the canyon and a world-renowned tourist attraction.

The Jökulsárgljúfur canyon traverses two volcanic systems, those of Fremrinámar and Askja. In the part of the canyon called Vesturdalur, some 7 km to the south of Ásbyrgi, the river crosses the Rauðhólar crater row on the Fremrinámar fissure swarm. Here, the cataclysmic jökulhlaups of the past have removed most of the tephra that made up the original volcanic cones, leaving a spectacular cluster of columnar-jointed rock formations called Hljóðaklettar (the cliffs of sound). Upstream to the south, the river and its canyon cuts across the 70 km long Randarhólar cone row and fissure, exposing the topmost part of the dyke that fed this 8000 year old eruption (Sæmundsson et al., 2012). Randarhólar belong to the Askja volcanic system and constitute one of the longest cone rows in Iceland.

Jökulsárgljúfur canyon. Top and middle: Hljóðaklettar and the Rauðhólar craters, 29 June 2016 © Snorri Baldursson. Bottom: Springwater mixes with the glacial waters of Jökulsá á Fjöllum at Hafragil, downstream from Hafragilsfoss © Guðmundur Ögmundsson.

The Icelandic highlands as an analogue for planetary surfaces

On 25 May 1961, President Kennedy announced that the United States would go to the Moon before the end of the decade, sparking an incredible challenge for the National Aeronautics and Space Administration (NASA) and its astronauts. Not only did this initiative require extraordinary technological advances, it also necessitated that astronauts learn how to explore otherworldly terrains on Earth to prepare for lunar surface operations. Few places, other than Iceland, could offer the pristine volcanic landscapes necessary for advanced lunar training, and in 1965 and 1967, two groups of American astronauts came to Iceland to develop their understanding of lunar geology as a prerequisite for exploring the Moon. These groups involved over two-dozen astronauts, including the first and last astronauts to have walked on the Moon (Neil Armstrong and Eugene Cernan, respectively).

Although Iceland continues to serve as an important analogue for lunar exploration, it has become increasingly important as a location for studying geologic processes and landforms that resemble those on Mars. The first detailed views of Mars came from the Mariner 4 mission in 1965. The images showed a heavily cratered surface, suggesting that Mars was a "dead world" much like the Moon; however, subsequent missions have revealed Mars to be far more Earth-like. Generally, Mars is cold and dry, but with polar ice caps and ample evidence suggesting that in the distant past Mars had flowing water on its surface (Carr, 2012). The similarities between Mars and Iceland were strengthened with the first image taken from the surface of Mars by the Viking 1 lander on 20 July 1976. This image, and many more that have followed, revealed that much of Mars has a barren wind-sculpted surface much like the Icelandic highlands.

Over the years, robotic exploration of Mars has continued and demonstrated that the "Red Planet" has been modified by a series of hydrologic and volcanic processes that are similar to those observed in Iceland. Of particular interest has been the recognition that Mars, like Iceland, is a land of "Fire and Ice" with enormous volcanoes and lava flows that have interacted with ice. Many of the volcanic systems show a close association with aqueous channels and are thought to result from a variety of magma-water interactions (Mouginis-Mark, 1985; Basilevsky et al., 2006), which may have generated habitable environments for microbial life (Cousins & Crawford, 2011). Volcanic eruptions on Mars are typically much larger than on Earth, but Iceland includes three of the largest historical flood lava eruptions on our planet: the 934–939 Eldgjá, 1783–1784 Laki and 2014–2015 Holuhraun events.

The Laki lava flow field is particularly important as an analogue for Mars because it features the same

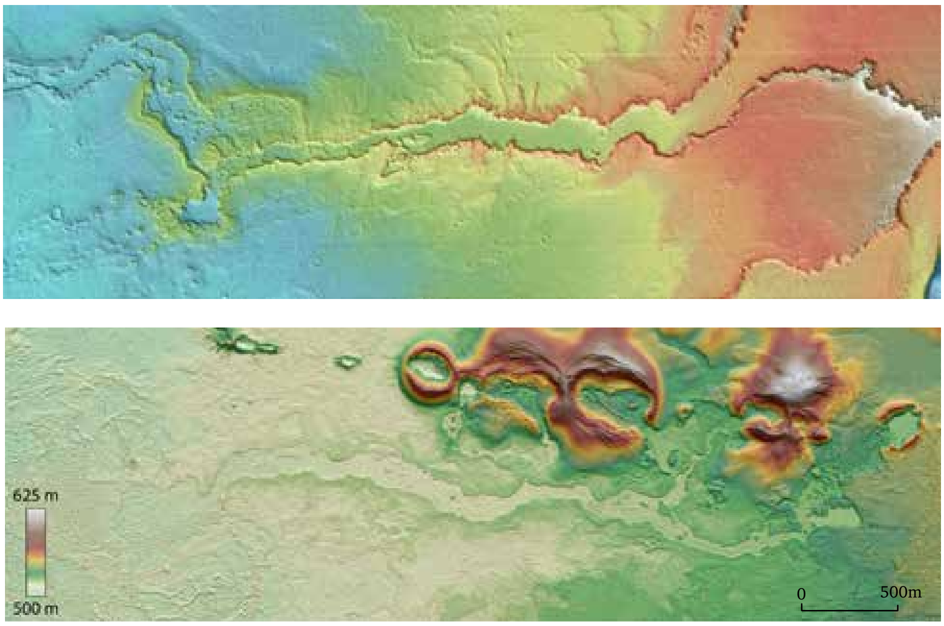
Left: In the 1960s, NASA sent astronauts to the Icelandic highlands to help them prepare for future operations on the lunar surface, 13 July 1965 © Kári Jónasson. Right: Eugin Cernan, one of the astronauts who had trained in Iceland, explores the Moon during the Apollo 17 mission © NASA.

surface structures and morphology as are observed on the Martian flow fields, and the fact that it includes numerous examples of secondary explosions formed by lava–water interactions (Thórðarson & Self, 1993; Thórðarson et al., 1998; Keszthelyi et al., 2000, 2004; Hamilton et al., 2010, 2011). These secondary explosions form distinctive landforms known as volcanic rootless cones which resemble crater cone groups formed within lava flows on Mars (Frey et al., 1979; Lanagan et al., 2001; Greeley & Fagents, 2001; Fagents & Thórðarson, 2007; Hamilton et al., 2010c, 2011). Rootless cones occur in a few other places on Earth, but nowhere are they better preserved than within the Laki lava flow and other parts of Iceland.

The more recent 2014–2015 Holuhraun lava flow field is morphologically like many lava flows in the Tharsis and Elysium Volcanic Provinces of Mars, and includes aa, pahoehoe, and transitional lava types, such as spiny and rubbly lava (Pedersen et al., 2017; Harris et al., 2017). Spiny and rubbly lava is generally associated with high-discharge fissure-fed lava flows on Earth (Rowland & Walker, 1987; Lockwood et al., 1999; Guilbaud et al., 2005; Dietterich & Cashman, 2014). Hence, Holuhraun provides an excellent analogue for lava flows on Mars (Keszthelyi et al., 2000, 2004; Jaeger et al., 2007, 2010).

The Holuhraun lava flow field also inundated a segment of the Jökulsá á Fjöllum river and developed an ephemeral hydrothermal system. Sampling of this hotspring has revealed three thermophile species: *Geobacillus stearothermophilus*, *Paenibacillus cisolokensi*, and *Pseudorhodoplanes sinuspersici*. The first two are well-characterised endospore thermophiles, whereas the last has a 96% match to known species, but none has ever been documented as being able to survive above a maximum temperature of 35°C. However, in this case the organism thrived above 50°C, which suggests that the Holuhraun hotsprings supported a novel species of the genus *Pseudorhodoplanes* (Christopher Hamilton, personal communication). The Holuhraun lava flow and its ephemeral hotsprings provide an example of the types of environments that could develop on Mars when large flood basalt lava flows inundate ground-ice bearing regions.

The 2014–2015 flow field at Holuhraun erupted in precisely the same part of the Icelandic highlands where, nearly fifty years earlier, Apollo astronauts came to train by exploring pristine otherworldly environments. In this extraordinary planetary analogue environment, numerous international field teams came to study the lava flow as an analogue for Mars (e.g. Hamilton, 2015). Thus, the Icelandic highlands provide a unique environment that is important as a planetary analogue site for the study of a wide range of geological and biological processes.



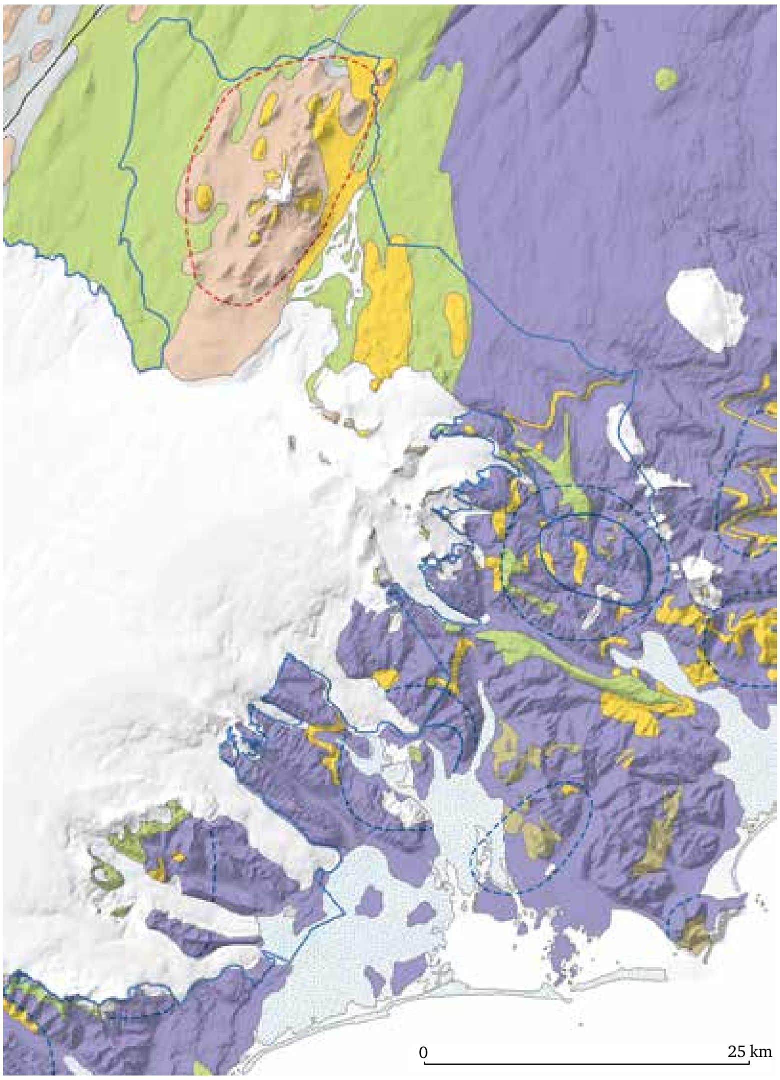
Top: Perspective view of a 1 m/pixel digital terrain model (DTM) showing the source region for a several hundred-kilometre-long lava channel near Olympus Mons. Bottom: Digital terrain model (DTM) of the same segment of the channel shown above (colours show the elevations in metres). Christopher Hamilton, unpubl. data.

Eastern region

The eastern region of the nominated property extends from Jökulsá á Fjöllum in the west to Lónsöræfi in the east. The exposed bedrock, which has not been incised as heavily by the Quaternary ice sheets as the bedrock in the southern region, spans the Grey Basalt formation to the Holocene in terms of age (Fig 2.8). Generally speaking, it becomes progressively younger from the east to the west. It features two volcanic systems, the Snæfell system of the intraplate Öræfajökull Volcanic Belt in the east and the Kverkfjöll volcanic system of the Northern Volcanic Zone in the west. The latter system produces the most plume-enriched magmas in Iceland and both systems feature prominent and glacier-capped central volcanoes.

The Snæfell system covers about 120 km² and is 22 km long and 11 km wide. Its central volcano, Snæfell (snow mountain), rises to 1830 m and features a small summit ice cap. It is Iceland's highest mountain outside the ice cap of Vatnajökull and the fourth highest central volcano in Iceland. The products of the Snæfell volcanic system sit discordant on the Grey Basalt formation bedrock. The Snæfell system has been active for about 400 thousand years and its bulk products are basaltic hyaloclastite units indicative of subglacial eruptions and major growth during glacial stages. Silicic volcanic formations are confined to the central edifice implying eruptions from a shallow-seated crustal reservoir. The youngest formations

Figure 2.8.
Simplified geological map of the eastern and part of the southern region of the nominated property, displaying the main geological features. Modified after Hjartarson & Sæmundsson (2014). See larger map in Appendix 1.1.



Vatnajökull National Park boundary
Extinct central volcanoes
Central volcanoes
Calderas
Historic lavas, <1100 years.
Prehistoric lavas, 1100–11,500 years.
Silicic prehistoric lavas, >1100 years.
Hyaloclastite (Móberg). Upper Pleistocene, <0.12 Ma.
Hyaloclastite (Móberg). Middle Pleistocene, 0.12–0.8 Ma.
Basaltic rocks, Lower Pleistocene, 0.8–2.6 Ma.
Basaltic rocks. Pliocene to Middle Miocene, 0.26-17 Ma.
Holocene sediments, <11,500 years.

The Hvannalindir oasis

Hvannalindir is situated in front of the Lindahraun lava north of Kverkfjöll and owes its existence to the freshwater stream Lindá that emerges as cold-water springs at the lava flow front. The sandy soil cover at Hvannalindir is up to two m thick and contains several tephra layers and three thick units of aeolian sand. The oldest tephra layer in the soils of Hvannalindir indicates that the oasis began to form about 1300 years ago, two centuries before the human colonisation of Iceland. The youngest tephra layer in the soil at Hvannalindir is the rhyolite tephra fall from the 1362 eruption at Öræfajökull. This demonstrates that, until the 14th century, the climate was favourable and the Hvannalindir oasis enjoyed a stable and perhaps lush vegetation cover. The aeolian sand unit towards the top of the soil cover shows that sometime after the 14th century the conditions changed for the worse. The climate and vegetation deteriorated as the Little Ice Age set in. However, Hvannalindir is still considered a haven of vegetation in an otherwise desert-like environment.

In the 18th century, Hvannalindir was the refuge of Iceland's most famous outlaw, Fjalla-Eyvindur ("Eyvindur of the mountains"; see section 2.a (x)). In those days it was a perfect hiding place because it was secluded and protected by large glacial rivers on three sides and on the fourth by the Vatnajökull glacier. Fjalla-Eyvindur lived here for almost a decade. The ruins of his home can be seen near the edge of the Lindahraun lava in the southeast corner of the oasis. Here, Fjalla-Eyvindur built a rather elaborate home out of rocks and turf, containing separate sleeping quarters, a kitchen, and a toilet that included an automatic flushing system (the river), which would have been a luxury in those days.

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are Holocene in age. Hot springs are present along the periphery of the central volcano, demonstrating that this is still an active system, although dormant at the moment (Höskuldsson, 2015).

To the southeast of Snæfell, in the area of the Eyjabakkar Ramsar Site, is the erosional remnant of a now extinct 2.4 Ma central volcano within the Grey Basalt formation (Höskuldsson & Imsland, 1998) providing a window into the volcanic activity within the axial rift at the onset of the ice age.

The ice-capped Kverkfjöll central volcano, which is positioned at the northern margins of the Vatnajökull ice cap, rises to 1930 m above sea level. The central volcano sits at the southern extremity of its volcanic system and is associated with a north-trending fissure swarm that is about 120 km long. The Kverkfjöll system is 20 km wide and covers 1650 km². The central volcano has two ice-filled calderas, the southern one completely covered by ice, and the northern one filled with ice but with an exposed caldera rim. The outlet glacier Kverkjökull flows through a prominent notch ("kverk" in Icelandic) in the rim of the northern caldera.

Activity on the Kverkfjöll volcanic system is confined to the period of the Móberg formation, because all of its volcanic products are normally magnetised (Upper Pleistocene). In the notches on either side of the central volcano, exposures reveal sequences of basaltic and minor andesitic hyaloclastite alternating with lavas of the same composition. However, the fissure swarm, commonly referred to as

Left: Snow lichens, *Stereocaulon* sp., in Krepputunga © Snorri Baldursson. Middle: Mt. Snæfell from air, 25 October 2003 © Skarphéðinn Þórisson. Bottom: Kreppa river, 17 August 2016 © Snorri Baldursson.

Top: Landscape in Krepputunga, 17 August 2016 © Snorri Baldursson. Bottom: Moulting pink-footed geese at Eyjabakkar, 12 July 2012 © Skarphéðinn Þórisson.

Kverkfjallarani (the tusk of Kverkfjöll), is typified by closely spaced, 3–5 km long and north-trending basaltic pillow lava (plus minor hyaloclastite) ridges formed by a series of subglacial effusive fissure eruptions under the Weichselian ice sheet, which was up to 2000 m thick in this region. This ice thickness explains the dominance of pillow lava in Kverkfjallarani and makes it the closest land-based resemblance to the volcanic architecture of a mid-ocean ridge (Höskuldsson et al., 2006). The narrow valleys between the ridges are partly filled by fissure-fed Holocene lava flows. The youngest of these lava flows, Lindahraun, dates back to the formation of the highland oasis Hvannalindir (Thórðarson & Höskuldsson, 2002, 2014; Box p. 49). Some of the lava fields extend to the plains to the north of the Kverkfjöll system. The longest of these lavas is the Krepputungur lava field, which is >60 km long and has a volume of at least 7 km^3 (Thórðarson & Self, 1998).

Activity within the Kverkfjöll central volcano during the Holocene has been established via tephrochronological studies. Some 70 eruptions are inferred to have taken place in prehistoric time and none in historic times (Óladóttir et al., 2011; section 2.b).

Evidence of at least two major jökulhlaups has been identified within the Holocene succession at Kverkfjallarani. These floods are estimated to have burst out from Kverkjökull outlet glacier with a peak discharge of 100,000 m^3s^{-1} (Carrivick et al., 2004). Smaller jökulhlaup events from Kverkfjöll have been relatively common in recent years. Their origin has mostly been the result of geothermal activity in the Efri- and Neðri-Hveradalur geothermal areas in Kverkfjöll, some of the best locations in Iceland to observe the interplay between geothermal activity and glacial ice. In Efri-Hveradalur is the glacier-bound lake Gengissig. Jökulhlaups from Gengissig are known to have occurred in 1987, 1993, 1997 and 2002. The maximum discharge in these events can reach 500 m^3s^{-1} (Guðmundsson & Larsen, 2013).

Southern region

The southern region of the nominated property (Fig 2.9) stretches from and includes the Lónsöræfi wilderness in the east to Skeiðarárjökull outlet glacier in the west. The geography of the region changes from east to west with grasslands and U-shaped valleys giving way to barren sandur plains. Yet, the landscape in this region is spectacular. It displays a great number of Vatnajökull's outlet glaciers, revealing their erosive power as they cascade through the mountains and carve out up to 1000 m deep U-shaped valleys. The region also displays the constructive power of the glaciers, which is realised via a deposition of sediments from their glacial rivers. This activity has formed a 3–24 km wide and about 130 km long stretch of sandur plains in front of the mountain ranges. In doing so, they have added about 500 km^2 to Iceland in the Holocene. Glacial geomorphological features are prominent and well preserved. They clearly delineate the maximum glacial extent of the Little Ice Age and other changes in global climate during past centuries (see section 2.a (iv)).

The bedrock in the southern region is also remarkable and the most varied within the nominated property. It has the greatest age span (Neogene to Holocene from east to west) and reveals the interplay between active volcanism and glacial erosion over the past 7 million years in a spectacular manner (e.g. Helgason & Duncan, 2001). The roots of the now extinct 4–7 Ma central volcanoes are exposed in the eastern part of the region due to extensive erosion by at least 20 Quaternary glaciations. This erosion has removed up to two km of crust, exposing the intricate inner structures and intrusions of central volcanoes. Moving west, the erosion becomes less profound and the shallower erosional levels reveal the architecture of the upper crust as it is in the active volcanic zones, where dykes are the dominant intrusions in the lava pile.

In the central to western part of the southern region are the Öræfajökull and Esjufjöll volcanic systems, which sit unconformably on the Neogene and Grey Basalt formations and define the southern branch of the Öræfajökull Volcanic Belt. A central volcano represents both systems and neither features a fissure swarm. The Öræfajökull system covers an area of 235 km², while the Esjufjöll system covers 275 km² (Jóhanesson, 2014). Collectively, these two systems along with the Snæfell volcanic system north of Vatnajökull may indicate an embryonic status of the Öræfajökull Volcanic Belt as an axial rift. Thus, they would be a manifestation of the progressive shift of the plate boundary in Iceland to the east (Einarsson, 2008; Thórðarson & Höskuldsson, 2002, 2014). The only Holocene volcanic formations within the southern region outside of the Vatnajökull glacier are within the Öræfajökull system. Its youngest volcanic formations are the products of the eruption in 1727.

The ice-capped Öræfajökull volcano towers over the scenery, with outlet glaciers reaching half way or all the way down to the surrounding sandur plains. These plains have been shaped during the Holocene by the deposits continually put down by the glacier rivers, but constructed by the voluminous deposits carried forth by the multiple glaciogenic as well as volcanogenic jökulhlaups that

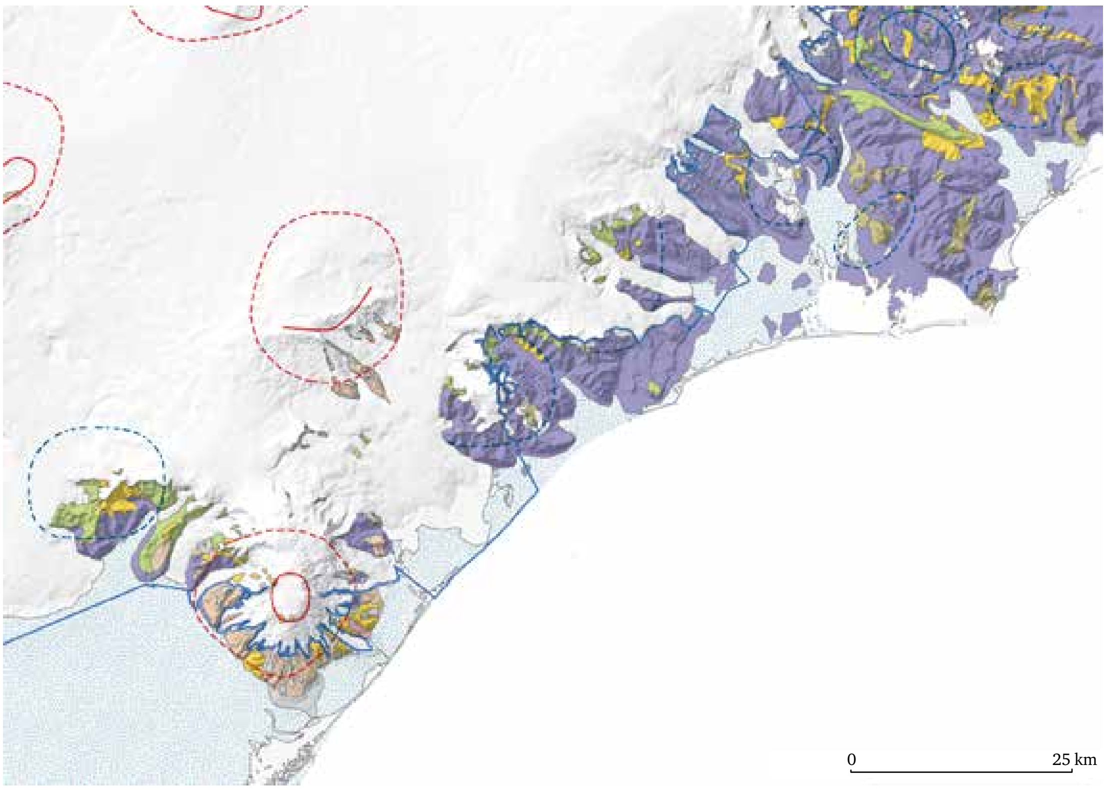


Figure 2.9.
Simplified geological map of the southern region of the nominated property, displaying the main geological features. Modified after Hjartarson & Sæmundsson (2014). See larger map in Appendix 1.1.

- Vatnajökull National Park boundary
- Extinct central volcanoes
- Central volcanoes
- Calderas
- Historic lavas, <1100 years.
- Prehistoric lavas, 1100–11,500 years.
- Silicic prehistoric lavas, >1100 years.
- Hyaloclastite (Móberg). Upper Pleistocene, <0.12 Ma.
- Hyaloclastite (Móberg). Middle Pleistocene, 0.12–0.8 Ma.
- Basaltic rocks, Lower Pleistocene, 0.8–2.6 Ma.
- Basaltic rocks. Pliocene to Middle Miocene, 0.26-17 Ma.
- Holocene sediments, <11,500 years.

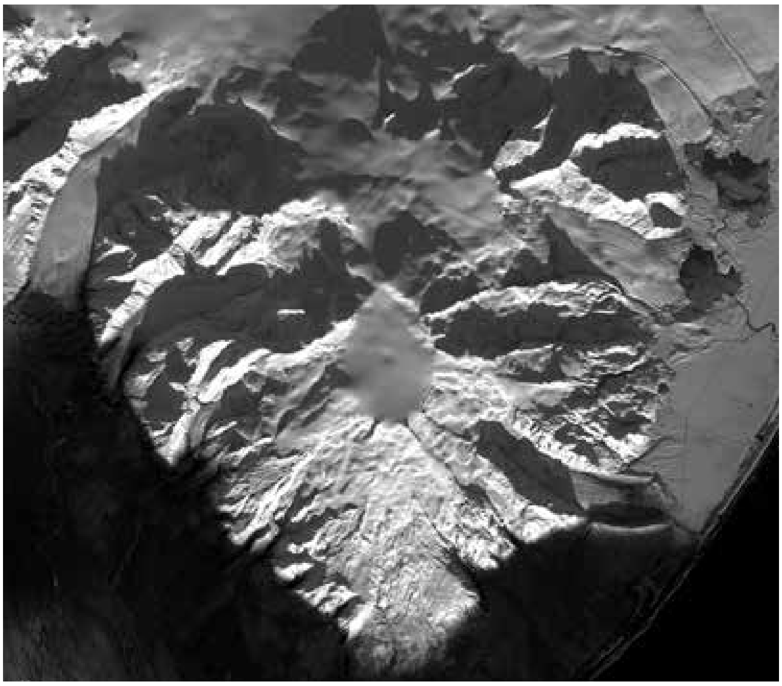
Previous page: Aerial view over the Skaftafell mountains and the valley of Kjós towards Öræfajökull central volcano, 13 September 2014 © Snævarr Guðmundsson.

punctuate the record on a decadal to centennial scale (Þórarinsson, 1958; Björnsson, 2017). Öræfajökull rises about 1850 m above its surroundings and its highest peak, Hvannadalshnjúkur, rises to 2110 m above sea level, making it the highest mountain in Iceland. Thus, it provides some of the most magnificent scenery within the nominated property. Öræfajökull is the third largest central volcano in Iceland, with a 12 km² and 600–700 m deep, ice-filled caldera. It is elongated slightly in the north-south direction with a basal diameter of 23 km and an east-west diameter of 21 km. The bedrock is oldest in the northwest part of the massif, where pre-Öræfajökull volcanics are believed to be 2.78–0.78 Ma. Younger volcanic rocks that make

Öræfajökull stirs

During the summer of 2016, the Icelandic National Seismic Network started to record seismic activity at the Öræfajökull central volcano. Since then, a steady increase has been seen in seismic activity. During the summer and autumn of 2017, earthquakes of magnitude 2 to 3 on the Richter scale were recorded and glacial outwash rivers from the volcano began smelling of sulfur. In late fall, a cauldron was detected at the surface of the ice-filled summit caldera. The cauldron was photographed on 19 November and regularly since then, with the last photo (at the time of writing) taken on 11 December 2017. These photos showed that the cauldron has deepened by two to three metres during this period, although the subsidence has been slowing down since then. The cauldron is slightly elongated with a diameter of some 1200 m.

Geodetic measurements around Öræfajökull indicate an uplift of the volcano exceeding that of the regional uplift generated by receding glaciers. Increased seismic activity, uplift and generation of cauldrons in the ice filled caldera show that at the Öræfajökull stratovolcano is waking up after 290 years of quiescence. However, it is not clear at the time of writing when or if the current unrest will end in an eruption.



Öræfajökull photographed from space, 17 November 2017. The caldera is seen as a tiny spot in the middle of the summit caldera © NASA USGS/Volcanology and Natural Hazard Group, University of Iceland.

The newly formed cauldron in the Öræfajökull caldera on 28 November 2017 © Ragnar Raxelsson (RAX).

up the proper Öræfajökull central volcano are most evident in the south of the massif (Thórðarson & Höskuldsson, 2014; Helgason & Duncan, 2001; Þórarinsson, 1958).

Holocene volcanic activity of Öræfajökull has been established via tephra-chronological studies around the volcano. This work has identified 13 Holocene eruptions, thereof two in historic time, one in 1362 and another in 1727 (Guðmundsson, 1998; Þórarinsson, 1958). The 1362 event is notorious in Iceland as it wiped out the then prosperous farming district of “Litla Hérað”, destroying up to 40 farms and presumably killing all the inhabitants (240–400 people). It is one of the largest historic eruptions in Iceland and the most powerful explosive (Plinian) one (see section 2.b).

The area to the east of Öræfajökull, from Breiðamerkurjökull to the easternmost reaches of the region at the Lónsöræfi wilderness, includes some of the more spectacular geological formations within the nominated property. In the mountain ranges of Suðursveit in the west to Mýrar in the east, late Neogene lava sequences are cut by dykes and unconformably overlain by basaltic lavas of Grey Basalt formation (Jóhannesson & Sæmundsson, 1998). Still further east, in the region beyond Hoffellsjökull and Höfn, the deeply incised 4–7 Ma bedrock succession features large microgranite and gabbro intrusions, representing the magma storage region in the fiery roots of the now extinct Neogene central volcanoes (Torfason, 1975; Friðleifsson, 1983, 1995; Thórðarson & Höskuldsson, 2014). The best place to explore these eroded central volcanoes is in the region of Lón and the Lónsöræfi wilderness area. Lónsöræfi area offers the eroded edifice of the extinct Kollumúli central volcano with its geothermally altered rhyolite and other basement rocks, which make up this highly colourful landscape. Another colourful place, very rich in rhyolite with basaltic intrusions, is the valley of Kjós at Skaftafell to the west of Öræfajökull volcano, exposing the roots of the ancient Skaftafell central volcano (Helgason & Duncan, 2001).

Western region

The western region of the nominated property (Fig 2.10) extends from Lómagnúpur in the east to the Skjálfandafljót river in the northwest. It encompasses the Eastern Volcanic Zone, which has been the most productive volcanic zone in Iceland for the last 10,000 years (Thórðarson & Höskuldsson, 2008). The region is under the influence of four volcanic systems. These are from north to south: Tungnafellsjökull, Bárðarbunga, Grímsvötn and Katla. The Katla central volcano is located outside Vatnajökull National Park, under the Mýrdalsjökull ice cap, but part of the 934–939 Eldgjá linear vent system extends into the southwestern part of the nominated property. Some of Iceland's largest volcanic events in recorded history have taken place in the ice-free part of the western region. Namely, on the western branch of the Bárðarbunga fissure swarm and on fissures within the Grímsvötn, Þórðarhyrna and Katla volcanic systems (see p. 31). The intense volcanism of the area has been attributed to the location of the centre of the Iceland mantle plume under the northwestern part of the Vatnajökull ice cap (Bjarnason, 2008; Wolfe et al., 1997).

The presence of the Eastern Volcanic Zone means that constructive forces primarily shape the geology and landscapes of the western region, where the volcanic landforms and edifices have been

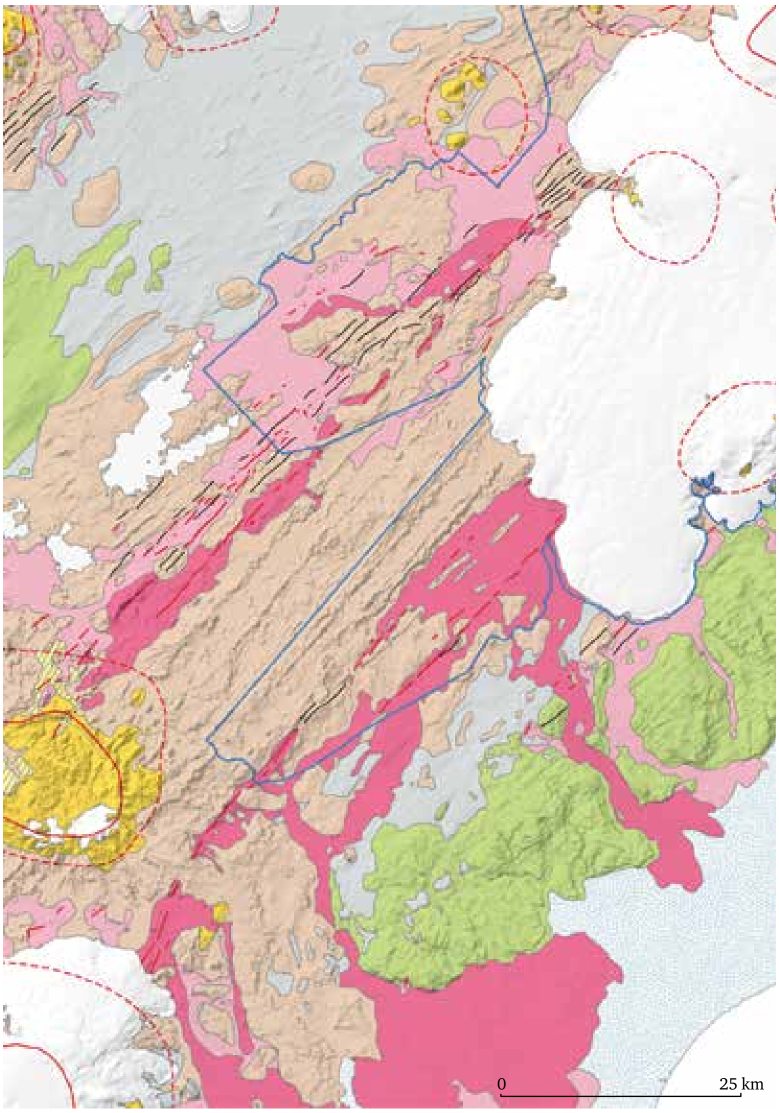


Figure 2.10.
Simplified geological map of the western region of the nominated property, displaying the main geological features. Modified after Hjartarson & Sæmundsson (2014). See larger map in Appendix 1.1.

- Vatnajökull National Park boundary
- Central volcanoes
- Calderas
- Fault
- Historic lavas, <1100 years.
- Prehistoric lavas, 1100–11,500 years.
- Silicic prehistoric lavas, >1100 years.
- Hyaloclastite (Móberg). Upper Pleistocene, <0.12 Ma.
- Hyaloclastite (Móberg). Middle Pleistocene, 0.12–0.8 Ma.
- Basaltic rocks, Lower Pleistocene, 0.8–2.6 Ma.
- Basaltic rocks. Pliocene to Middle Miocene, 0.26-17 Ma.
- Holocene sediments, <11,500 years.

Geothermal surface features within the Vonarskarð caldera: A boiling mud pool (top), sulfur mound (middle) and a colourful hot spring (bottom), 20 July 2010 © Snorri Baldursson.

created by subglacial and subaerial basaltic fissure eruptions. This is particularly prevalent in the central part of the region, between the rivers Skaftá and Tungnaá, where the landscape is typified by 16 closely-spaced tindar formations (i.e. hyaloclastite ridges) forming up to 44 km long mountain ridges, each formedby subglacial eruptions during the last two glacial stages (Vilmundardóttir & Snorrason, 1997). The tindar formations trend northeast to southwest and form a spectacular mega scale, linear volcano-tectonic fabric that is unprecedented elsewhere on Earth (Fig 2.10). The tindar formations of Kambar and Fögrufjöll are e.g. a prime example of these structures and north of them is the picturesque lake Langisjór, 20 km long and ca. 2.5 km wide. No volcanic formations of Holocene age are found in this part of the nominated property. However, it is partly covered by tephra from the 1477 Veiðivötn eruption, which is up to two m thick in places (Vilmundardóttir & Snorrason, 1997).

Tungnafellsjökull glacier in the far north of the western region is the central volcano of the Tungnafellsjökull system. It covers an area of 565 km² and is 57 km long and 15 km wide (Jóhannesson, 2014). Tungnafellsjökull is a relatively small (99 km³) central volcano that rises up to 1523 m above sea level and some 700 m above the surrounding plains. The edifice is made up of subglacial hyaloclastites and subaerial lava formations, indicating that it has been constructed over several glacial and interglacial stages. There are two calderas within the Tungnafellsjökull central volcano, the Tungnafellsjökull and Vonarskarð calderas (Einarsson, 2015). The ice-filled Tungnafellsjökull caldera measures 4 x 9 km, and is elongated NE-SW. The Vonarskarð caldera to the southeast is similar in its dimensions and horseshoe-shaped with its opening facing the Bárðarbunga central volcano.

The rocks in Vonarskarð caldera have been intensely altered by its very active geothermal system (Einarsson, 2015). This system, although small, displays a great variety of geothermal surface features, including fumaroles, colourful hot springs, boiling mud pools, permanently flowing warm streams, steaming grounds and sulfur mounds. Also, of interest is the high-grade surface alteration that has been observed within the caldera. This surface alteration includes the high-temperature mineral assemblage actinolite-epidote-wollastonite-quartz, which is assumed to be formed at temperatures above 300°C and pressures above 100 bars, i.e. under at least a 1000 m thick ice cap of the last (Weischelian) glaciation (Friðleifsson & Jóhannesson, 2006).

Bárðarbunga central volcano of the Bárðarbunga volcanic system is also situated in the far north of the western region within the northwest corner of Vatnajökull glacier (see p. 35). A subglacial mountain ridge stretches 20 km to the southwest from Bárðarbunga to the nunatak Hamarinn on the western margins of Vatnajökull. Hamarinn is a second central volcano in the Bárðarbunga volcanic system. To the southwest of the Bárðarbunga central volcano is the segment of the system's fissure swarm, commonly referred to as the Veiðivötn fissure swarm. It is characterised by extensive southwest to northeast-trending volcanic fissures and tindar formations. Low topographic relief typifies the part of the fissure swarm that lies within the nominated property; pristine as well as wind-blown lava and tephra fields, and youthful extensional faults and grabens

The Grímsvötn eruption 2011.
Top and middle: Scientists explore the crater on 2 June © Hrafnhildur Hannesdóttir.
Bottom: The eruption cloud on 22 May © Magnús Tumi Guðmundsson.

(Vilmundardóttir, 1982). Prominent features in this area are (i) the 1862–1864 Tröllahraun lava field (Þórarinsson & Sigvaldason, 1972), (II) the graben Heljargjá with a vertical displacement of tens of metres (Larsen et al., 2013) and (iii) the subglacial pillow lava sheet Bláfjöll (Jakobsson & Guðmundsson, 2008).

The subglacial Grímsvötn central volcano, to the south-southeast of Bárðarbunga, is part of the Grímsvötn volcanic system, which covers 1425 km² and is 100 km long and up to 23 km wide (Thórðarson & Höskuldsson, 2008). The central volcano is equal to Bárðarbunga in size (98 km³). It features three subglacial calderas, although the southernmost caldera is the only one that is clearly visible through a horseshoe-shaped 13 km long escarpment demarcating the southern caldera walls. Mt. Grímsfjall (1722 m) is the highest peak on this escarpment and is commonly ice-free during summer. The south caldera contains an ice-covered lake, with a 240–300 m thick floating ice shelf, that is maintained by geothermal activity within the volcano and forms a 7 x 6 km visible depression in the ice surface (Guðmundsson & Larsen, 2015).

Due to extensive ice cover, the geological details of the volcano are poorly constrained. However, the existence of a composite caldera suggests a mature central volcano that has probably been active for >100,000 years (Guðmundsson & Larsen, 2015). Most of Mt. Grímsfjall is comprised of hyaloclastite that is crosscut by numerous metre-thick dykes, but young pyroclastic deposits cap the peak. The Grímsvötn system is tholeiitic in character and its central volcano is Iceland's most frequently erupting volcano with 6–11 events per century for at least the last 8500 years (Óladóttir et al., 2011). Most of these eruptions are small and their cumulative volume during the Holocene is estimated at about 32 km³ (Jakobsson, 1979). However, recent studies show that the Grímsvötn volcanic system produced a series of very large explosive eruptions in the early Holocene, which have an estimated collective tephra volume of 100 km³ (Thórðarson, pers.comm.). Furthermore, two fissure eruptions have taken place in the subaerial part of the system, the prehistoric Lambavatnsgígar (0.1 km³) and the 1783–1784 Laki eruption (15 km³; Box p. 65). Hence the total volume of magma produced by the Grímsvötn volcanic system in the Holocene could be as much as 115 km³ of magma. This implies an average magma output rate for the Grímsvötn system of 0.6–1 km³ per 100 years, which is about 10–15% of the total magma output by the Icelandic mantle plume and about one third of the estimated magma output (3.6 km³/100 years) of the Hawaiian mantle plume (Thórðarson & Larsen, 2007). These extraordinary magma output rates are not unique to Grímsvötn and are matched by the Katla, Bárðarbunga and Askja volcanic systems (e.g. Thórðarson et al., 2003; Thórðarson & Höskuldsson 2008; Hartley et al., 2016).

As indicated above, the Grímsvötn central volcano most frequently features small (<0.1 km³ of tephra) explosive basalt eruptions within the main caldera; all recent eruptions (1998, 2004 and 2011) have occurred at the southern rim of the caldera fault (Jude-Eton et al., 2012; Guðmundsson et al., 2013; Guðmundsson & Larsen, 2015). These events quickly melt their way through the ice and progress from subglacial eruptions to subaerial phreatomagmatic eruptions. Melting through the overlying 50–200 m thick ice takes from minutes to 1–2 hours. Most of the erupted tephra is deposited on the Vatnajökull ice cap and plume heights rarely exceed 10 km. Subglacial eruptions on the volcano flanks (i.e. outside of the Grímsvötn calderas) seem to occur once or twice each century, and tend to be larger than the ones within the caldera. The best-known event is that of the 1996 Gjálp eruption (Box p. 64).

The subglacial central volcano Þórðarhyrna (1660 m) is situated in the southwest corner of Vatnajökull ice cap and is the main volcanic edifice of the Þórðarhyrna volcanic system. This system covers about 407 km² and is 78 km long and up to nine km wide. The only known eruptive events on the system are a silicic explosive eruption at the central volcano in 1903 and the ca. 6000 BP Núpahraun basaltic fissure eruption (7 km³) that took place on a 60 km long subaerial vent system to the southwest of Þórðarhyrna.

The Katla volcanic system, which covers about 1750 km² and extends into the western margin of the nominated property, features the ice-capped Mýrdalsjökull central volcano. Mýrdalsjökull is the second largest (385 km³), after Hofsjökull (475 km³), central volcano in Iceland and has featured 20 historic eruptions and more than 300 events during the Holocene (Óladóttir et al., 2005, 2008). During the Holocene, 8–10 lava-producing eruptions have taken place on the ice-free part of the system, all relatively small in volume. The exception is the 10th century Eldgjá eruption, which is the most voluminous flood lava eruption to have occurred on Earth in the last 11 centuries (Thórðarson & Larsen, 2007). The southwestern end of the vent system is beneath Mýrdalsjökull (Björnsson et al., 2000). It then continues subaerially in the form of a mixed cone row trending northeast for 70 km until it terminates 6 km short of Vatnajökull (Larsen, 2000; Thórðarson et al., 2001).

The Eldgjá fissure is thus one of the longest in Iceland and reaches into the southwest part of Vatnajökull National Park. Eldgjá was dominantly an effusive eruption, producing up to 20 km³ of lava (Sigurðardóttir et al., 2015). However, 2.7 km³ of tephra was also produced (Larsen, 2000) in at least 16 explosive episodes at vents along the full length of the fissure. This volume of tephra is on a par with the 1362 Plinian eruption of Öræfajökull (Sharma et al., 2008). Although, only briefly mentioned in The Book of Settlement (Landnáma), the Eldgjá event is most likely the event that drew the settlement of Iceland to an end (see section 2.b).

Opposite: The southwestern cone row of Lakagígar seen from Mt. Laki, 11 July 2011 © Snorri Baldursson.

Gjálp 1996

The Gjálp eruption of 1996 was the first large-scale subglacial eruption to be monitored in detail (Guðmundsson et al., 2004) and this is the only tindar-forming, subglacial fissure eruption observed on Earth to date. The eruption provided a test case for numerous scientific studies, including on glacier melting and the glacier response to that melting, dynamics of volcano-ice interactions and post-eruption edifice evolution (Jakobsson & Guðmundsson, 2008 and references therein).

The eruption lasted for 13 days or from 30 September to 13 October 1996. The eruption site is midway between the central volcanoes of Grímsvötn and Bárðarbunga (Fig 2.11). The eruptive fissure was seven km long; it produced 0.42 km³ of material (recalculated as dense rock) and melted some four km³ of ice. The melting rate during the eruption was 0.4–0.6 km³ per day and the eruption broke through the 550–750 m thick ice on the third day (Guðmundsson et al., 1997).

The eruption was most intense for the first four days, with a maximum mass eruption rate in the order of 1000 m^3s^{-1}. After breaking through the ice, the subaerial eruption plume was fed through a 200–300 m wide and 50–100 m high chimney in the ice. Rhythmic explosions resulted in black tephra-laden clouds that rose to heights of 500 metres, while the thermally buoyant eruption plume rose to altitudes of approximately 3–5 km. The eruption produced minimal tephra fallout, which was mostly confined to the ice cap. The vigour of the eruption could be monitored by three methods, firstly by the volume of the depression created in the ice above the eruptive vents, secondly the volume of meltwater accumulating in the Grímsvötn caldera lake and thirdly the intensity of the volcanic tremor (Einarsson et al., 1997).

The Gjálp eruption site lies within the water catchment area of Grímsvötn. Hence, the meltwater from the eruption drained into the subglacial Grímsvötn lake, adding to the geothermal meltwater already present (Fig 2.11) (Einarsson et al., 1997; Guðmundsson et al., 2004, 1997).

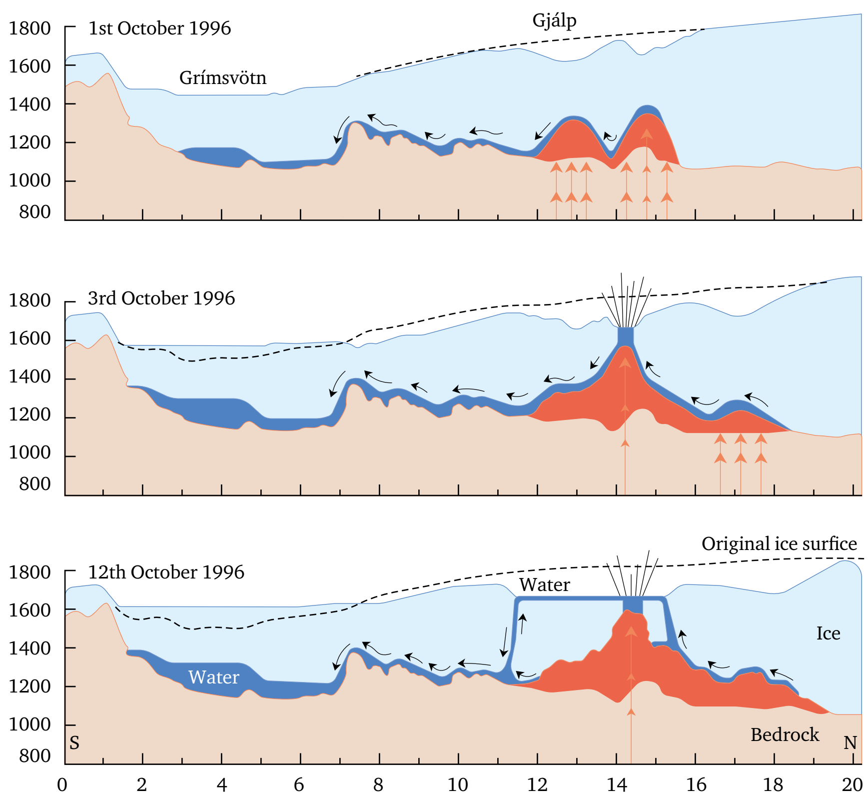


Figure 2.11.
Left: Transect through the Gjálp eruption site showing the build-up of a subglacial edifice and the path of meltwater to lake Grímsvötn. Reconstructed after Sigmundsson et al. (2013). Above: Location of the Gjálp fissure, between the central volcanoes of Bárðarbunga and Grímsvötn. See also Box p. 87.

The 1783–1784 Laki eruption

The 1783–1784 Laki eruption was one of the largest and most devastating flood lava eruptions ever witnessed by man (Þórarinsson, 1967, 1969a; Thórðarson, 1991; Thórðarson & Self, 1993; Thórðarson, 2003; Thórðarson et al., 2003). As discussed in section 2.b, the consequences of the eruption were disastrous for Iceland and for large parts of the Northern Hemisphere because of its atmospheric and environmental effects (Steinþórsson, 1992; Thórðarson et al., 1996; Thórðarson & Lintleman, 2001; Thórðarson & Self, 2001, 2003; Thórðarson, 2005; Oman et al., 2006; Schmidt et al., 2010, 2011, 2012).

The Laki vent system is 27 km long, extending from Úlfarsdalur valley in the west towards the tip of the Síðujökull outlet glacier of Vatnajökull in the east. It consists of 10 northeast-trending en echelon fissure segments, which collectively contain more than 140 cones and craters. Typically, each fissure is delineated by a row of scoria and spatter cones, although two tuff cones interrupt the pattern. The Mt. Laki hyaloclastite formation divides the vent system into two almost equally long segments, the southwest and northeast cone rows.

Lava produced on the fissure segments southwest of Mt. Laki flowed initially straight to the west into the Skaftá river gorge and dammed the Skaftá river, such that on the second day of activity it was dry except for the water derived from local tributaries. At the same time a branch of the lava began to flow south across the Síða highlands and joined the lava advancing down the Skaftá river gorge on day 17 of the eruption (Fig 2.12). The lava first emerged from the gorge on 12 June 1783 and thereafter spread out onto the cultivated lowlands of the districts of Síða, Landbrot, and Meðalland (collectively known as the Fire District). The fissure segment northeast of Mt. Laki issued lava to the south and north of the active vents. Lava flowing to the south advanced down the Hverfisfljót river gorge, a distance of 25 km, before reaching the lowlands of Síða and Fljótshverfi on 7–9 August 1783. The Laki lava field covers 600 km² and has a volume of 14.7 ±1 km³. In addition, explosive activity on the Laki vent system supported 13 km high eruption columns, which dispersed 0.4 km³ of tephra over 750,000 km² of land and sea.

The Grímsvötn central volcano erupted intermittently during the Laki eruption and continued to erupt on and off well into 1785. The last day that fires were seen at Grímsvötn was 26 May 1785.

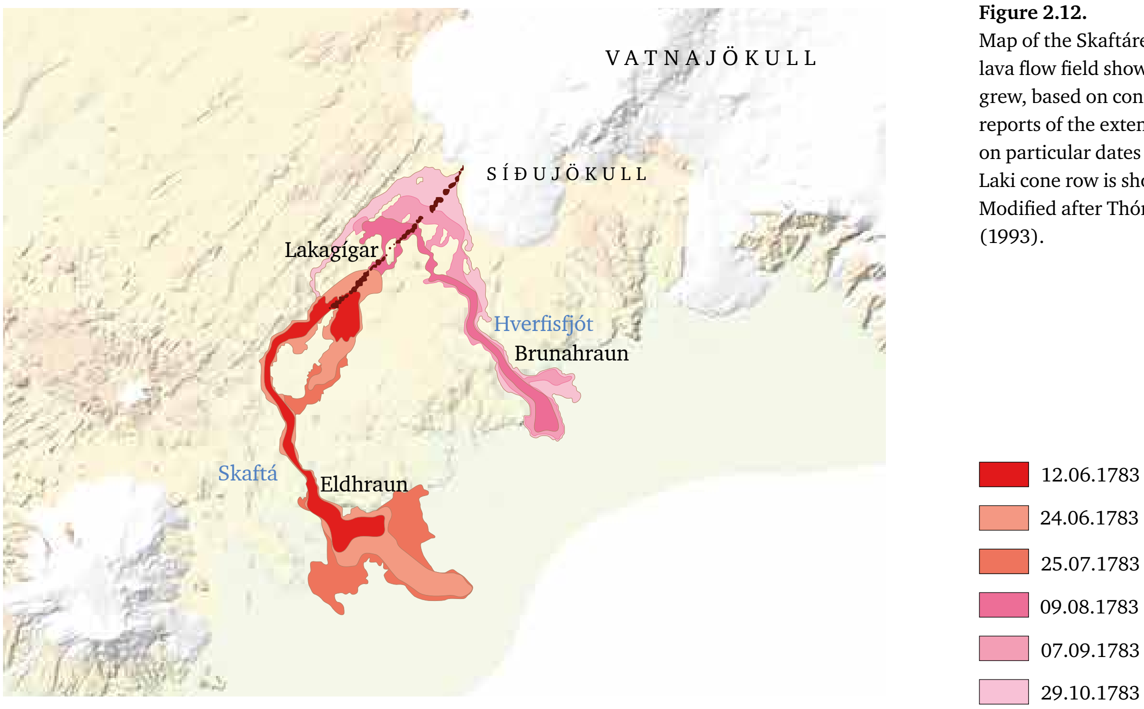
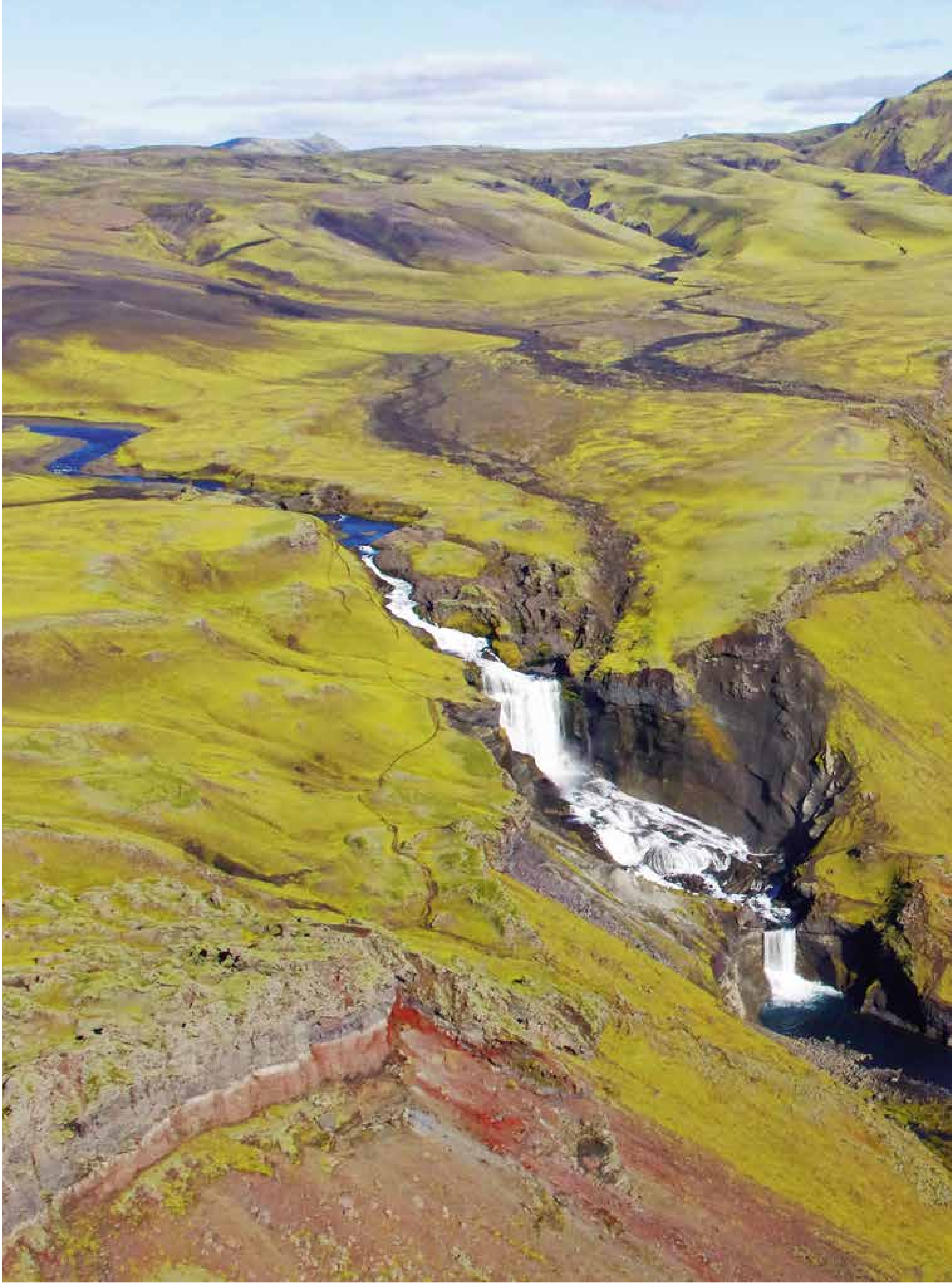


Figure 2.12.
Map of the Skaftáreldahraun lava flow field showing how it grew, based on contemporary reports of the extent of the lava on particular dates in 1783. The Laki cone row is shown in black. Modified after Thórðarson & Self (1993).



Previous page: The Eldgjá chasm from air. Ófærufoss waterfall to the left, Mt. Gjátindur in the back, 22 September 2010 © Snorri Baldursson.

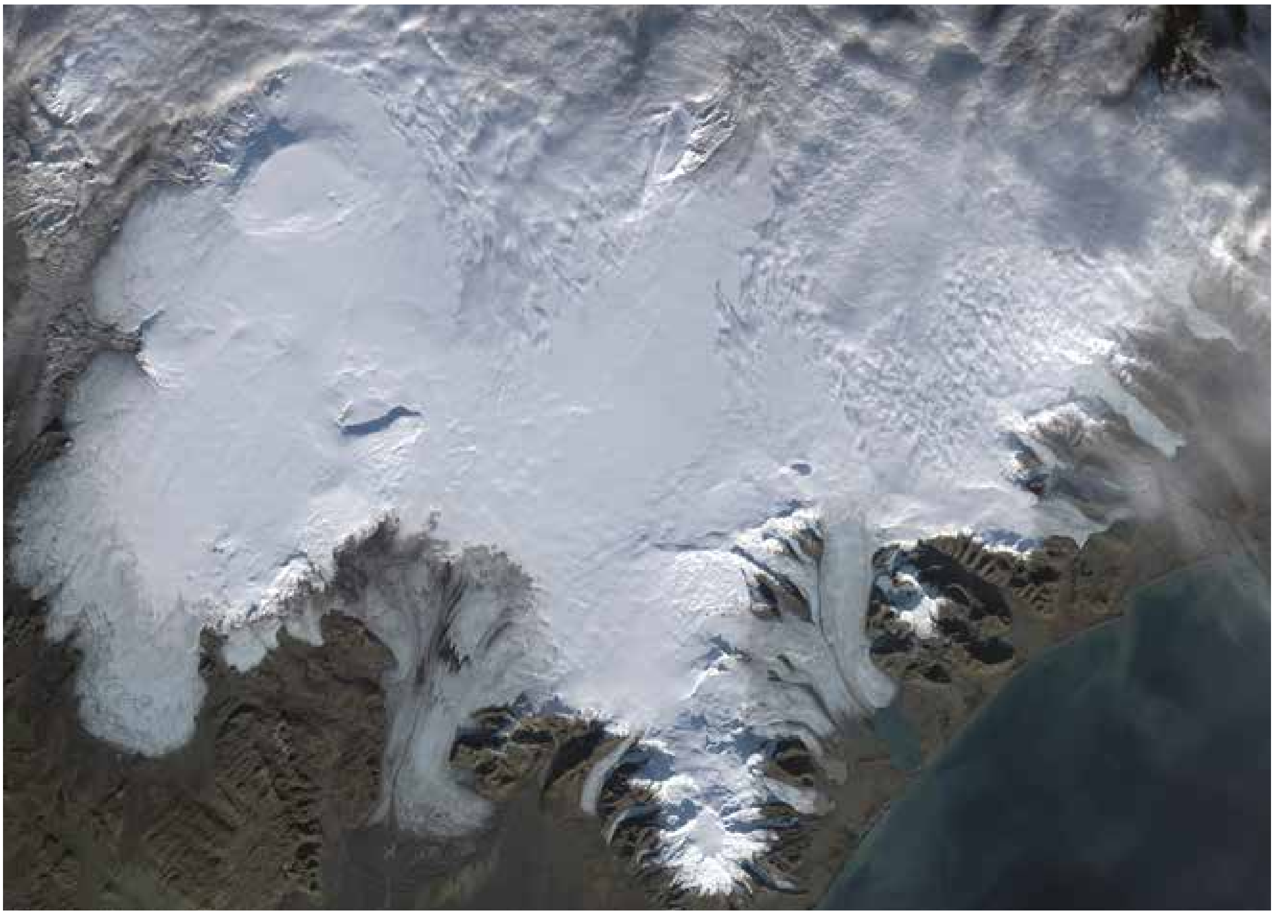
2.a (iii) Glaciology – the Vatnajökull Ice Cap

The temperate Vatnajökull ice cap is at present 7800 km² and is Europe's largest ice cap by volume. It contains ice domes, ice flows and numerous outlet glaciers, some of which surge at irregular intervals. Vatnajökull conceals several active volcanoes, valleys and glacial troughs. Volcanism and geothermal heat maintain subglacial lakes that may flood and cause jökulhlaups in some of the glacial rivers carrying melt water from the ice cap. During the last century, Vatnajökull has lost 10% of its volume and its outlet glaciers are currently retreating at an unprecedented rate due to a warming climate.

As noted above, Iceland's geological history during the last 2.8 million years is marked by repeated loading and unloading of glacial ice. However, the Weichselian ice sheet that covered the entire country during the last glacial maximum is believed to have disappeared by the early Holocene when climate was warm. Evidence suggests that the Vatnajökull ice cap began to form around 4000 BP (see section 2b (ii)).

Currently, the ice cap covers almost 8% of Iceland and the water it stores equals 17 years of the country's annual precipitation (Björnsson, 2017). The ice cap is very important for the hydrology of the country and a part of the global reservoir of ice stored in glaciers outside the polar regions, the melting of which accounts for a third of the rise in sea level since the beginning of the 20th century. The existence of many subglacial volcanoes adds to the dynamic nature of the ice cap, and they have proved hazardous to the neighbouring settlements. The ice cap is close to populated areas and travel routes, and the numerous outlet glaciers are popular tourist destinations. Every year, it needs to be accessed for search-and-rescue operations.

Vatnajökull viewed from space, 1 November 2017. Notice the prominent calderas of Bárðarbunga (upper left), Grímsvötn (middle left) and Öræfajökull (bottom middle) © NASA USGS/Volcanology and Natural Hazard Group, University of Iceland.



How do glaciers form?

Glaciers form when more snow accumulates over the year than melts during the summer. As layers of snow accumulate, the buried snow grains become more and more tightly packed and are converted to firn, which subsequently metamorphoses to glacial ice as the firn recrystallises. This process takes place in the accumulation zone at high altitudes. The thick mass of ice deforms under its own weight and flows downstream like thick dough or molten metal, and a glacier is born. The ice flows downhill towards the ablation zone where higher temperatures intensify the melting of snow and ice, and the melting exceeds accumulation of snow over the year.

The oldest ice and the largest ice crystals of the ice cap are found at the snouts of the outlet glaciers. The ice there has travelled the longest route along the glacier from the upper parts of the accumulation zone (Björnsson, 2017). According to the age of tephra layers analysed from various outlet glaciers of Vatnajökull, the oldest ice is approximately 1100 yrs old (Larsen et al., 1998).

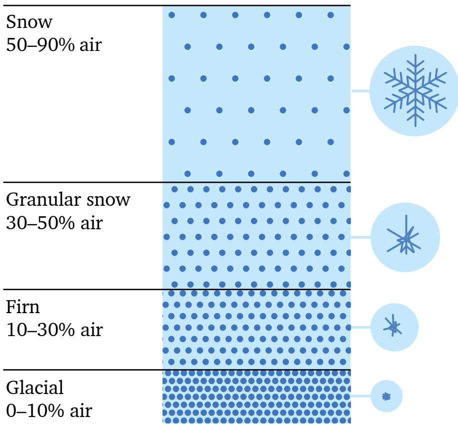


Figure 2.13
Formation of glacial ice.

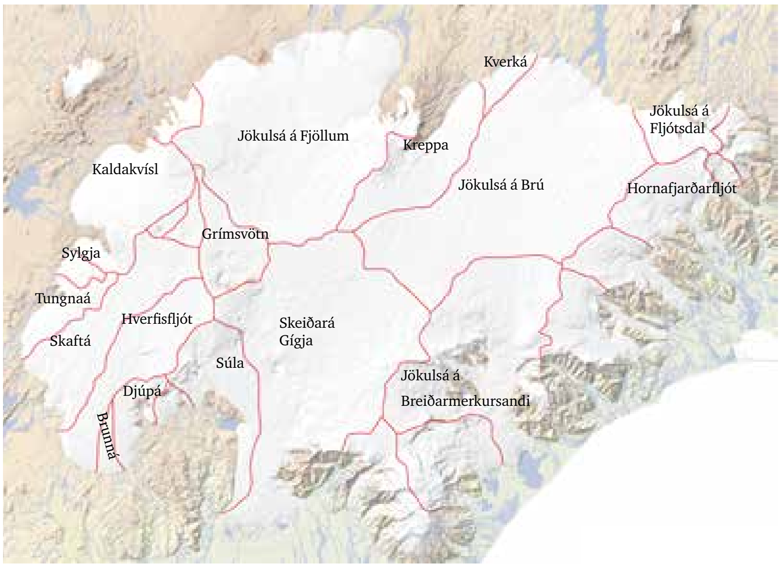
Global warming in the Arctic takes place at a rate of almost twice the global average. It is likely that climate change in the coming decades will lead to the most rapid environmental changes that have occurred in Iceland for centuries or millenia. Vatnajökull reveals the properties of temperate glaciers and provides a unique setting to explore and research the relationship between glaciers and climate change. Vatnajökull has high mass turnover rates and is among the most sensitive ice caps worldwide to climate perturbations. Research on the history of climate change and its effects on the ice cap is an important contribution to international science. Knowledge and understanding of these processes is vital to be able to predict and evaluate climate change in the future.

Vatnajökull has been the object of scientific research for decades and even centuries, with the first detailed description of the outlet glaciers dating to the end of the 18th century. Hence, glaciological data in Iceland is substantial. The easy motorised access to the interior of Vatnajökull has greatly facilitated research and the accessible outlet glaciers and surrounding landscapes make for a natural laboratory in glaciological research (Björnsson, 2017).

Geometry of the ice cap

Vatnajökull is the largest ice cap in Europe by volume and the second largest by area at about 7800 km²; only Austfonna ice cap in Svalbard has a slightly larger area. It contains 3200 km³ of ice, which is equal to a 30-m thick ice layer distributed over the whole of Iceland. Vatnajökull conceals active central volcanoes, numerous valleys, plateaus and mountains. Its outlet glaciers have created

Figure 2.14.
Water divides and drainage basins of selected rivers draining from Vatnajökull. Modified after Björnsson (2017).



mountainous landscapes and dug out deep subglacial troughs. Vatnajökull is on average 400–500 m thick, at most 950 m. It rises to over 2000 m above sea level and includes the contry's highest point, Hvannadalshnjúkur, measuring 2110 m. The base of the glacier reaches its lowest point, some 300 m below sea level, underneath the two most active outlet glaciers, Skeiðarárjökull and Breiðamerkurjökull (Björnsson, 2017).

The temperate ice cap, i.e. warm-based and nowhere frozen to its bed, is composed of ice domes, ice flows, and numerous outlet glaciers. There are five main ice domes, Kverkfjöll at the north edge of the ice cap, Breiðabunga to the east, Háabunga in the centre, Bárðarbunga and Grímsfjall in the western part. The ice-capped Öræfajökull central volcano forms a mountain range extending south from the central ice cap. Steep and crevassed outlet glaciers descend towards the lowlands to the south and east, reaching an elevation of 50–100 m on the outwash plains, whereas more gently sloping and generally larger outlet glaciers flow to the west and north, terminating at an elevation of 600–800 m. Since the turn of the 21st century, proglacial lakes have been forming in front of almost all the south flowing outlet glaciers, and the pre-existing ones have been increasing in size. Major glacial rivers originate in Vatnajökull and enter the sea in North, East and South Iceland (Fig 2.14).

Skeiðarárjökull (1380 km²) is the largest outlet glacier to flow south from Vatnajökull. Its outwash plain, Skeiðarársandur, most of which lies outside the nominated property, is the largest sandur in front of an active glacier worldwide. Seismic measurements in the area indicate 100 m thick sediment deposits near the glacier margin, thickening to 250 m at the coast (Guðmundsson et al., 2002). The sediments have piled up during the last 10,000 years from the general action of glacial rivers as well as jökulhlaups (Gomez et al., 2000). Altogether some 40 jökulhlaups onto Skeiðarársandur have been recorded, the first being in the 14th century (Þórarinsson, 1979), most of them originating in the geothermal, subglacial lake of Grímsvötn, but also due to eruptions in the nearby subglacial central volcanoes.

Breiðamerkurjökull outlet glacier calves into Jökulsárlón on Breiðamerkursandur, which is the largest proglacial lake in Iceland, connected to the sea via a narrow, deep channel. Breiðamerkurjökull is the only glacier in Iceland presently calving into sea water and is one of the most dynamic outlet glaciers of Vatnajökull. Breiðamerkurjökull accumulates ice from many valley glaciers and long medial moraines have formed between them; similar features can be seen in Alaska and Svalbard.

The Kverkfjöll mountains and the Kverkjökull outlet glacier divide Vatnajökull's northern border into two large and flat outlet glaciers. To the west is Dyngjujökull (about 1000 km²), which

Top: Aerial view over Skeiðarárjökull outlet glacier, 20 August 2013 © Walter Huber. Bottom: Aerial view over Mt. Pálsfjall and the western part of Vatnajökull, 10 August 2010 © Snævarr Guðmudsson.

reaches as far as Bárðarbunga. In the east is Brúarjökull, Vatnajökull's largest outlet glacier (about 1600 km²). It makes up one fifth of the surface area of the ice cap and is the broadest and flattest outlet glacier in Iceland. It has an average thickness of 445 m, and its total volume is estimated to be some 728 km³, which is also just over one fifth of all the ice of Vatnajökull (Björnsson, 2017).

Surface topography

Several surface maps of Vatnajökull have been created during the last few decades. Digital elevation models (DEMs) of Vatnajökull have been made based on elevation profiles measured by barometric altimetry (Björnsson, 1988), using differential GPS measurements, and some areas have been mapped with various remote-sensing methods using satellite images (Magnússon et al., 2005; Berthier et al., 2006; Foresta et al., 2016). DEMs have also been created from contour lines of topographic maps (Guðmundsson et al., 2017; Hannesdóttir et al., 2016) and aerial images (Belart, unpublished data).

During the International Polar Year (IPY) programme in 2007–2009, an effort to produce accurate DEMs of the main glaciers in Iceland using airborne lidar technology was initiated (Jóhannesson et al., 2013). The purpose was to obtain a good estimate of the current rate of change in glacier geometry and to establish an accurate baseline for monitoring of future changes. The lidar DEMs have a very high spatial resolution compared with other glacier surface maps, typically with a relative accuracy of 5–10 cm. The lidar mapping included a 500–1000 m wide ice-free buffer zone around the ice cap, which contains many glacial geomorphological features, and therefore the new DEMs have proved useful in geological investigations of proglacial areas (e.g. Jónsson et al., 2016). Comparison of the lidar DEMs with older maps confirms the rapid ongoing volume changes of the Icelandic ice caps, which have been shown by mass-balance measurements since 1995/1996.

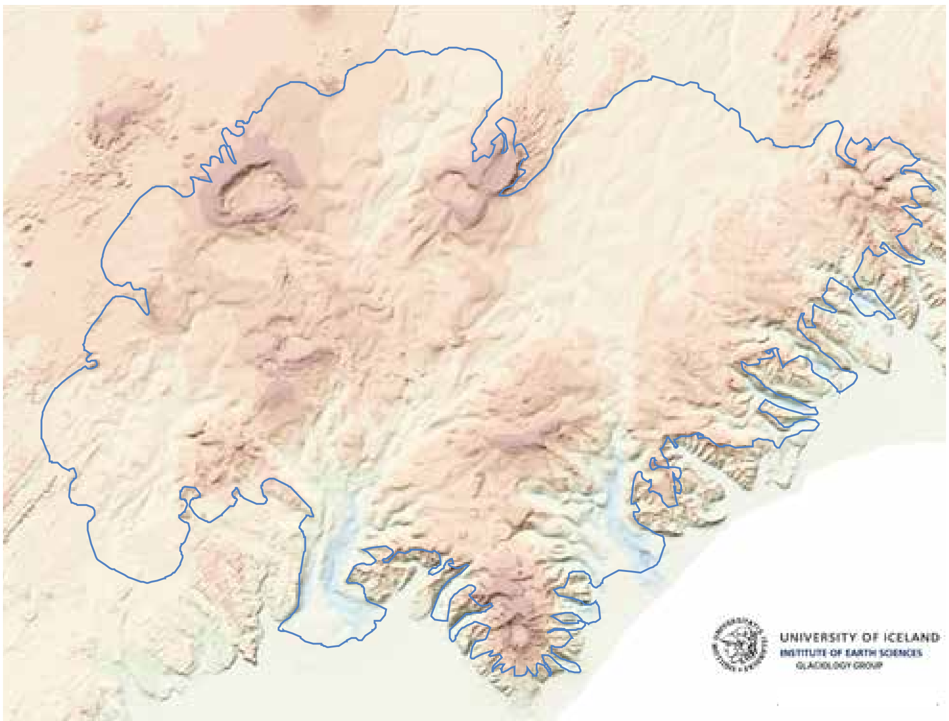


Figure 2.15.
The bedrock topography of Vatnajökull ice cap. The large calderas of Bárðarbunga and Kverkfjöll are prominent, as is the steep Öræfajökull volcano. Notice the deep troughs that Skeiðarárjökull and the eastern arm of Breiðamerkurjökull have carved out.

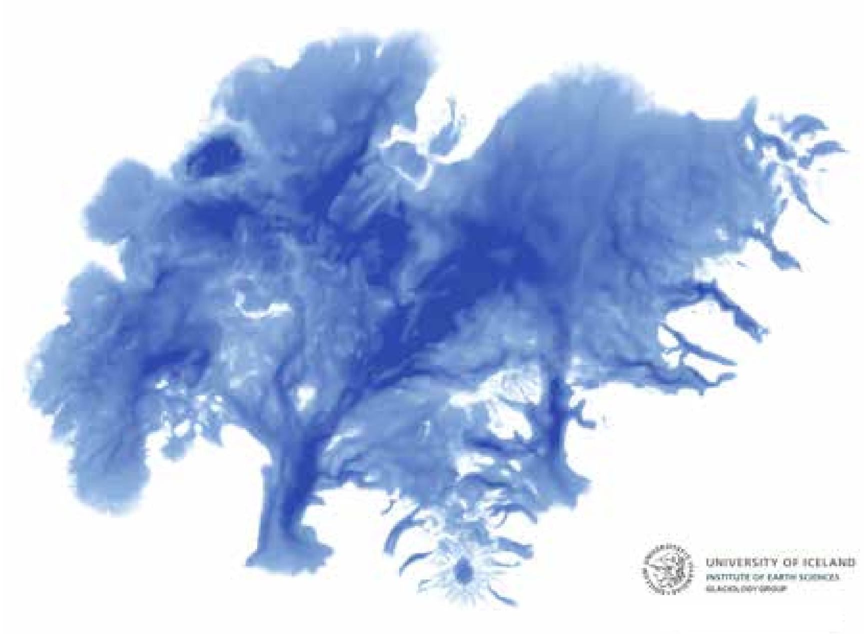


Figure 2.16.
Ice thickness map of Vatnajökull. The intensity of the blue colour indicates the ice thickness, with the scale going from 0 (white) to 1000 m (dark blue).

Subglacial topography

The very first measurements of the thickness of Vatnajökull were done during a French-Icelandic expedition in 1951 (section 2.b). A turning point was made in 1976–1978, when researchers from the University of Iceland managed to build a device that sent radio waves down to the glacial bed and recorded their echoes reaching the surface of the ice. Similar radio echo soundings had been utilised for a decade on the polar ice of the Greenland ice sheet and in Antarctica, but this had not previously been successful on temperate glaciers. Thus, systematic mapping of the bedrock beneath the Icelandic ice caps began in 1980. The radio echo-sounding device is hauled with a snowmobile or snow sledge to measure continuous profiles of radio waves. The waves are sent down to the bed of the glacier, the travelling time is recorded and from this the ice thickness can be calculated.

Altogether approximately 10,000 km of profiles have been measured, with 200 – 1000 m average spacing on the ice cap. Point measurements are also done by foot in areas where motorised vehicles cannot operate, for example in heavily crevassed areas and in the ablation area. Maps of the subglacial topography has been produced by interpolation of the measurements (Fig 2.15; Björnsson 1986, 1988, 2017; Magnússon et al., 2012).

The radio echo sounding measurements have enabled the digital “lifting” of the ice cap off the underlying land surface and revealed previously unknown landscapes and geological formations,

Deep troughs

Deep troughs (“djúp” in Icelandic) were carved into the continental shelf during earlier glaciations, including Skeiðarárdjúp, Breiðamerkurdjúp, and Hornafjarðardjúp. The southern mountains of Vatnajökull formed bays during the last glacial period, when the sea reached inland as far as Skaftafell, Mávabyggðir, Esjufjöll, and to the mountains east of Breiðamerkurjökull.

Previous page: Iceland's highest peak, Hvannadalshnjúkur (2110 m), 19 February 2012 © Snævarr Guðmundsson.

including the geometry of volcanic systems and ice-filled calderas, the location of eruption sites and deep troughs and valleys carved out by the glaciers during the Little Ice Age and previous glaciations. A valley, less than 700 m above sea level, stretches northeast across the bed of the ice cap, from Skeiðarárjökull towards Brúarjökull. This is also the area of thickest ice. Vatnajökull rests on a 600–800 m plateau. Almost 90% of its bed lies above 600 m, but only 20% above 1100 m which is the height of the snowline or the equilibrium line altitude (ELA) on the ice cap's southern margin. The relatively small accumulation area above the ELA maintains and feeds the rest of the ice cap.

Radio echo sounding measurements have revealed where water is stored within the ice cap, the location of water and ice divides, channels and sources of jökulhlaups from lakes, geothermal areas and subglacial eruptions. The bedrock maps are used in conjunction with surface maps to determine the boundaries of the glacial river catchment areas. The surface and bedrock maps form the basis for studies of glacier-volcano interactions and provide a reference datum for monitoring temporal changes in the geometry and flow of the glaciers in response to basal geothermal activity as well as to changes in climate.

Mass balance

The mass balance of a glacier is a critical concept in glaciology. Mass balance is a measure of the relative gains and losses of ice from the glacier, or its "health". If the glacier gains more mass than it loses, the mass balance is positive and the glacier will eventually advance. The mass balance changes throughout the year, but usually the annual mass balance is calculated from one autumn to the next. Accumulation during winter is measured by drilling ice cores in the spring. At the same time stakes are dug into the snow and the ablation of the summer months checked in autumn by measuring the elevation of the stakes above the snow/glacier. Remote sensing techniques (using aerial photographs and satellite images) are increasingly being used to measure mass balance.

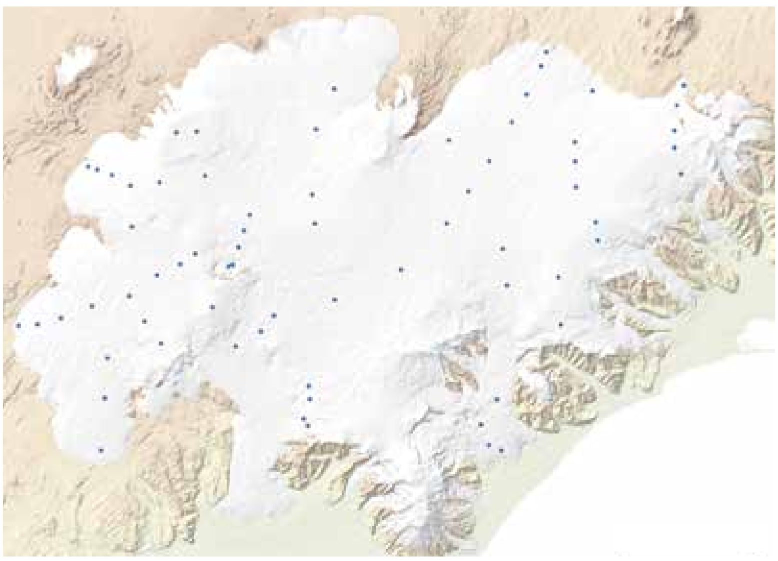


Figure 2.17.
The mass balance survey sites on Vatnajökull, measured by the Glaciology Group of the Institute of Earth Sciences, University of Iceland, in cooperation with the National Power Company.

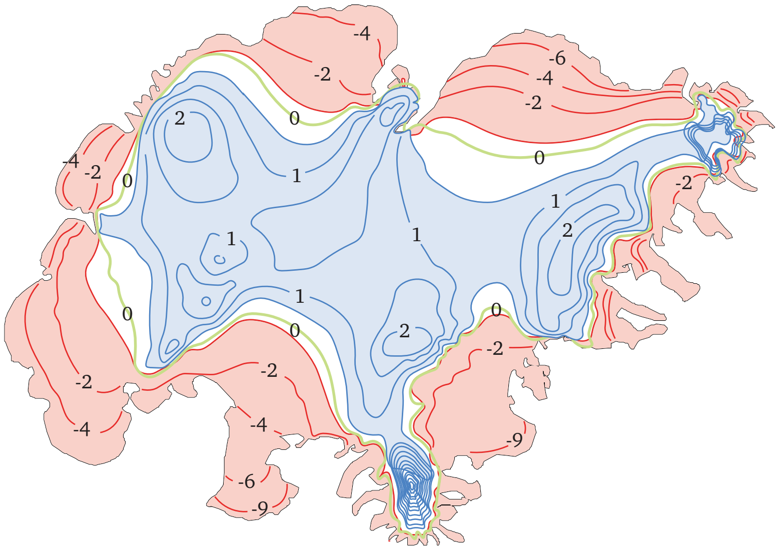


Figure 2.18.
The net mass balance of Vatnajökull during the glaciological year 2015–2016. Modified after Pálsson et al. (2016).

Mass balance

Mass balance measurements are made at almost 70 sites within the Vatnajökull ice cap (Box p. 76; Fig 2.17). The measurements are based on snow probing and stake measurements of snow thickness and snow/ice melting, as well as measurements of snow density at specific locations. The resulting comprehensive mass balance data set is used in studies of glacier volume changes, to estimate melt-water contribution to glacial rivers, in mass balance modelling and to evaluate altitudinal and regional variations of mass balance in response to climatic variations. The mass balance record together with the energy balance measurements of the automatic meteorological stations are further used for calibration of glacier models. The mass balance sensitivity of the ice cap to climate warming is among the highest worldwide (De Woul & Hock, 2005).

Digital mass balance maps, for every year since 1996, have been manually interpolated (Fig 2.18), using the in situ mass balance measurements and the observed mass balance gradient, which is the relation between elevation and mass balance (Björnsson & Pálsson, 2008, provide details of the method).

The annual mass balance of Vatnajökull was positive during the first years of measurement, but has been negative since 1995, except for 2014/2015 (Fig 2.19). The average mass balance after 1994 is minus (-) 0.65 m water equivalent (m.w.e.). The total mass loss since 1994 is 14.2 m.w.e. This is equal to an ice volume of 126 km^3, some 4% of the total volume of the ice cap (Pálsson et al., 2016). The mass loss of the ice cap over the last two decades reflects higher summer temperatures, longer melting seasons, warmer winters reducing the proportion of precipitation falling as snow, and earlier exposure of ice in spring, due to less winter snow accumulation (Björnsson et al., 2013). Moreover, exposed ice has low albedo; it reflects solar energy less well than fresh snow.

For the inland outlet glaciers, the mass loss averaged 8 m.w.e., but 20 m.w.e. for the southern outlets, confirming a clear difference in the mass balance sensitivity for glaciers in maritime and relatively more continental climates. The net mass loss of the outlet glaciers since 1995 has shown considerable annual variation with some in-land outlets having annual mass balance close to zero in some years.

Figure 2.19.
Specific mass balance record from 1991 to 2016. The annual net mass balance of the ice cap has been anywhere between +1.5 and -1.5 m during the measurement period, since 1991. After 1995 it has been negative for all years, except 2014/2015. After Pálsson et al. (2016).

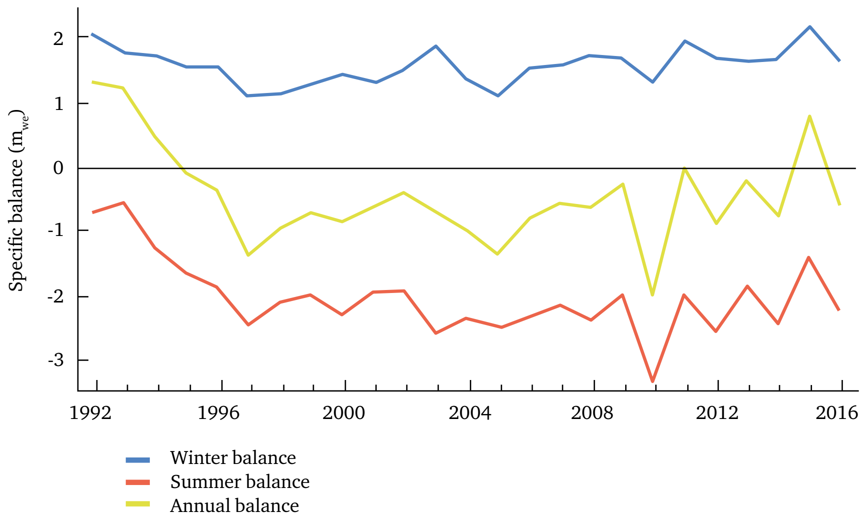
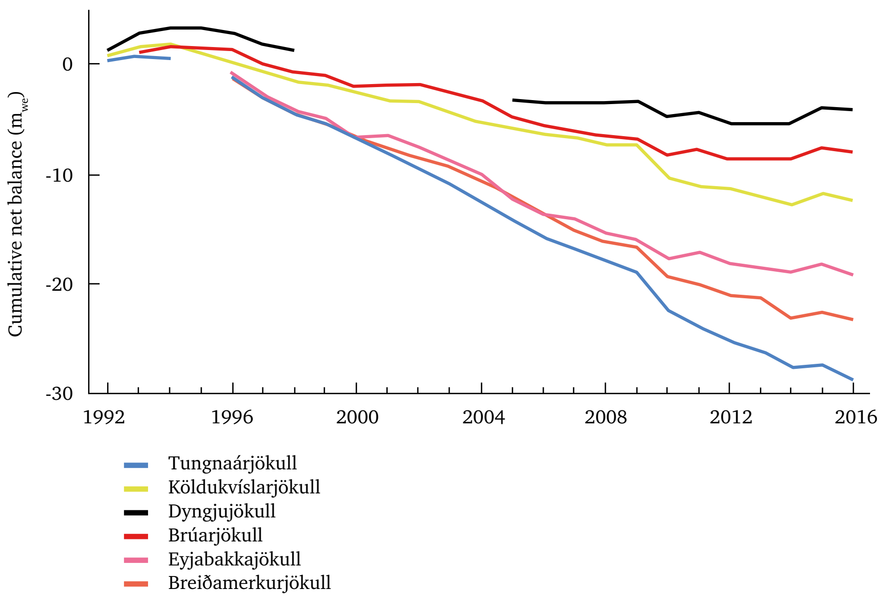


Figure 2.20.
Cumulative net mass balance of selected outlet glaciers of Vatnajökull. After Pálsson et al. (2016).



Aerial view over the Morsárjökull outlet glacier and Öræfajökull central volcano on 10 August 2010 © Snævarr Guðmundsson.

The tephra fallout from volcanic eruptions can have a direct influence on the mass balance during the year following the eruption. The size of ash particles and the thickness of ash layers are especially decisive for the melt (e.g. Dragosics et al., 2016b). Thin ash layers increase the snow and ice melt, but if they exceed a critical thickness they provide insulation. Deposition of dust on the glacier surface causes positive radiative forcing (an increased surface absorption of energy) and enhanced melting due to the reduction of surface albedo. Icelandic volcanic dust, which is mainly composed of basaltic material, is darker and absorbs solar radiation more readily than mineral dust from other regions. For northern Vatnajökull, a major dust source is Dyngjusandur (Box p. 42; Wittmann et al., 2017). There, dust deposition can cause a 40% increase in snowmelt. Melt due to geothermal activity and occasional smaller eruptions at the base of the glacier amounts to only 4% of the total surface ablation (Björnsson et al., 2013). The winter snow rapidly buries any ash layers in the accumulation area and they are washed away by meltwater in the ablation area.

The equilibrium line altitude (ELA)

The line that separates the accumulation and ablation zones on a glacier is called the equilibrium line, sometimes referred to as, but not necessarily synonymous with, the snowline. The elevation of this line depends on temperature, precipitation and the surrounding landscape. If the climate conditions remained constant, neither the ELA nor the glacier margin would change. However, there are fluctuations in the climate so that the elevation of the ELA varies from year to year. The average ELA over a historic time perspective provides an indication of the climate in the past.

The ELA on southern Vatnajökull varies in position, but is generally in the range of 1000–1100 m above sea level. The ELA on the western part of the ice cap is at around 1200 m, and on the northern part it is about 1300 m above sea level. At the end of the 19th century, the ELA on southeastern Vatnajökull was probably some 300 m lower than today. The accumulation areas of the south-flowing outlet glaciers were thus much larger (see section 2.b).

Since the start of mass balance measurements on Vatnajökull, the ELO has moved up and down by between 200–400 m. As a result, the accumulation zone of the ice cap has varied from 20–70% of the total surface area, during the same period. A 100-m shift in the ELA results in a change in the annual net mass balance of about 0.7 m (Björnsson, 2017). The snowline elevation at the end of summer, which can be traced from satellite and aerial images, can be used as a proxy for the ELA on temperate glaciers.

Ice velocities

Average summer surface velocities have been monitored by GPS instruments on Vatnajökull (e.g. Howat et al., 2008; van Boeckel, 2015). There is an increase in surface velocity during summer compared to winter in the centre areas of some of the outlet glaciers, especially close to the ELA. The summer velocity is twice the winter velocity, which suggests that basal sliding is increased in the melting season. Velocity maps over large areas have also been compiled from satellite data (e.g. Magnússon et al., 2007; Howat et al., 2008; Nagler et al., 2012) (Fig 2.21) and terrestrial radar interferometry (Voytenko et al., 2015). The velocity measurements data set maintained by the Institute of Earth Sciences at the University of Iceland

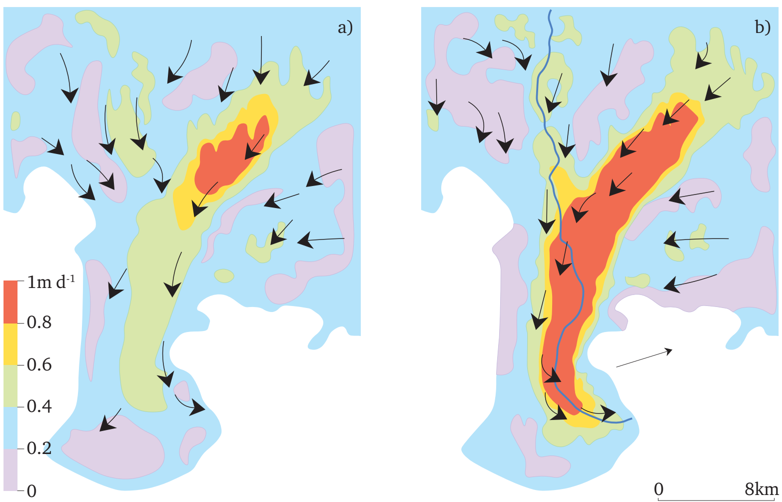


Figure 2.21.
The horizontal velocity field of Skeiðarárjökull at the end of December 1995 (a) derived from ascending and InSAR pairs and on 27–28 March 1996 (b) during the beginning of the Gjálp jökulhlaup, derived from a single ascending pair. The blue line in (b) shows the estimated flood path of the jökulhlaup. Modified after Magnússon et al. (2007).

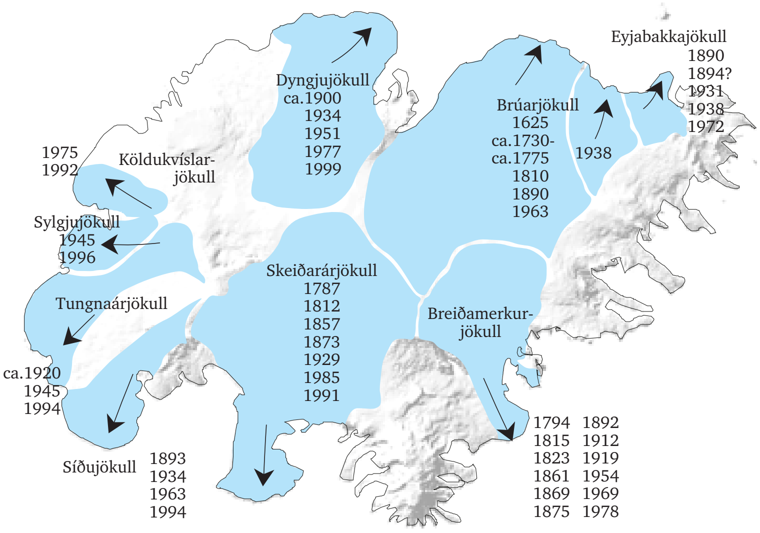


Figure 2.22.
Historic surges of the outlet glaciers of Vatnajökull ice cap. After Björnsson et al. (2003).

allows surges to be predicted. Some glaciers, known as surge-type glaciers, have periods of rapid forward movement, during which they advance much more quickly than normal. No surges have been observed in Vatnajökull since the 1990s when several outlet glaciers surged (Fig 2.22).

Surges

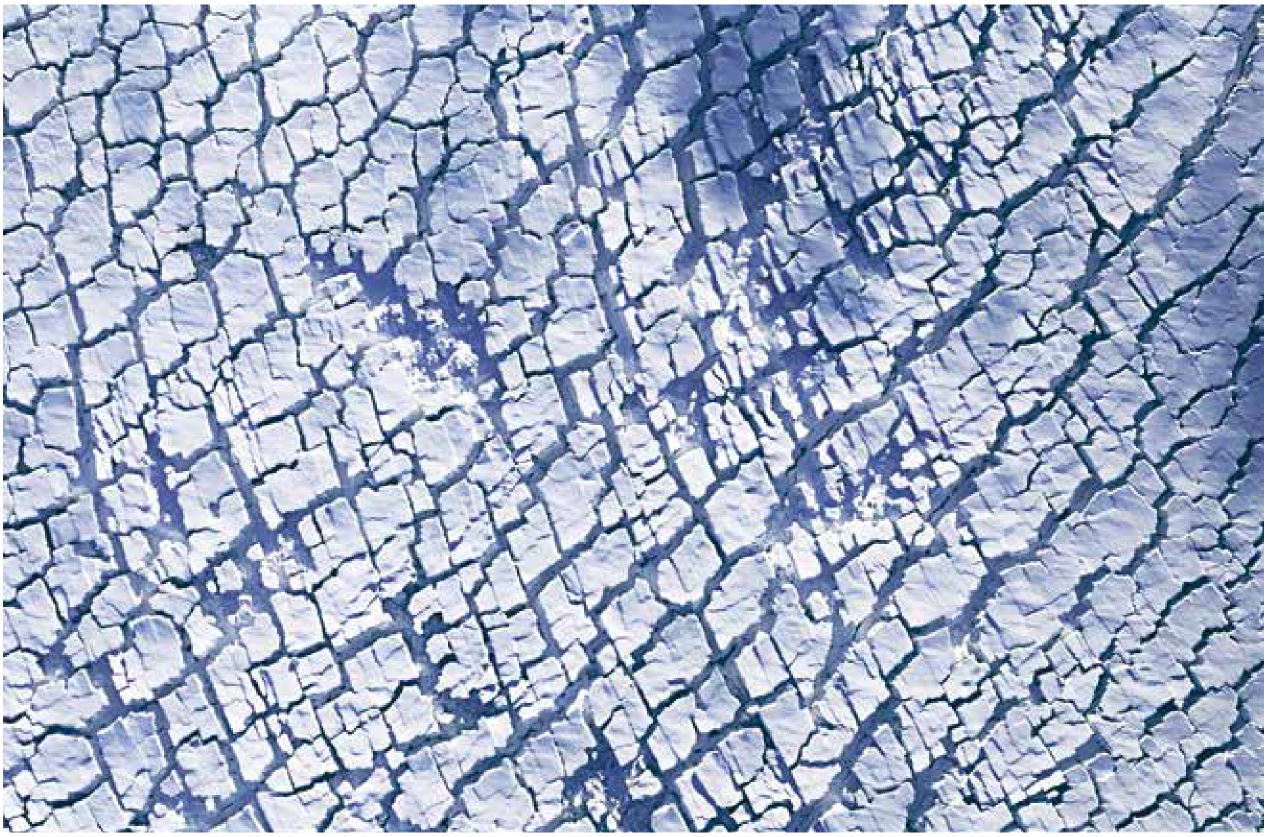
Surges are temporal instabilities in a glacier's movements. The frequency of surges varies from a few years to a whole century between glaciers and does not seem to be linked to glacier size or mass balance. While steeply sloping glaciers move sufficiently rapidly to keep in balance with the annual accumulation of snow and ice, surge-type glaciers are characterised by gently sloping surfaces (typically 1.5–4°) and they move too slowly to remain in balance with the accumulation rate. The increasing imbalance is periodically "corrected" by a short-term surge forward.

Surge-type outlet glaciers cover 75% of Vatnajökull's surface, and many of them have a history of regular surges (Björnsson et al., 2003). Major surges, with return periods ranging from several years to a century, have occurred in all the large lobate outlets on the

The Skaftá jökulhlaup on 2 October 2015 © Tómas Jóhannesson.

Next page: Ice gully in Breiða-merkurjökull, 6 June 2017 © Þorvarður Árnason.

Top: Tungnaárjökull like a turbulent sea after a surging event, 8 February 1995. Middle: Towering ice wall at the Síðujökull terminus (notice the person in front of it) on 20 April 1994. Bottom: The completely ruptured surface of Síðujökull during a surging event, 25 February 1994 © Oddur Sigurðsson.



northern, western and southwestern flanks of Vatnajökull. The steep and active valley glaciers draining the southeastern and northwestern flanks of Vatnajökull are not known to surge. Skeiðarárjökull and the eastern arm of Breiðamerkurjökull have a long surge history. Lake sediments can preserve surge records, as sediment deposition increases dramatically during surges, and can thus extend the history of known surges. The surge history of Eyjabakkajökull has been interpreted in this way (Striberger et al., 2011).

The surge process can take 2–3 years from the first signs of increased sliding and subsequent downglacier propagation of the surge wave. During surges, the mass transport can be up to 25% of the total ice flux and this affects the whole ice cap, including the location of ice divides, the flow of ice, the size and shape of the ice cap as well as water within the glaciers. The glaciers commonly experience uplift, crevasse formation and propagation of surface bulges for a few weeks, that occasionally result in an advance of the terminus, which can last for about 2–3 months. Following surges, the surface areas of the outlets expand, leading to an increase in melt and runoff

Two surging glaciers

Repeatedly measured surface profiles on Tungnaárjökull in western Vatnajökull show a classic example of the surge-related cycle of mass accumulation and expulsion. For approximately 50 years following the surge that ended in 1946, Tungnaárjökull thickened in the reservoir area and thinned and steepened in the receiving area. The next surge of Tungnaárjökull, in the early to mid-1990s, resulted in a readvance of the glacier terminus relative to its measured position in 1992, and surface drawdown in the reservoir area extending 30 km up-glacier from the terminus (Björnsson, 2017).

Surges in Brúarjökull are among the largest in Iceland, and they considerably affect the meltwater channels. Following the surge in 1963–1964, the ablation area increased in size by 160 km². Approximately 70 km³ of ice were transported down from the accumulation area, which resulted in a lowering of the surface by 60 m, and the terminus advanced close to 10 km (Guðmundsson et al., 1996). The peak velocity of ice-front advance during the 1963–1964 surge was more than 120 m/day over a period of three months (Þórarinsson, 1969b). This exceeds the velocity of the fastest ice streams in Antarctica and Greenland (Echelmeyer & Harrison, 1990; Joughin et al., 2002; Scheuchl et al., 2012).

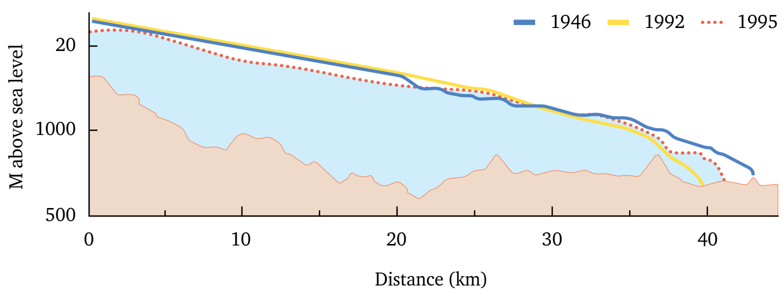


Figure 2.23. Elevation changes in Tungnaárjökull during surges. Tungnaárjökull surged in 1946, then retreated about 4 km until 1992 and grew thicker above 1100 m. In 1995 it surged forward about a kilometre and its surface above an altitude of 1100 m subsided. From Björnsson (2017).

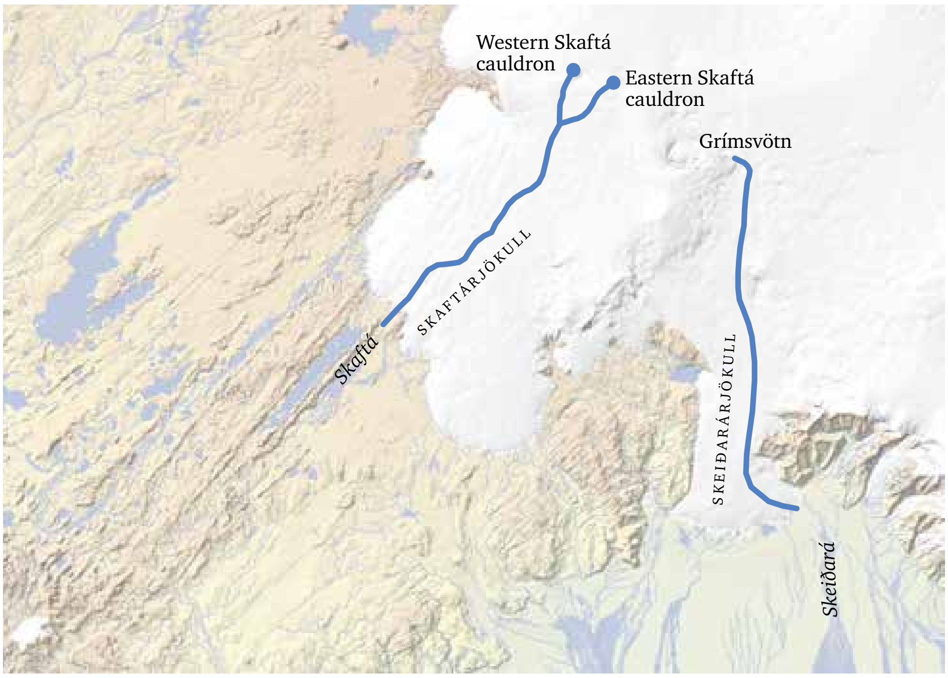


Figure 2.24.
Locations of the Grímsvötn volcanic caldera and the Skaftárkatlar geothermal fields in western Vatnajökull and the flow paths of jökulhlaups from the subglacial lakes at these sites. Source: Icelandic Meteorological Office.

into the glacial rivers. Surface elevation changes from satellite data reveal that three outlet glaciers in post-surge stages are presently experiencing thickening over large areas at high elevation; Brúarjökull, Síðujökull and Dyngjujökull (Foresta et al., 2016).

Jökulhlaups

Jökulhlaups or glacial outburst floods occur frequently at many locations in Iceland, and the Icelandic term has been internationally adopted as the name for glacial floods of this type. Jökulhlaups may occur through steady melting of ice above geothermal areas, melting by magma-ice interaction during a volcanic eruption, or through the release of water stored in marginal lakes dammed by glaciers. The Grímsvötn subglacial caldera lake is the source of the most widely known jökulhlaups. They were released into the Skeiðará river after travelling 50 km along the bed of Skeiðarárjökull outlet glacier. Skeiðará has recently changed its course, and now joins the river Gígja further west. Jökulhlaups have also regularly occurred in the river Skaftá, from the Skaftárkatlar subglacial lakes (Fig 2.24).

Jökulhlaups are very important as geomorphological agents in glacial environments, and they have shaped the landscape at many locations on Earth, e.g. the channelled scablands in the northwest United States. Large prehistoric jökulhlaups also formed the Jökulsárgljúfur canyons within the nominated property (Box p. 90). As jökulhlaups may have a very rapid discharge increase, they are considered extremely dangerous and a significant public hazard for settlements.

Research on jökulhlaups from Grímsvötn led to the development of a now classical theory of jökulhlaups (Björnsson, 1974; Nye, 1976; Cuffey & Paterson, 2010) that has been further developed by several researchers (Spring & Hutter, 1982; Clarke, 1982, 2003) and applied at many locations on other glaciers (Clarke et al., 2004; Engeset et al., 2005). Recent research has revealed that jökulhlaups can be categorised into two main types, rapidly and slowly rising floods (Björnsson, 2002; Jóhannesson, 2002), which

The Gjálp Jökulhlaup 1996

On the 4th of November 1996, a high frequency tremor appeared on seismographs on Mt. Grímsfjall, indicating that an ice barrier restraining the water in the Grímsvötn lake was failing (Einarsson et al., 1997). The water then migrated some 50 km under the ice until it appeared 11 hours later as a several-metres-high flood wave onto Skeiðarársandur outwash plain. The jökulhlaup peaked in discharge at around 45,000 m^3s^{-1} in the evening of 5 November, with a maximum areal cover of some 700–800 km^2 (Fig 2.25). The sediment-laden water broke off angular blocks of ice, up to 2,000 m^3 in size, from the snout of Skeiðarárjökull. These were dislodged and transported with the jökulhlaup as the flood water gushed over the sandur plains. The total volume of flood water is estimated to have been 3.5 km^3. The jökulhlaup destroyed 10 km of Route 1 on Skeiðarársandur and the bridge over Gígjukvísl river, and left broken power lines in its wake.

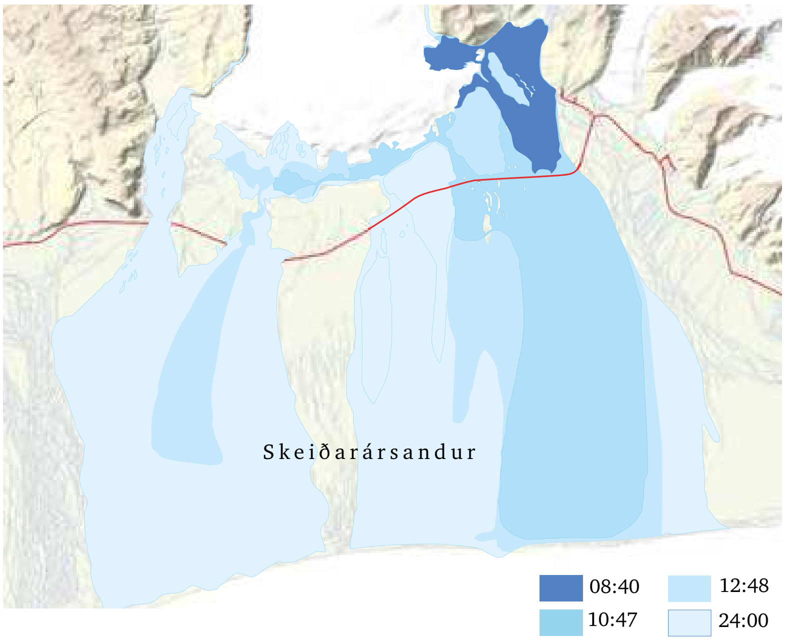


Figure 2.25.
The growth of the Gjálp jökulhlaup on 4 November 1996. The breaks in red line show where the main ring road (No.1) was ruptured. Source: Icelandic Meteorological Office.

are characterised by marked differences in the way the water flows under the ice (Fig 2.26). Several unresolved questions remain about the physical mechanisms that determine the development of these floods and future observations of jökulhlaups from Grímsvötn and Skaftárkatlar may be expected to be at the centre of future research in this field, as they have been in the past.

Jökulhlaups from Grímsvötn and Skaftárkatlar

For centuries, geothermal heat has melted ice within the Grímsvötn caldera. Meltwater collection beneath the Grímsvötn ice shelf has led to regular jökulhlaups that emerge from beneath the Skeiðarárjökull outlet glacier (Björnsson, 1974, 1975). Jökulhlaups from Grímsvötn into Skeiðará river have been reported since the middle ages. In the largest jökulhlaups, almost all the Skeiðarársandur outwash plain, ca. 1000 km^2 in area, has been flooded. In the early part of the 20th century, jökulhlaups from Grímsvötn occurred approximately once per decade with a maximum discharge of tens

Large ice blocks (note the person standing between the blocks to the right) left by the Gjálp jökulhlaup, 4 January 1997 © Oddur Sigurðsson.

of thousands of m³/s (Björnsson, 1992, 2002). After ca. 1940 and until 1996, the floods occurred every 5 years or so with a maximum discharge less than 10,000 m³/s as the volume of the source lake became smaller. After the Gjálp eruption and the extreme jökulhlaup in 1996 (Box p. 87), jökulhlaups from Grímsvötn have become smaller and they occur irregularly. Typical slowly rising jökulhlaups from Grímsvötn reach maximum discharge in 1–3 weeks and terminate approximately a week after the maximum discharge is reached.

Eruptions within Grímsvötn do not cause jökulhaups because the water level of the subglacial lake does not rise, when the floating ice cover melts. However, volcanic eruptions may accompany outburst floods. This can happen because the pressure on the shallow magma chamber underneath the subglacial lake decreases when the water level in the lake falls, enabling the magma to reach the surface. Such eruptions occurred at the end of jökulhlaups in the years 1922, 1934 and 2004, and there were many other examples of this in the 19th century (Þórarinsson, 1974b; Björnsson, 2017).

Skaftárkatlar (the Skaftá cauldrons) northwest of Grímsvötn are depressions in the glacier surface, formed by geothermal melting at the bottom of the glacier. Geothermal activity in the region causes meltwater to collect in subglacial lakes at two locations beneath the cauldrons at the base of the glacier, where the ice cap is 300–450 m thick. The two lakes release jökulhlaups into Skaftá, a river emerging from the Skaftárjökull outlet glacier. The subglacial flow path of the Skaftá jökulhlaups is 40 km long (Fig 2.24) and seems to be confined between two SW–NE trending hyaloclastite (móberg) ridges. After emerging from the glacier, the floodwater follows the course of the Skaftá river. A hydrometric station 28 km downstream records the rise in water level, from which the floodwater discharge can be calculated (Einarsson et al., 2017).

Aerial view of Skeiðarársandur and the Gjálp jökulhlaup on 4 November 1996. Lómagnúpur in the foreground, Öræfajökull in the back © Oddur Sigurðsson.

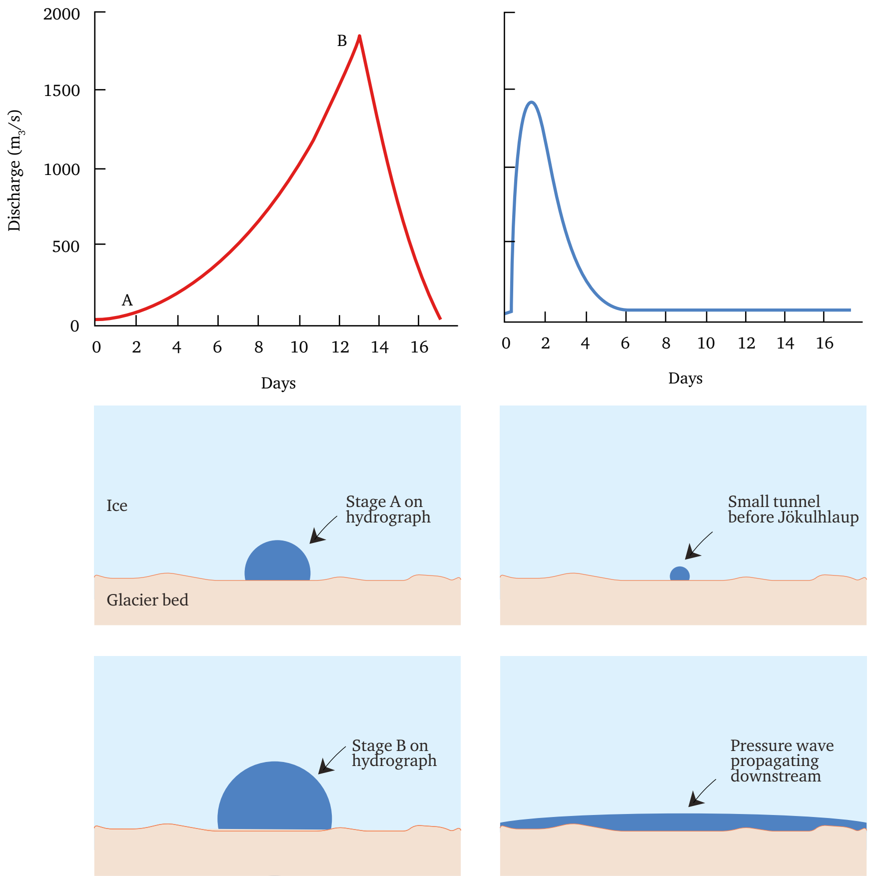


Figure 2.26.
Two different types of jökulhlaups. Left column: A "classical", slowly rising jökulhlaup flows initially through a narrow tunnel at the base of the ice. As the flood progresses, the tunnel expands and can accommodate more water. Right: In a fast-rising jökulhlaup, the pressure in the floodwater front is sufficient to lift the glacier locally and the water forces its way rapidly under the ice. The tunnels may grow to a diameter in the order of 10 m in some cases and the pressure wave can lift the glacier up to one m across several km.

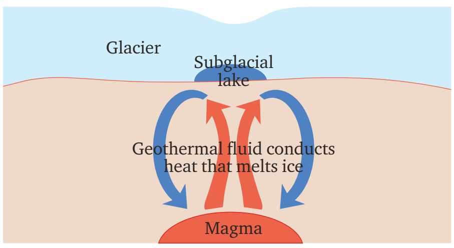


Figure 2.27.
Collection of meltwater in a subglacial lake above a geothermal system. Meltwater from the glacier percolates downward into the crust and is heated by contact with hot rock at several km depths. The water then warms up and rises again. The melting of the ice creates a depression above the water and the thicker ice around the lake forms a pressure seal that prevents outflow of the water. Thus, a cupola of water can form underneath the ice and remain stable until a critical pressure level is reached and the water forces its way out below the ice. From Björnsson (2017).

During jökulhlaups from the Skaftá cauldrons, 0.05–0.5 km³ of meltwater are released from the subglacial lakes, leading to a rapid drop of the ice surface over 2–3 days, and the formation of 50–150 m deep surface cauldrons. The cauldrons are 2–3 km in diameter and deep concentric crevasses form around them during the subsidence. Each cauldron has emptied every 2–3 years on average since the start of regular monitoring in 1955. The measured amount of water released allows determination of the average melting rate due to the subglacial geothermal areas and therefore of the power output of the geothermal systems, estimated to be approximately 800 MW below the eastern cauldron and 500 MW below the western cauldron. No clear picture has yet been obtained of the location of geothermal vents at the bottom of the lakes, but it is likely that plumes of warm water rise through the water column at discrete locations within the 1–3 km² areas of the two lakes.

The behaviour of jökulhlaups from the Skaftá cauldrons is very different from those originating in Grímsvötn. Floods from Grímsvötn display a slow rise in discharge over several weeks, due to a steady enlargement of the subglacial tunnel, and then a sudden drop in discharge occurs when the lake has emptied out. The typical Skaftá floods, on the other hand, rise very rapidly during 1–2 days and then subside slowly in 1–2 weeks. One major aim of recent research in the Skaftá cauldrons and vicinity has been to increase understanding of the mechanisms governing the behaviour of these two distinct types of jökulhlaups. GPS-measurements of vertical movements of the glacier surface during recent jökulhlaups from Skaftárkatlar support the hypothesis that the floodwater initially propagates along the flowpath as a pressure wave, lifting the glacier over the floodpath suddenly by ca. one m (Jóhannesson, 2002; Einarsson et al., 2016) (Fig 2.26).

The role of jökulhlaups in the making of the Jökulsárgljúfur canyon

Jökulhlaups have had a significant role in landscape evolution north of the Vatnajökull ice cap. It is hypothesised that the 28-km long Jökulsárgljúfur canyon formed during the Holocene by jökulhlaups that originated from Vatnajökull ice cap and flooded the path of Jökulsá á Fjöllum glacial river. Several attempts have been made to identify and interpret the impact of jökulhlaups in the river during the Holocene (Þórarinsson, 1950; Sæmundsson, 1973; Tómasson, 1973; Elíasson, 1974, 1977; Sigbjarnarson, 1996; Waitt, 2002; Carrivick et al., 2004; Kirkbride et al., 2006; Baynes et al., 2015a, 2015b). This includes recent research on the geomorphic impact and sedimentary evidence of jökulhlaups close to the floodwater source (e.g. Carrivick et al., 2004; Carrivick, 2007; Marren et al., 2009) and on modelling the hydraulic conditions of the floods (e.g. Alho et al., 2005; Carrivick, 2006, 2007; Carrivick et al., 2013).

The jökulhlaups were the results of either subglacial eruptions in the Kverkfjöll, Grímsvötn or Bárðarbunga volcanic systems (Björnsson, 2009), or the release of floodwater from an ice-dammed lake to the south of Kverkfjöll (Björnsson, 2002). The first jökulhlaup ca. 9000 years ago, initialised the formation of the Jökulsárgljúfur canyon at the northern coast at Ásbyrgi, with later floods contributing to the upstream erosion of the canyon to its present location at Dettifoss (Baynes et al., 2015b). Many pieces of evidence along the entire canyon support the interpretation that it was carved out by several extreme jökulhlaups, separated by thousands of years; unlike many canyons on Earth, the erosion has not been continuous through time. These floods were enormously powerful and are believed to have excavated the canyon within the space of hours or days. When the velocity of flow reaches 15 m^3s^{-1}, air pockets may form in the water, and when these abruptly collapse, powerful pressure waves are formed that smash into the rock and shatter it. The flood easily carries the fragmented rocks away and the process continues.

The discharge of the largest jökulhlaup has been estimated at 900,000 m^3s^{-1} covering around 1400 km^2 of land (Alho et al., 2005). This flood left extensive evidence of flood inundation across the landscape, such as boulder fields, gravel dunes and recent river sediments far away from the present river course. In the smallest flood, around 200,000 m^3s^{-1}, some fifth of this amount of water was released. The floods filled the Jökulsárgljúfur canyon and flooded the neighbouring area, shaping the land through erosion and the deposition of sediments. Catastrophic glacial floods of this magnitude are rare but not unique to Iceland. These jökulhlaups are the largest floods that have occurred in Europe and are believed to number among the 10 largest floods in the world during the Holocene. However, the largest Jökulsá á Fjöllum jökulhlaup was ca. 20 times lesser in terms of discharge and power per unit area than the Altai palaeoflood – the largest known flood on Earth (Alho et al., 2005).

Evidence for jökulhlaups within the canyon itself ranges from abandoned river terraces to the dry, 3 km long, 1 km wide, up to 100 m deep, canyon of Ásbyrgi in the north. The bedrock geology of the upper 5 km of the canyon, where the three largest waterfalls are located, Selfoss, Dettifoss and Hafragilsfoss, consists of distinct basalt lava flows stacked on top of each other (seen clearly in Fig 2.29). At each of the three large waterfalls, the river flows from the top of one lava flow onto the top of the underlying lava, highlighting the importance of the local geology for the morphology of the canyon.

Detailed geochronological work by Baynes et al. (2015b) reconstructed the evolution of the upper part of the canyon and demonstrated that its erosion occurred through the upstream retreat of the waterfalls. The waterfalls erode when flow conditions are strong enough to topple the basalt columns that make up the lava flow layers. Below this threshold flow condition, calculated to be a water depth of 8 metres, the basalt columns do not topple and the waterfalls therefore do not retreat, leaving the canyon in a “dormant” state. Baynes et al. (2015b) showed that this threshold was exceeded and the upper 5 km of the Jökulsárgljúfur canyon eroded during two periods of extreme flooding, approximately 5000 and 1500–2000 years ago. During these flood periods, the waterfalls in the canyon retreated at least 3 km over very short periods of time.

At the Jökulsárgljúfur canyon, several factors combine to facilitate the frequent surpassing of the threshold between erosion regimes, leading to a transition to highly destructive block toppling and the retreat of large waterfalls regularly over the past 9000 years. Thus, the geologically young Jökulsárgljúfur canyon has great value as an example of a landscape evocative of regular, significant and destructive transitions between erosion process regimes during discrete short-lived events separated by thousands of years.

Skaftárkatlar and Grímsvötn subglacial lakes

The subglacial lakes of Skaftárkatlar and Grímsvötn are among only a handful known outside of Antarctica, and their physical and chemical properties distinguish them from volcanic crater lakes at the surface, and place them among some of the most “extreme” habitats on Earth (Box p. 133). Hot-water drilling is used for temperature measurements and sampling (Thorsteinsson et al., 2007; Jóhannessson et al., 2007). The Skaftárkatlar lakes are isolated from the surface by nearly three hundred metres of overlying ice, which completely blocks sunlight and almost entirely shuts out the atmosphere. As a result, there is essentially no dissolved oxygen in

Figure 2.29.
Photographs of the upper part of the Jökulsárgljúfur canyon, with the terraces, that indicate the historic river bed, highlighted in red, green and yellow. In (B), the lava flow layers that make up the geology of the area can be clearly seen in the canyon walls to the right. From Baynes et al. (2015).

the lakes, and no light to drive oxygen-producing photosynthesis. Instead, interaction of the hot rising steam with rock and magma leads to the incorporation of various chemicals (SiO_2, SO_4, Na, Cl, Ca, F) and volcanic gases (CO_2, H_2S, the latter quite toxic) to form a geothermal fluid that enters the subglacial lake through vents on the lake bed. This fluid then rises through the water column in plumes, causing melting at the base of the overlying ice. Cold meltwater sinks and convective circulation is established in the subglacial lake. Melting glacial ice keeps temperatures in the range of 3.5–4.7°C, i.e. slightly above the temperature of water at maximum density, which is 4°C at atmospheric pressure but 3.2–3.4°C at the pressures encountered in the lakes (Jóhannesson et al., 2007).

Glaciers outside the Vatnajökull ice cap
Within Vatnajökull National Park are smaller glaciers bordering the main ice cap, namely Tungnafellsjökull (32 km^2), Hofsjökull eystri (3 km^2) and eight smaller glaciers on Mt. Snæfell (collectively 6 km^2). Just outside the border of the National Park are some more small glaciers, including the cirque glaciers on Jökulgilstindar and Tungutindar, and the small ice cap of Þrándarjökull (15 km^2).

Ice cave in Vatnajökull © Árni Tryggvason.

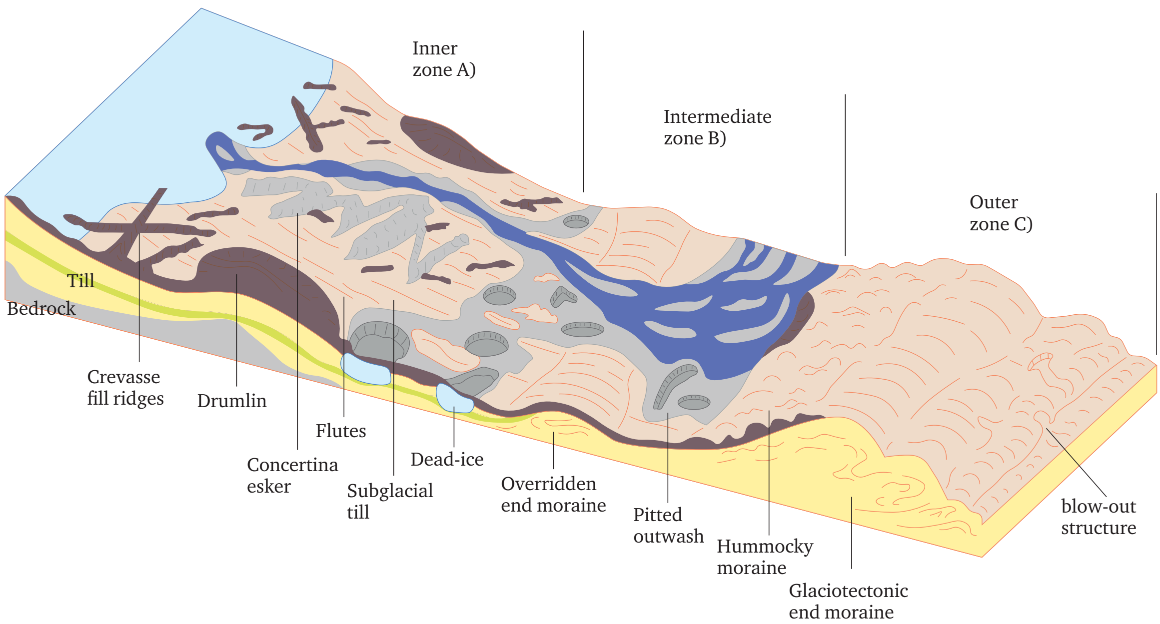
2.a (iv) Glacial Geomorphology

All around the periphery of Vatnajökull ice cap are textbook examples of glacial geomorphological processes and landforms. The mapping of the forelands of receding glacier snouts assists in understanding the nature of spatial and temporal landform evolution and provides a modern analogue for Quaternary environments. Vatnajökull's outlet glaciers have been central to the study of glacial landforms and sediments. As they retreat freshly deposited features and landforms are uncovered that are easily accessible for study and repeat measurements.

Particularly powerful modern analogues for glacier behaviour are provided by the landform-sediment assemblages on the forelands of contemporary surging glaciers like Tungnaárjökull, Brúarjökull and Eyjabakkajökull (see Ingólfsson et al., 2016, for a review). From their forelands come diagnostic criteria for the recognition of imprints of fast ice flow on the landscape. They are looked upon as modern analogues for the land terminating palaeo-ice streams and surging ice sheet lobes of the last glaciation (Evans et al., 1999). During the quiescent phase of surging glaciers, they retreat and landform sediment assemblages are exposed and imprinted with information on sub-glacial and ice-marginal driving processes (Sharp, 1985; Sharp & Dugmore, 1985; Bennett et al., 2000; Evans & Rea, 2003; Evans et al., 2007, 2009a; Benediktsson et al., 2008; Kjær et al., 2006, 2008; Schomacker et al., 2006, 2014; Waller et al., 2008). The geomorphic signatures left by surge-type glaciers vary and range from glaciotectonic end moraines formed by folding and thrusting, crevasse-squeeze ridges, pitted outwash, zig-zag eskers, abnormally long fluting, to extensive dead-ice fields (Fig 2.30).

The recently deglaciated forelands of the southern non-surging outlet glaciers of Vatnajökull also constitute an ideal outdoor classroom and laboratory for studying the impacts of glaciers on landscapes (Evans, 2016). Students from all over the world visit the area every year to explore the very accessible and freshly exposed glacial geomorphology. Research groups have mapped the forelands

Figure 2.30.
An example of a surging glacier landsystem model from Eyjabakkajökull. (A) Outer zone of glaciotectonic end moraines consisting of deformed pre-surge sediments. Hummocky moraine occurs on the backslope of the end moraine. (B) Intermediate zone of active, channelled outwash as well as inactive, pitted outwash deposited on top of stagnant ice. (C) Inner zone of subglacial till, flutes, drumlins, crevasse-fill ridges, and concertina eskers. From Schomacker et al. (2014), after Evans & Rea (2003).



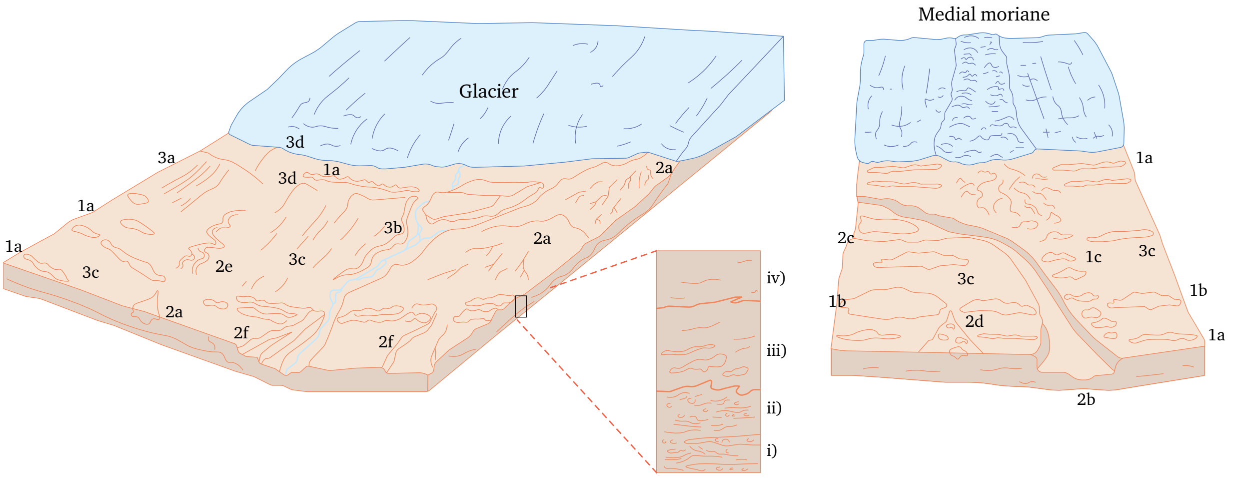


Figure 2.31.
Diagnostic characteristics of the active temperate glacial landsystem in southern Iceland, showing the marginal morainic domain (1a push moraine, 1b composite push moraine, 1c medial moraine-fed dump moraine), the glacifluvial and glacilacustrine domain (2a proglacial sandur fan, 2b incised and terraced outwash or spillway, 2c glacial lake deposits, 2d pitted outwash/ kame and kettle topography, 2e esker, 2f terraced sandur fan), and the subglacial domain (3a overridden moraine, 3b overridden outwash head, 3c flutings) with a typical sediment sequence comprising i) outwash, ii) Type B glacitectonite, iii) Type A glacitectonite, and iv) subglacial traction till. From Evans & Twigg (2002), after Kruger (1994).

and increased our knowledge about glacier processes and glaciation imprints, including immense downwasting (surface lowering) into overdeepenings, and the findings can be applied to reconstructions of ancient glaciations all over the world (e.g. Evans et al., 1999). Particularly significant has been the development of the glacial landsystem model for active temperate glaciers, which dominate the style of glaciation along the south margin of Vatnajökull and have become the default modern analogue for reconstructing mid-latitude ancient ice sheet margins (Fig 2.31). The rapid retreat of these outlet glaciers has involved the operation of a range of glacial geomorphological process-form regimes that are perfect modern analogues or exemplars characterising landscape change of the kind that will pertain to most glacierised landscapes around the world in the coming decades and centuries (e.g. Evans & Twigg, 2002; Evans, 2003, 2005, 2010; Bennett & Evans, 2012; Bradwell et al., 2013; Evans & Orton, 2014; Jónsson et al., 2014; Storrar et al., 2015; Chandler et al., 2016; Evans et al., 2016).

The following section presents selected examples of the fresh glacial geomorphological landforms created by the rapidly retreating outlet glaciers within the nominated property and highlights their importance in understanding ongoing glacial geomorphological processes.

Aerial view over the foreland of Dyngjujökull, 13 August 2017 © Walter Huber.

Breiðamerkurjökull/Fjallsjökull

Breiðamerkurjökull secured international status in the earth science realm with two significant developments in glaciology/glacial geomorphology. Firstly, a mapping programme initiated in 1964 by Rob Price and Gordon Petrie of the University of Glasgow (Howarth & Welch, 1969) and then in 1998 by Evans and Twigg (2002) led to the production of a series of glacier foreland maps (Fig 2.32; Appendix 1.3) with detailed glacial landform-sediment assemblages. A similar map sequence was produced by Evans et al. (2009a) for Fjallsjökull. Year to year surveying augmented the mapping

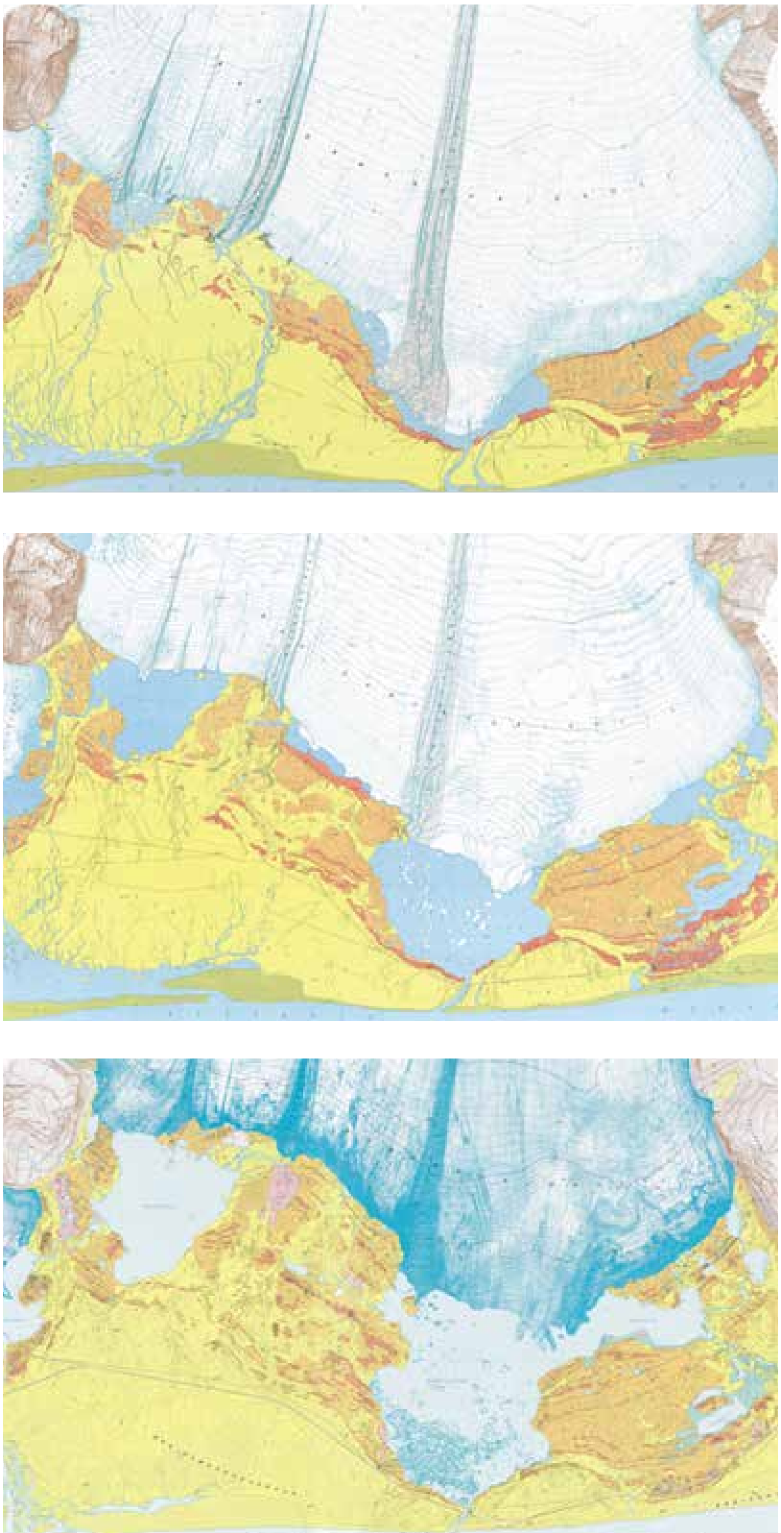


Figure 2.32.
Breiðamerkurjökull forefield at different times, 1945, 1965 and 1998, highlighting the rapid and ongoing geomorphological changes occurring in front of Vatnajökull's outlet glaciers. From Evans (2016), after original mapping by Howarth & Welch (1969) and Evans & Twigg (2002). See Appendix 1.3 for more detail.

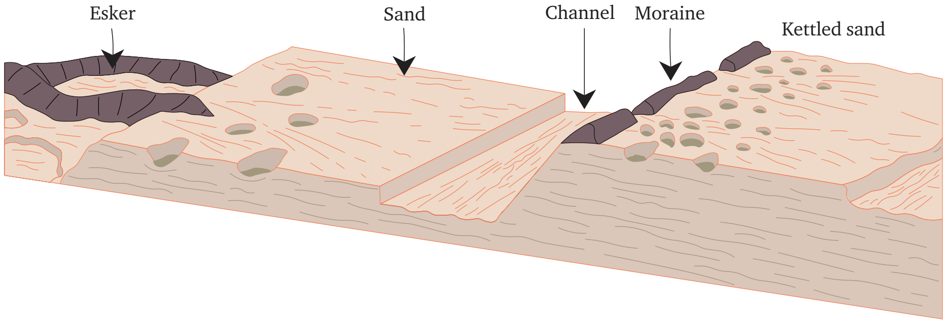


Figure 2.33.
Price's (1969) original block diagram portraying the juxtaposition of landforms typical of deposition around the margins of temperate lowland glaciers and based on the surveys of the Breiðamerkurjökull foreland.

with many case studies on evolving glacial landforms like eskers (Howarth, 1971), pitted outwash fans (Price, 1971), proglacial lakes and drainage (Howarth & Price, 1969; Price & Howarth, 1970) and push moraines (Price, 1970). Together these studies have elevated the Breiðamerkurjökull and Fjallsjökull foreland to the status of the type site for the active temperate glacial landsystem, with the first modern analogue process-form model for such a setting being published in 1969 by R.J. Price (Fig 2.33). Modern surveying and mapping has continued to develop the initial models, for example on eskers (cf. Howarth, 1971; Storrar et al., 2015) and on pitted outwash (Price, 1969, 1971; Evans & Twigg, 2002; Storrar et al., 2015). The expanding database on landform change has also been linked to climate change drivers and presented as a case study for glacier change in a warming world for schools.

Secondly, the daring experiments of glaciologist Geoffrey Boulton and co-workers in the 1970s (Boulton et al., 1974; Boulton & Jones, 1979) identified the third mode of glacier flow, subglacial bed deformation. The initial experiment included excavating a tunnel through the ice just above the bed of the west lobe of Breiðamerkurjökull so that four boreholes could be drilled downwards into the underlying till. Strain markers were implanted into the till at various depths and left for a period of 136 hours. This revealed a two-layer till, with an upper deforming till layer ("A horizon") that was distinct from an underlying, more consolidated stiffer till layer ("B horizon"). It was estimated that nearly 90% of the forward movement of Breiðamerkurjökull was taking place in the deforming layer. From this came a seminal research paper by Boulton and Hindmarsh (1987) in which a flow law for subglacial till was derived, forming the foundation for research on till and glacier dynamics on soft-bedded substrates. Boulton and colleagues were to return to the Breiðamerkurjökull foreland in 1988/1989 when they instrumented a till prior to it being overrun by a mini-surge at the eastern glacier margin, allowing the simultaneous measurement of strain rate profiles within the till and sliding at the ice-till interface (Boulton et al., 2001; Boulton, 2006). This has formed a centrepiece of our modern understanding of the interactions between subglacial till behaviour and glacier dynamics.

Fláajökull

The earliest map of Fláajökull is the Danish Geodetic Survey map of 1904, which depicts the glacier margin some 300 m inside the maximum historical limit. This limit was dated by a variety of methods to the period 1870–1894 AD (Evans et al., 1999; Dabski, 2002, 2007). In the early to mid-1990s, a number of south Vatnajökull outlet glaciers, including Fláajökull, readvanced and maintained a quasi-stationary ice front for around five years (cf. Bennett & Evans, 2012; Bradwell et al., 2006). This was significant at Fláajökull in that it resulted in the construction of a composite push moraine (Evans, 2003, 2005; Evans & Hiemstra, 2005) typical of stationary temperate glacier snouts (Evans, 2013; Krüger, 1993). This moraine was being initiated at the time of aerial photograph capture in 1989 and was observed during its construction and abandonment over the period 1993–2002, allowing a full understanding of the process-form relationships and process sedimentology associated with submarginal till accretion and moraine genesis (Evans & Hiemstra, 2005). Other unusual glacial landforms on this foreland include till eskers (Evans et al., 2010; Evans et al., 2016) and crevasse squeeze ridges not related to surging (Evans et al., 2016). Overridden moraines are also well displayed.

These landform details comprise a glacial landsystem that displays invaluable evidence for spatial and a temporal change in process-form regimes. Ice recession has produced a distinct set of landform patterns that can be related to changing glaciological conditions through time and hence allow us to refine the active temperate piedmont lobe landsystem model. Firstly, multiple arcs of overridden moraines are the products of composite push ridge construction during phases of glacier stillstand which were then overrun by the glacier, probably during its advance to the Little Ice Age maximum. Secondly, recessional push moraines, deposited on the surfaces of the overridden moraines, display two clear patterns, including closely spaced and more linear forms on the outer foreland and, in contrast, sawtooth and partially superimposed forms on the inner foreland. Finally, the distribution of crevasse squeeze ridges and till eskers on the inner foreland indicates that sub-marginal conditions were conducive to the squeezing of till into full-depth crevasses and tunnels in the snout during the more recent period of glacier recession. The underlying control on these changes is the topography of the substrate that was inherited by the glacier snout as it advanced and retreated from its historical Little Ice Age maximum.

Recent mapping by Jónsson et al. (2016) has indicated that a cluster of 15 drumlins has been exposed following a retreat of the glacier from a large end moraine formed in 1995. Drumlins are not as common in the forefields of modern glaciers as in Pleistocene landscapes and those at Fláajökull are very subdued. Single drumlins or drumlins in small groups have been observed in modern glacial environments elsewhere in Iceland.

Brúarjökull

Brúarjökull has experienced some of the largest and fastest surges known to have occurred in northern-hemisphere glaciers, with major velocity fluctuations switching between active surging of a few months' duration and quiescent phases lasting from 70 to 90 years (Fig 2.34; Todtmann, 1960; Þórarinsson, 1969b; Raymond, 1987). During the two most recent surges, initiated in 1890 and 1963, the glacier advanced 8–10 and 9 km, respectively, affecting an area of more than 1400 km^2 (Þórarinsson, 1969b; Guðmundsson et al., 1996).

Despite its relatively remote and inaccessible location, compared to the southern outlet glaciers, the geomorphology of the Brúarjökull forefield is comparatively well known (Todtmann, 1960; Evans

& Rea, 1999, 2003; Evans et al., 2007). The newest geomorphological work includes detailed maps of the Brúarjökull central forefield (Evans et al., 2007; Kjær et al., 2008; Benediktsson et al., 2008; Ingólfsson et al., 2016). A study of the large 1890 Brúarjökull surge moraine resulted in a sequential model that illustrates the stepwise formation of a surge-type glacier's end moraine. Spectacular crevasse-squeeze ridges on the foreland have become the type site for such landforms in glacial geomorphological research. They form by the squeezing of subglacial till upwards into the crevasses formed by the surge event (Evans & Rea, 1999, 2003; Rea & Evans, 2011) and have been used as diagnostic criteria for palaeo-surging in ancient glaciated terrains in North America (Evans et al., 1999, 2008, 2016). Other features that have proven to be critical to the explanations of ancient glaciated terrains are ice-cored drumlins (Schomacker et al., 2006) and long flutings (Evans & Rea, 2003; Evans, 2016). Also at the site, Kjær et al. (2006) suggested a new mechanism to explain motion of surge-type glaciers, where subglacial deformation was subordinate to till sliding during Brúarjökull surges. The extremely rapid ice flow observed during the 1963–1964 surge (ca. 120 m per day) was sustained by over-pressurised water causing decoupling at the bedrock beneath a thick sediment sequence that was coupled to the glacier.

The Brúarjökull studies have provided new information about subglacial and sub-marginal processes of fast-flowing glaciers and thus help to understand the mechanism behind the formation of sediment wedges at the grounding line of ice streams, such as those recently discovered at the margin of the Whillans Ice Stream in the west Antarctic and at the margins of palaeo-ice streams in the eastern Ross Sea and in the Bjørnøyrenna Trough, Barents Sea. Given the ice flow velocities of Brúarjökull during surges (100–120 m/day) the formation of the tectonic end moraine is concluded to have formed within 5 days, and the moraine ridge in about 1 day, a time scale previously unheard of.

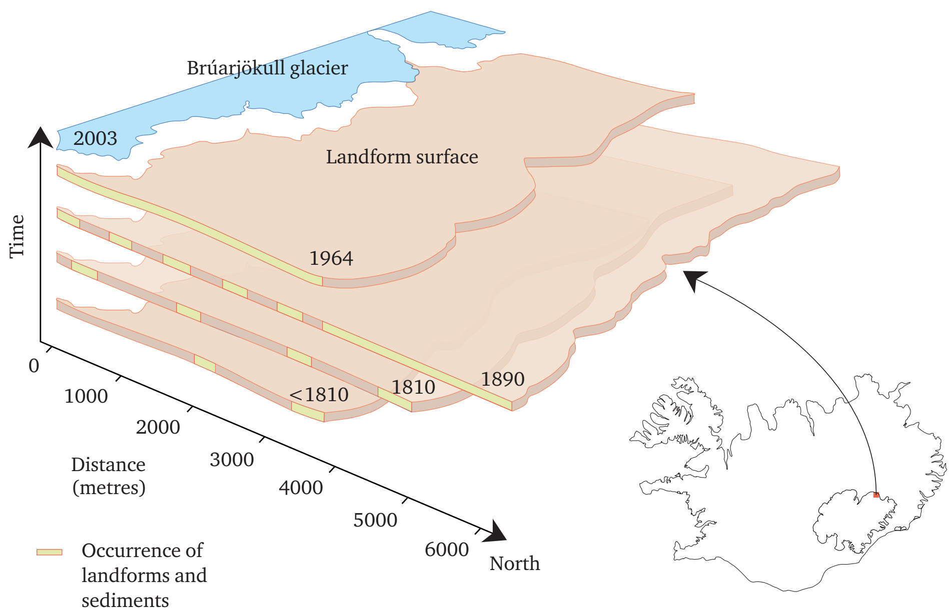


Figure 2.34.
The present terrain surface of Brúarjökull is the cumulative result of at least four surge events: pre-1810, 1810, 1890 and 1963–1964. From Kjær et al. (2008).

Eyjabakkajökull

The landforms at Eyjabakkajökull have been reasonably well studied (e.g. Clapperton, 1975; Sharp, 1985a, 1985b; Croot, 1988; Evans & Rea, 1999, 2003; Benediktsson et al., 2010) and, like those at Brúarjökull, provide a modern analogue for the impacts of terrestrial palaeo-ice streams and surge-type ice sheet lobes with a remarkably high level of detail due to excellent preservation and young age (Fig 2.30). The geomorphology of the Eyjabakkajökull forefield reflects the impact of multiple glacier surges. In fact, the surge history of Eyjabakkajökull reaches 2200 years back in time as recorded by sediment cores from lake Lögurinn. During the colder Little Ice Age (1450–1900) the frequency of surges of Eyjabakkajökull seem to have increased, according to the sediment record (Striberger et al., 2012).

An important diagnostic landform left by surge-type glaciers are zig-zag eskers, which were first described from Brúarjökull by Knudsen (1995), who called them “concertina eskers”. These have more recently been re-classified as zig-zag eskers by Benn and Evans (2010), because they have not been compressed in the ice as Knudsen suggested, but rather deposited in sequential straight segments by supraglacial streams that exploited the dense network of crevasses produced during the surge. They are common features on the forelands of surge-type glaciers, specifically having been described from Eyjabakkajökull and Brúarjökull (Knudsen, 1995; Evans et al., 1999; Evans & Rea, 1999; Kjær et al., 2008), from three surge-type glaciers on Svalbard (Hansen, 2003; Lovell et al., 2015) and in Novaya Zemlya (Grant et al., 2009). Their apparent rarity amongst the range of glacial landforms is likely a reflection of their misidentification in ancient glaciated landscapes; indeed, the Icelandic examples have become the type locality for zig-zag eskers and they have initiated a wider appreciation of the landform, with ancient examples now being recognised on palaeo-ice sheet beds (e.g. Evans et al., 2016).

Also, diagnostic of glacier surging and beautifully demonstrated at Eyjabakkajökull are glacitectonically thrust end moraines. The prominent 1890 surge end moraines of Eyjabakkajökull are like those of the famous surge-type glaciers on Svalbard (e.g. Boulton et al., 1999; van der Meer, 2004) and are indicative of a specific set of surge-induced processes including proglacial stress field deformation of materials that lay beyond the advancing glacier snout. The Eyjabakkajökull surge moraines are particularly valuable to glacial geomorphologists in that they can be related to a precise process-form regime, having been reconstructed in a time-sequence model by Croot (1988) and re-visited because of its unusual clarity as a sediment-landform assemblage by Benediktsson et al. (2010).

Heinabergsjökull/Skálafellsjökull

The Heinabergsjökull/Skálafellsjökull foreland (Appendix 1.3, p. 352) is an instructive modern analogue for the evolution of active temperate landsystems that have developed in mountain terrains with high glacio-fluvial sediment yields (Evans & Orton, 2015; Fig 2.33). This is a palaeoglaciological setting that numerical palaeo-ice sheet modelling (e.g. Hubbard et al., 2009) reveals to be the average style of glaciation (McCarroll, 2006; Porter, 1989) during a typical cold stage, i.e. upland glaciation with lowland piedmont lobes or valley glaciers. The foreland of Skálafellsjökull also contains some of the most impressive flutings with stoss boulders of any site in Iceland. On the southwestern side of the foreland a vast expanse of glacial eroded bedrock ridges displays some of the finest examples of glacial erosional landforms such as roches moutonnées, whalebacks and crag-and-tail forms and their adornments of striae, chattermarks, gouges and grooves (Evans & Orton, 2014; Chandler et al., 2015, 2016a, 2016b), all of which are uncommon in the normally till- and outwash-covered forelands of Iceland.

Skaftafellsjökull

Very striking features on the Skaftafellsjökull foreland, especially when viewed from altitude, are the dense network of partially overprinted sawtooth-shaped push moraines that document historical snout recession. Indeed, they are a text book example of such landforms (Evans et al., 2017; Fig 2.35). These moraines form a significant part of a glacial landsystem typical of the Icelandic south coast active temperate piedmont lobes, wherein widespread basal melting and deformation of water-soaked till produces flutings and sub-marginal till squeezing. The tendency for the till to be squeezed by ice loading results in its migration into radial crevasses to produce the sawtooth or hairpin-shaped moraines. The most characteristic process-form regime of these active temperate glaciers is that of recessional annual push moraine construction in response to seasonal temperature fluctuations, with the tendency of the glacier snout to commonly display winter advances even when in overall recession (Boulton, 1986; Chandler et al., 2015, 2016a, 2016b; Evans & Twigg, 2002; Krüger, 1995). Additionally, a prominent composite push moraine complex, recording a period of positive mass balance when the glacier margin was subject to relative stability in the mid-1990s, occurs in the mid-foreland.

Morsárjökull

Morsárjökull is famous for its surface banding or ogives (also known by glaciologists as "Forbes bands"), which were the subject of some of the earliest investigations of such features in the 1950s

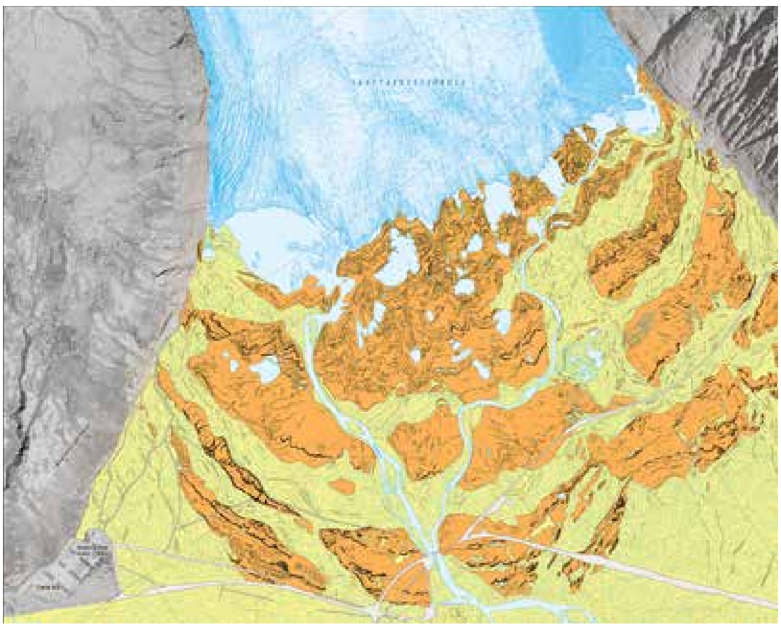
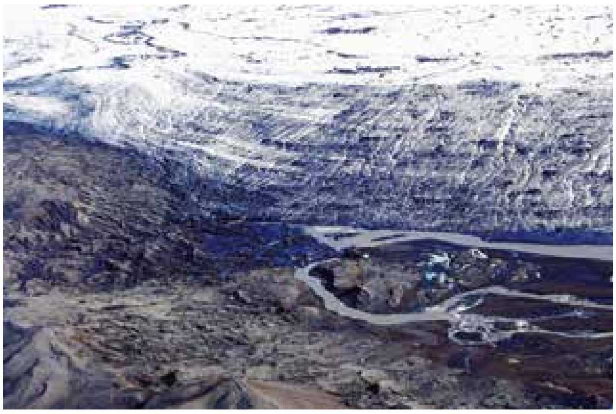


Figure 2.35.
A glacial landsystem map of Skaftafellsjökull. From Evans et al. (2017). See Appendix 1.2 for more detail.

Aerial view of the forelands of: Eyjabakkajökull, 24 October 2017 © Skarphéðinn Þórisson (top); Síðujökull, 22 September 2010 © Snorri Baldursson (middle) and; Skaftafellsjökull, 13 September 2014 © Snævarr Guðmundsson (bottom).



(King & Ives, 1955, 1955a, 1955b). More recently the ongoing recession of Morsárjökull has been associated with the intermittent delivery of rock slope failure debris to the glacier surface, the most recent spectacular event being in 2007 (Sæmundsson et al., 2011). Its foreland therefore contains details of the spatial distribution of sediment-landform associations pertaining to the operation of a typical active temperate outlet glacier of the south Vatnajökull ice cap (Evans et al., 2017; Appendix 1.3), but more specifically is an exemplar for the debris-charged glaciated valley landsystem, with characteristics further indicative of “uncovered alpine glaciers” (Benn et al., 2003). The supraglacial morainic debris supplied by rock slope failures has a short residence time in glacier systems in southern Iceland due to their strong coupling with the proglacial fluvial system and resulting efficient sediment transfer. However, areas of more substantial latero-frontal moraine still document phases of rock slope failure onto the snout and the passage of the debris to the ice margin, a process-form regime that is being observed in real time at Morsárjökull.

Tungnaárjökull

Tungnaárjökull is a 17-km wide glacier lobe of the western margin of Vatnajökull, Iceland, which periodically surges over a series of parallel volcanic bedrock ridges. The historical oscillations of Tungnaárjökull can be charted back to the late 1800s AD and annual measurements since 1955 show that the glacier underwent continuous recession until a surge over a maximum distance of 1.2 km in 1994–1995 (Freysteinsson, 1968; Sigurðsson, 1994; Andrzejewski, 2002). Historical records indicate that the glacier also surged by 1 km in 1945 and by around 450 m sometime between 1915 and 1920 (Þórarinsson, 1964; Freysteinsson, 1968).

The influence of bedrock topography on the distribution of glacial landforms and sediments prompted Andrzejewski (2002) and Evans et al. (2009b) to sub-divide the glacier foreland into areas that are characterised by distinctive landform assemblages, together comprising a surging glacial landsystem. Although local topographic constraints have resulted in some minor differences, the landform-sediment assemblages on the Tungnaárjökull foreland conform to the surging glacier landsystems model of Evans & Rea (2003). The outer zone A(cf. Fig 2.30) of thrust block moraines, hill-hole pairs and push moraines can be identified along the former margins of the 1880–1890, 1945 and 1995 surges. The intermediate zone B of hummocky moraine located on the down-glacier sides of topographic depressions and often draped on the ice-proximal slopes of the thrust block and push moraines is particularly well developed. The inner zone C, comprising long, low amplitude flutings produced by subsole deformation during the surge and crevasse-squeeze ridges produced at surge termination, is also well developed throughout the whole foreland. Intrazonal landforms of surging include ice-cored, collapsed outwash. The Tungnaárjökull foreland is an ideal modern analogue for repeat surging into areas of hard bedrock and upland ridges, and hence is a valuable variant of the surging glacier landsystem model derived from the north Vatnajökull ice lobes.

2.a (v) Wilderness and Landscape

The wilderness and landscape values found within the nominated property are rooted in the dynamic interplay between volcanism and a temperate glacier, the core of the property's Outstanding Universal Value. The wilderness values reflect the property's naturalness, integrity and pristineness, whereas the landscape values provide compelling visual evidence of the long-term creative interaction of the natural processes which have shaped the property over time. Landscape diversity is apparent on many scales and provides the foundation for diverse aesthetic experiences, ranging from pastoral to sublime. Such aesthetic appreciation is furthermore heightened by the perception of these landscapes as being inherently wild and free, created solely by Nature and neither modified nor controlled by human agency.

A prime motivation for the establishment of Vatnajökull National Park in 2008 was to conserve a large, intact area in pristine condition, both for the sake of nature itself and for the benefit of present and future generations of humans. Most of the park (95%) lies within the boundary of the central highlands (defined as the land above homelands, at 400–500 m above sea level), a plateau which covers around 40% of the total land area of Iceland. The central highlands have never been permanently inhabited by man and were until the mid-20th century a remote and inaccessible area, without roads or other man-made infrastructure. Excluding Svalbard, the Icelandic central highlands are the largest remaining wilderness in western Europe (Box p. 106).

The eastern half of the central highlands, containing Vatnajökull National Park, has remained much less developed than the western half and its naturalness has therefore not been compromised to any significant extent. The northern perimeter of Vatnajökull and the

From Tungnaáröræfi wilderness, 25 July 2011 © Snorri Baldursson.

areas immediately to the north of it were once part of the largest untouched wilderness of Iceland. The Kárahnjúkar hydropower plant, with its dams, Hálslón reservoir and other infrastructure, has resulted in the insertion of a 3000 km² wedge of human landscape modification into this wilderness.

Aside from the large Hálslón and subsidiary reservoirs, infrastructure found in this part of the highlands is low-key and almost exclusively related to outdoor recreation and tourism, mostly taking the form of discreet overnight huts, campsites and ranger stations operated by regional touring associations or the park itself. In most cases, these services are assembled into one place, thus minimising landscape fragmentation and wilderness degradation. A simple system of gravel roads runs to and between service areas. The policy of Vatnajökull National Park is to keep roads to the bare minimum and to retain their primitive state. Roads are furthermore only open during the summer, i.e. from around mid-June to the end of August, being snowed in for the remainder of the year.

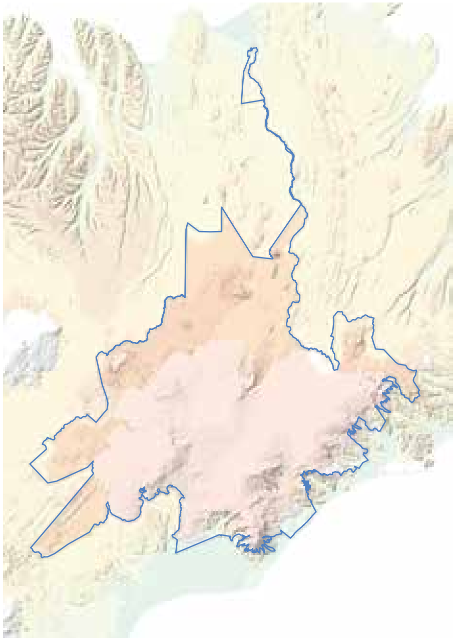


Figure 2.36.
Wilderness map of the nominated property. Wilderness areas are denoted by a orange overlay. The areas with no colour overlay are impacted by infrastructures such as service areas, huts, main roads and reservoirs. The impacts of these structures differ depending on their size and function. For example, the Hálslón reservoir of the Kárahnjúkar power plant in the northeastern part of the property has a much larger impact than e.g. a small round-up hut. Source: Árnason et al. (2017). See larger map in Appendix 1.1.

Iceland and Finland are the only European countries, so far, that have established national legislation concerning wilderness protection. In Iceland, this legislation dates to 1999 but was revised in 2015, after the current Nature Conservation Act No. 60/2013 came into effect. The act defines wilderness in the following way: "an area of uninhabited land that is usually at least 25 km² in size or so that one can enjoy solitude and nature without disturbance from man-made structures or the traffic of motorised vehicles and at least 5 km away from man-made structures and other evidence of technology, such as power lines, power stations, reservoirs and main roads." (translation, Jóhannsdóttir 2016).

In 2016, the first National Planning Strategy of Iceland was approved. One of its mandated tasks is to develop a map of wilderness areas, based on the revised legal definition. The first map of this sort has recently been released, focusing on the central highlands (Fig 2.36; Árnason et al., 2017). According to this map >90% of the highland area of Vatnajökull National Park is wilderness. As the map does not yet extend to lowland areas, a definitive statement cannot be made about the remaining (5%) of the park. However, much of the lowlands within the park are largely undeveloped, retaining most of their natural integrity. In total, it is safe to assume that around 85% of the nominated property is wilderness according to Icelandic law.

The wilderness character of the nominated property is not primarily related to ecology and biodiversity sensu Kormos et al. (2017), as is the case for many large protected areas around the globe, including World Heritage sites. In contrast, its wilderness character is more related to landscape- and aesthetic values. In this sense, the highlands of Vatnajökull National Park may be regarded as "perceptual wilderness". Vegetation and wildlife is scarce and most of the area is a de facto desert, albeit with several biologically important oases (see section 2a (vii)). However, there are many and diverse landscape features resulting from the ongoing interaction of unrestrained geophysical processes, several of which are rare or even unique globally. These landscapes evoke the feeling of sublime beauty and the sense of being created before one's eyes (Box p. 110).

The results of the first systematic landscape survey conducted in Iceland reveal that Vatnajökull National Park contains within its

The central highlands of Iceland (verbatim from Þórhallsdóttir, 2002)

Historical and archaeological evidence shows that farming was attempted in parts of the central highlands of Iceland first after the settlement of the country (9th to 11th century A.D.), but proved unsustainable and was soon abandoned (Þórarinsson, 1974b). Hence, most of the highland has never been inhabited or farmed, although it has traditionally been used for summer grazing of sheep.

The Icelandic wilderness differs from its closest latitudinal counterparts in Scandinavia, America, and Greenland, in that it does not, nor has it ever had, an indigenous population. The three words used to describe the central highlands each reflect the Icelanders' sentiments towards the inland. The two traditional words are "óbyggðir", meaning "uninhabited land" and "öræfi", meaning "wasteland". The third word is used in the recent Icelandic wilderness protection legislation; "víðerni", meaning "a land of distant views".

The central highlands rise behind Icelanders in a literal and in an abstract sense. Farms often form a single line on the lowlands, facing either the sea or a valley bottom. Behind the farm, steeply rising mountains, scree slopes, and cliffs divide the inhabited from the uninhabited, and the known and predictable from the mysterious and untamable. The highland was a place where man was tested to his limits and often lost. Countless stories, poems, and legends tell of hazardous journeys through the highlands and of the ghosts of those who perished on the way, haunting travellers in mountain huts or visiting people in their sleep to complain about their fate. Other poems praise the landscape, the vistas, and the freedom; fertile valleys were supposed to nestle up against the glaciers, inhabited by terse people sometimes willing to help a traveller in distress. Farmers had to venture into the highlands once a year to collect the sheep in September, and this was one of the highlights of their whole year.

Undeniably, the central highlands play a significant role in the national identity of Icelanders. A recent comparative survey in three Scandinavian countries (Iceland, Denmark, and Sweden) demonstrates this; when asked what participants felt was the single most important common national heritage, landscape came first in ahead of language and history.

As a wilderness experience, Iceland is quite distinct from Scandinavia or Alaska. It cannot offer encounters with large animals, or the opportunity to observe them in the wild or in large numbers. Its scale, 40,000 to 50,000 km², is of course less daunting than truly great wildernesses of the world. The Icelandic highlands can be traversed centrally through their shorter axis in one day with about 300 km between the last farm in the south and the first in the north. While they may not have any landscape types that are truly unique, the central highlands of Iceland offer a more diverse visual experience than is available in most other countries. They are a rich mosaic of colours, landforms, and textures on a scale that can be sampled in a car journey of 3–5 days.

The central highlands may be unrivalled as a virtual textbook on the processes shaping the surface of the earth through the action of glaciers, volcanoes, wind, and water. The resulting landforms are presented with great clarity because of their recent age and lack of vegetation. It is a land that simultaneously looks ancient and is obviously still being created. The second distinctive feature of the central highlands is their openness. It is a totally treeless landscape, often with a monotonous foreground but spectacular distant views of glaciers and blue mountains framing the horizon. The long expanses of rolling, dark grey, basaltic moraines are broken by oases of vegetation in the depressions, often dominated by willows, angelica, geranium, and other herbs, usually with springs and running water. The greens of the vegetation and the deep blue of the spring water contrast sharply with the surrounding desert.

Although much of the highlands are covered by basaltic moraines, there are areas offering a different scenario. Several rhyolitic areas, usually displaying geothermal activity, are characterised by multi-coloured, striated mountains in bright tones of yellow, pink, green, and blue. North of Vatnajökull, in parts of the 3400 km² Ódáðahraun lava field, fields of tortuous black lava are half submerged in shining yellow pumice.

The Icelandic central highlands are mostly harsh, often hostile, and in some places decidedly alien compared to most other parts of the world. It is clearly a place where man does not belong. In all the 1100 years of human history in Iceland, only two people (a couple in the mid-18th century) are known to have been able to carve out a living there. Except for tracks and occasional mountain huts, much of the central highlands remains free of visible modern technology.

Next page: Aerial view over Eyjabakkajökull, Eyjabakkar and Mt. Snæfell © Skarphéðinn Þórisson.

borders six of the eleven main landscape types identified, indicating a high level of landscape diversity on national level (Þórhallsdóttir et al., 2010). A more recent analysis of landscapes within the central highlands shows that the park contains seven out of nine landscape types identified on this regional scale (Hoffritz, 2017). Some of these types cover large areas and thus comprise entire landscape units.

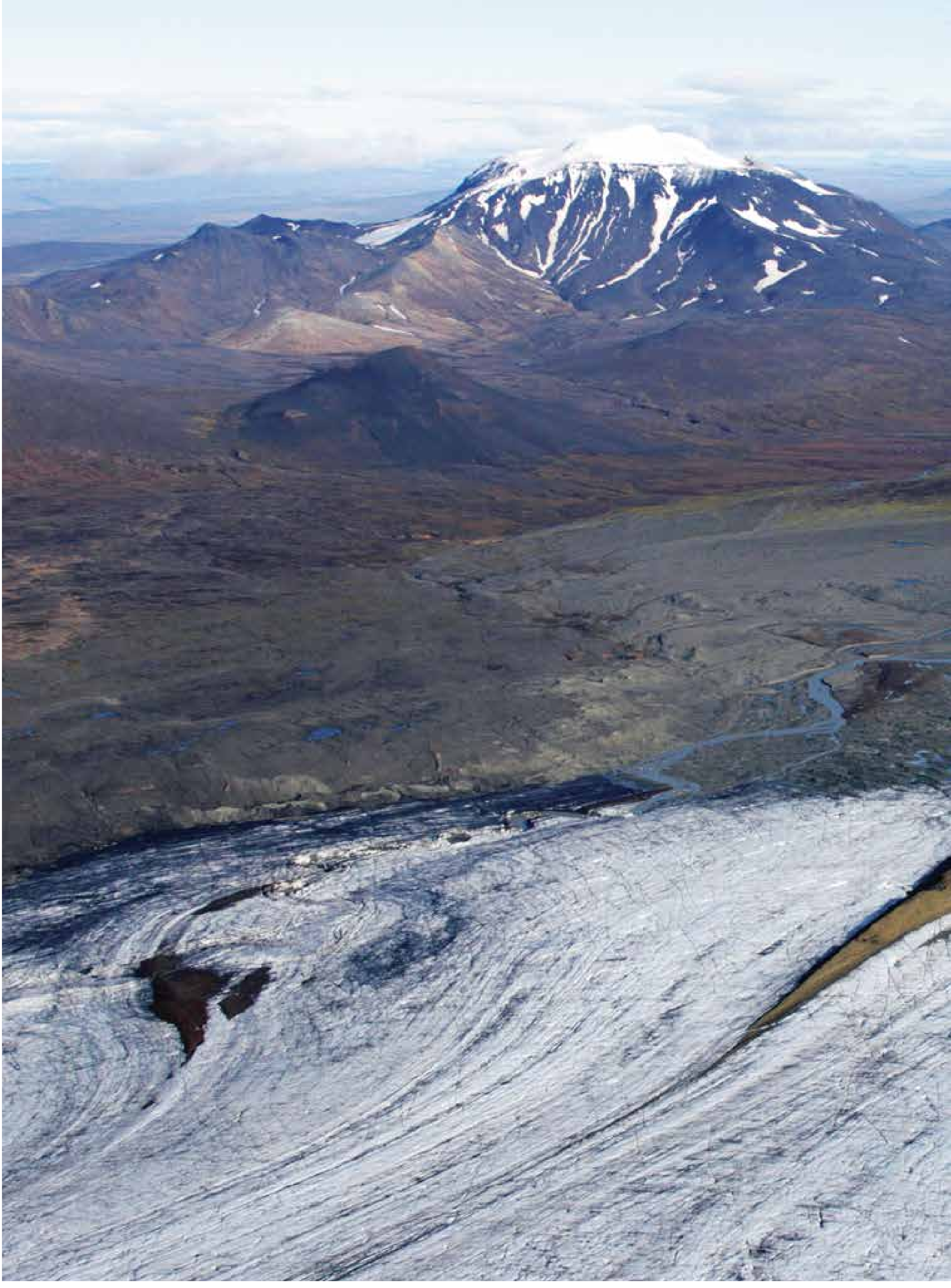
However, the said nationwide and regional analyses do not do complete justice to the landscape diversity found within the park, as this can be locally very high, typically where there is or has been strong interaction between contrasting geophysical processes. Furthermore, although many of the landscape types found in Vatnajökull National Park (e.g. lava fields, geothermal areas or glacial landscapes) are common in Iceland, most of them are globally rare. It is also highly unusual in a global context to find so many rare landscape types grouped together in a refined space.

The beauty of evolving landscapes

The landscapes of Vatnajökull National Park (and Iceland as a whole) are characterised by the ease of access and visibility of the ongoing geological processes and the resulting landscape features. Because of sparse vegetation and thin soil cover, volcanic outcrops are characteristically clean and beautifully exposed. Sensing the Earth's history through direct contact with the elements can offer an opportunity for a variety of profound aesthetic experiences. The senses are captured and one is drawn into the moment of being possessed or even overwhelmed by beauty.

Beauty refers to the moment when we perceive just to perceive, when we look to the sky to admire it and not to check how the weather will be. It refers to the type of relation created when a certain objective reality, colour, smell, or distinct forms in the landscape, capture the attention in a way that is impossible to escape. At such moments, a decentring of the self may occur and one senses oneself as a part of the perceived environment (Jóhannesdóttir, 2016). However, aesthetic experiences are of many kinds as explained by Brady (2010; Box p. 110).

The aesthetic experience of the sublime natural beauty of rapidly evolving landscapes, such as found within the nominated property, differs from experiences that are built on viewing nature only in terms of "standing reserve", i.e. as something unchangeable (Heidegger, 1996, p. 318). In this respect, the aesthetic value of Vatnajökull National Park is of no less importance than its scientific value. It is not only a scientific gem in terms of glacial geomorphology (Evans, 2016), but also an aesthetic gem and a flagship location for having profound aesthetic experiences where people's spiritual and moral understanding of nature and its creation can be initiated and developed (Jóhannesdóttir, 2017, personal communication). In our times of a global environmental crisis such understanding is more urgent than ever.



The “terrible beauty” of Vatnajökull National Park

Beauty is at the core of aesthetic experiences that come in many variants. They can be described in terms of wonder, the sublime, joy or serenity. Even ugliness and terror are part of the aesthetic scale. In her paper The Sublime, Ugliness and “Terrible Beauty” in Icelandic Landscapes, Emily Brady notes: “We can position beauty, the sublime and ugliness along a scale of positive and negative aesthetic value. On the positive side of the scale are varieties of beauty (including “terrible beauty”), with sublimity somewhere in the middle, and varieties of ugliness lying on the negative side” (Brady, 2010, p. 130). Brady has also argued that the concept of the sublime suits well to describe Icelandic landscapes: “vast lava fields, glaciers, barren, treeless mountains, stunning calderas and so on provide cases of the contemporary sublime [...] (Brady, 2008, p. 54)”. The main reason why Icelandic landscapes create the feeling of the sublime according to Brady is that this nature is young geologically, it is always moving and being re-created and this fact awakens the imagination easily. As a glaciovolcanic area, the nominated property is still very much in the becoming.

The landscapes of the nominated property are extreme landscapes that can be contrasted with the more common landscapes of towns, cities, rural areas, woodlands, parks and valleys. As Brady has pointed out “difficult” aesthetic experiences of extreme landscapes are more likely to expand and enrich our aesthetic experiences than the more easy and positive appreciation of for example rural landscapes or woodlands. By “difficult” she is referring to “aesthetic responses which involve feelings of unease, discomfort, something being unresolved or somehow unfitted to our capacities, as well as experiences which take unusual effort or are challenging in some way” (Brady, 2010, p. 125).

Páll Skúlason and Sigríður Þorgeirsdóttir have also observed that difficult experiences can provide an opportunity for metaphysical experiences (Þorgeirsdóttir, 2010) and the possibility for a spiritual understanding of nature (Skúlason, 2008).

The results of a qualitative study, where the aim was to shed light on aesthetic experiences of glacial and geothermal landscapes in Iceland (Jóhannesdóttir, 2015), support Brady’s claim that Icelandic landscapes provide cases of the contemporary sublime. The study, conducted partly within the nominated property, i.e. in Kverkfjöll and on Svínafellsjökull and Falljökull outlet glaciers, demonstrated that experiences of these extreme landscape types are characterised by the feeling of wonder and awe, and an experience that could be described by the notion of the sublime; a journey through the aesthetic scale that Brady describes. Moving up the glacial outlets of Vatnajökull, the moraines, the menacing moulins, the small holes in the ice filled with clear-blue water, the sound of the water running through the ice, the smell of the cold air, and the forms created by wind and water in the ice capture one’s attention in such a way that it creates a strong feeling of beauty, wonder and awe or even terror. The forms and the atmospheres created by them are so rare and different from most people’s everyday environments.

Interplay of steam and ice at Efri-Hveradalur, Kverkfjöll, 13 August 2017 © Snorri Baldursson.

2.a (vi) Soil

Vegetated soils of Iceland are characterised by basaltic Andosols, while Vitrisols (weathered tephra) and Leptosols (gravel) characterise denuded and desert areas. Active aeolian processes, frequent tephra falls, and a sub-arctic climate with freeze-thaw cycles greatly modify the Icelandic soils and make them quite exceptional and difficult to assign to global classification schemes.

Leptosols, Vitrisols and Glaciers dominate the soil types of the highland areas of the nominated property, and throughout the neovolcanic zones of Iceland, while brown Andosols are most common in lowland areas (Fig 2.37). Organic Histosols (peat) are mainly found in the older stratigraphic series of Iceland, east and west of the neovolcanic zone (Arnalds, 2008) and may be considered rare within the nominated property. However, the nature of Icelandic Andisols allows for a great capability of storing carbon due to their mineralogical properties, the frequent burial of horizons by tephra fall and a relatively cool climate (Arnalds, 2015).

The sandy deserts of Vatnajökull National Park

The sandy deserts of the Icelandic central highlands and the nominated property are among the largest volcanic desert surfaces on Earth (Edgett & Lancaster, 1993; Arnalds et al., 2001). Darkly coloured or black deserts such as those dominating the land

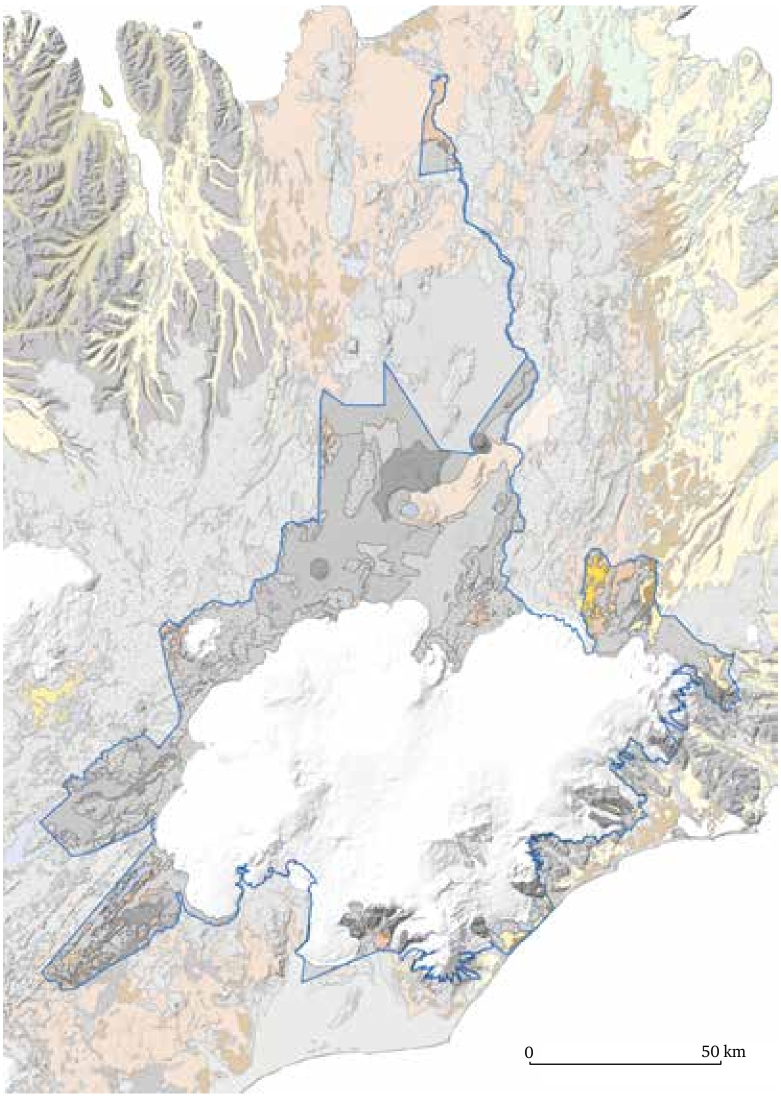


Figure 2.37.
Soil map of the nominated property. Source: The Agricultural University of Iceland. See larger map in Appendix 1.1.

north and west of Vatnajökull are globally unique. The surface materials are of various types, including recent lava fields, tephra, sandur (outwash plains), sandy lavas and sandy lag gravel. Recent rough-surfaced lavas act as an entrapment for advancing sand and volcanic ash until they are full and become what is termed "sandy lavas". Aeolian materials also accumulate in the older glacial till, creating the "sandy lag gravel" surfaces.

Some of the areas that are now deserts, such as the areas north of Askja, were vegetated in previous times (Arnalds, 1992). Their desertification is attributed to lowering of ecosystem resilience by sheep grazing, with subsequent destruction by volcanic ash deposition, mainly from the Veiðivötn eruption in 1477. Closer to the ice cap, there are sandy deserts formed by purely natural processes, with most of the sand originally deposited by jökulhlaups or as volcanic ash during eruptions. The surfaces are unstable and continue to emit and receive aeolian materials. Desert conditions are maintained by a combination of factors. These include a lack of seed sources and instability of the surface, which prevents natural succession – young seedlings are either killed by moving sand or uprooted by frost heaving and needle-ice formation – and poor water retention compared to soils of vegetated systems in Iceland, making these surfaces vulnerable to periodic draughts. In fact, the black sand surface may, in direct sunlight, heat up to over 50°C. The resulting rapid water evaporation can lead to the formation of low-pressure systems over the highland desert areas (Ashwell, 1986).

The existence of desert surfaces under the sub-arctic conditions prevalent in the Icelandic highlands is somewhat of a paradox and shows that common definitions of deserts based on rainfall only are inadequate, and that the fate of water in the ecosystem is more important than rainfall per se.

Soil formation in front of receding outlet glaciers

Apparent changes within the young glacier forefields of southeastern Vatnajökull include the colonisation of plants and the commencement of soil formation. Climate, parent material, biota, topography and time are generally considered the most important factors influencing soil formation (Jenny, 1941). The climate southeast of Vatnajökull is mild oceanic (Einarsson, 1984), and the parent material of the glacier moraines is mainly basaltic rocks from volcanic eruptions (Jóhannesson & Sæmundsson, 2009).

The location of the glacier termini, determined from morphological features, maps and aerial images, creates a baseline and age chronosequence for vegetation succession and soil formation in the glacier forefields. Thus, a chronosequence is a space for time substitution, creating ideal settings for estimating the rate of change (Jenny, 1941; Matthews, 1992). The ample precipitation, mild climate and high chemical weathering rates of the basaltic rocks and tephra create excellent conditions for soil forming processes, where secondary clay minerals are formed (Egli et al., 2010; Gíslason, 2008). The proglacial areas of southeast Vatnajökull are therefore ideal sites for studying volcanic Andosol development. This has been studied in the forefields of two outlet glaciers of southeast Vatnajökull: Skaftafellsjökull, a relatively small and sheltered outlet glacier (Vilmundardóttir et al., 2014a, 2014b) and Breiðamerkurjökull, the fourth largest outlet glacier in Iceland (Björnsson, 2009; Vilmundardóttir et al., 2015).

Soil development

Over time, morphological, physical and chemical processes alter the moraine material. Finer grains are translocated by wind and water, plants establish on the surface, and organic material accumulates in the soil creating an AC horizon sequence in the older moraines. The dark brown coloured A horizon represents the soil with the highest biological activity by both plants and fauna while the C horizon is the parent material. The A horizon is thickest on the oldest moraines of Skaftafellsjökull, while it remains much thinner throughout the chronosequence in the Breiðamerkurjökull forefield.

The initial values of soil pH measured in H_2O were around 8 or higher (Table 2.3), an effect of the basaltic material and lack of influence from precipitation (Gíslason & Eugster, 1987). The soil pH lowers steadily over time and is the only parameter to reach a steady state, around 6, over the 120-year study period. The soil pH is lower in the topsoil due to the influence of plants and precipitation. Carbon and nitrogen accumulate over time as plant detritus is broken down and its elements incorporated in the soil (Brady & Weil, 2004). The youngest moraines contain very little carbon and nitrogen, but the oldest soils of Skaftafellsjökull have the highest concentrations of 1.8% C and 0.1% N (Table 2.3).

Although the span of the chronosequences is only around 120 years, there is also a noticeable and significant increase in the concentration of secondary clay minerals forming in the soils by chemical weathering (Vilmundardóttir et al., 2015).

Table 2.3.
Selected soil properties of moraine soils and comparative properties of the soils under birch woodland found closest to the two glacier forefields at Skaftafellsheiði and Stórihnaus close to Kvísker. From Vilmundardóttir et al. (2014a); Vilmundardóttir et al. (2015).

Depth (cm)	Age (years)	Bulk density (g/cm^3)	OM %	C %	N %	pH H_2O
Skaftafellsjökull						
0-10	8	1.4	0.8	0.1	<0.01	7.4
0-10	65	1.3	1.3	0.3	0.02	6.5
0-10	120	1.1	2.7	1.8	0.10	5.7
0-10	Birch woodland	0.5	16.8	6.6	0.49	6.0
Breiðamerkurjökull						
0-5	0	1.2	0.6	0.0	0.00	8.3
0-5	8	1.2	0.6	0.0	0.00	7.0
0-5	67	0.8	2.8	1.1	0.05	6.0
0-5	122	1.0	2.5	1.0	0.05	6.0
0-5	Birch woodland	0.6	22.1	10.3	0.45	5.3

The development of soils is a slow process. When the proglacial soils are compared to those under mature birch woodlands, for example in Skaftafellsheiði, it may be assumed that more than two or three centuries are needed for the soils to attain the properties of typical well drained volcanic soils under robust vegetation. This is evident in the high bulk density values, low organic matter, C and N values and low concentrations of aluminium and iron (Table 2.3).

The proglacial forefield of Breiðamerkurjökull is a showcase of how seabirds can bring nutrients in from the marine environment and impact the young, developing terrestrial ecosystem, and it is somewhat parallel to the study settings on the volcanic island Surtsey (Magnússon et al., 2009).

Although the carbon accumulation rates are slower than in sites of reclamation or young forests, the natural vegetation succession and soil formation occurring within the estimated 1285 km² of deglaciated forefields are of high value as a sink of carbon (Sigurðsson et al., 2013; Vilmundardóttir et al., in print).

Avifauna speeds up soil formation

The rates of soil formation within the Breiðamerkurjökull forefield are considerably slower compared to Skaftafellsjökull. However, "hot spots" for soil formation with lush vegetation and thick, nutrient rich topsoil are found within Breiðamerkurjökull's moraines. These spots are bird hummocks, forming on sites where seabirds regularly perch and defecate. The great skua, *Stercorarius skua*, and the Arctic skua, *Stercorarius parasiticus*, have colonized the proglacial moraines, and the Breiðamerkursandur outwash plain is one of the largest breeding grounds for the great skua (Lund-Hansen & Lange, 1991). These hummocks highly contrast with the surrounding moraines, both regarding vegetation and the underlying soils, and have formed on surfaces as young as 18 years old. Because of the enriched soils grasses thrive well in these hummocks, creating a dense but fine root system. The vegetation traps sediments and this leads to rapid accumulation of nutrients and soil as shown by high N values compared to the surrounding moraines (Table 2.4). Bird hummocks have been described from other parts of the world but are

Table 2.4.
Selected soil properties of the bird hummocks on the moraines of Breiðamerkurjökull. From Vilmundardóttir et al. (2015).

Depth (cm)	Age (years)	Bulk density (g/cm³)	OM %	C %	N %	pH H_2O
0-5	18	0.8	2.9	1.3	0.09	6.2
0-5	30	0.5	8.0	3.8	0.34	5.3
0-5	82	0.6	17.0	9.1	0.59	5.6
0-5	122	0.3	13.6	6.1	0.40	5.5

2. a (vii) Climate

The climate of the nominated property is diverse and reflects the fact that it extends across Iceland, from north to south, includes Iceland's largest ice cap, and spans elevations from sea level to the country's highest point. Its landscapes, mountains and glaciers also greatly influence the weather.

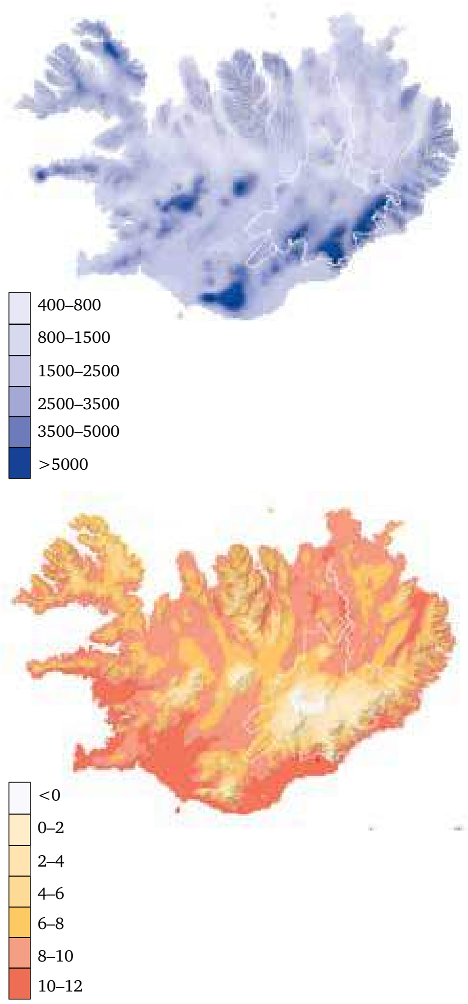


Figure 2.38.
Mean annual precipitation in mm(top) and mean July temperatures in °C (bottom). Source: Icelandic Meteorological Office.

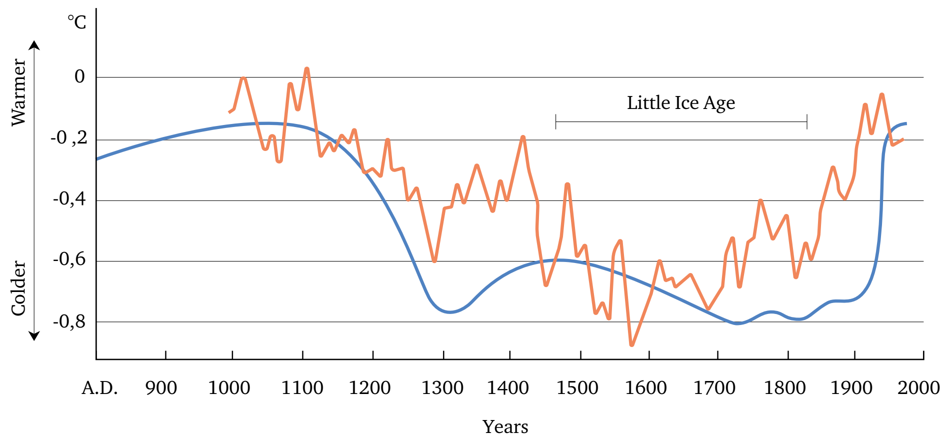
The climate in Iceland is influenced by the atmospheric circulation of the North Atlantic area and the oceanic boundaries defined by the warm Irminger current and the cold East Greenland current (e.g. Einarsson, 1984; Ólafsson et al., 2007). The temperate Icelandic ice caps and glaciers are sensitive to variations in the climate (e.g. Aðalgeirsdóttir et al., 2005; Flowers et al., 2005; Björnsson et al., 2013). The warm North Atlantic current results in a milder climate than expected given the global position. Iceland lies in the northern part of the North Atlantic storm track, and high amounts of precipitation are delivered to the country's glaciers. The precipitation, along with the rugged terrain and relatively low temperatures, control the location of the main ice caps (Fig 2.38).

Temperature proxies from oxygen isotopes in ice cores from the Greenland ice sheet have been used to estimate the history of past climate in the North Atlantic region and are believed to reflect the conditions in Iceland quite well (Björnsson, 2017; Fig 2.39). Accordingly, the climate was coldest from ca. 1450 til the end of the 19th century, during the Little Ice Age. From the settlement of Iceland (about 874 CE) until the 13th century, the climate was similar to the period from 1920 to 1960, with mean temperatures ca. 1°C higher than during the coldest parts of the Little Ice Age, but probably ca. 2°C lower than the warmest period of the Holocene. Few areas in Iceland have been affected by the climate fluctuations of the last few hundred years to the same extent as southeast Iceland. During the Little Ice Age the climate grew colder and glaciers expanded to an unprecedented size in historical times.

<u>Climate of the nominated property</u>

Several automatic meteorological stations have been operated on Vatnajökull every summer since 1994. Atmospheric temperature, humidity, radiation, wind and variations in snow depth or changes in the elevation of the ice surface are measured at the stations. Heat flux available for melting is calculated from the measurements. The results of these measurements indicate that during the ablation season (from June to mid-September), radiation usually

Figure 2.39.
Annual mean temperatures in Iceland over the last 1100 years. The Little Ice Age (ca. 1450–1900) is clearly indicated. Iceland enjoyed a warm climate in the first centuries after settlement (870–1262) and again during the last century or so (1918–2017). Orange line, temperature proxies based on oxygen isotopes in ice cores from the Greenland ice sheet. Blue line, estimate from Þórarinsson (1974b). Modified after Björnsson (2017).



provides two thirds of the melt energy, and the rest is due to heat flux from turbulent air currents. In the higher parts of the ice cap, the heat flux brought by winds becomes proportionately less important.

On the ice cap, katabatic wind is dominant, i.e. air that has cooled, by radiation or by melting snow and ice, sinks and slides down the sides of the ice cap in all directions. The air becomes warmer on its way, and when it reaches the glacier margin it can be either warmer or colder than the air lying over the highland plain. The former situation is more common in winter, when the snow-covered highland area cools about as fast by radiation as the ice cap does. And the latter is typical in summer when cold air streams off the glacier, out onto snow-free land warmed by the Sun.

Energy arriving as radiation from the Sun is absorbed, reflected and emitted by the Earth; the balance of this is called the radiation budget, and it is different for snow-covered and snow-free ground. Dark-coloured, dry lava fields north and west of Vatnajökull ice cap exaggerate this difference in the summer. The vast sandur plains cool rapidly under clear skies when the Sun is below the horizon, but they warm up quickly in the sunshine of long summer days. Thus, the desert highland areas of the nominated property have large daily fluctuations in temperature, wind and vertical air movement. Above the ice cap, the diurnal temperature oscillation is much smaller, surface cooling takes place most of the time, solar energy melts the snow or ice surface but the air temperature changes little (Trausti Jónsson, 2017, pers. comm.).

Precipitation

Southerly winds bring most precipitation to Iceland, while easterlies are most common. This means that southeast Iceland enjoys the highest precipitation in the country. Furthermore, the precipitation increases with surface elevation in places where mountains enhance the updraught and condensation. In the lowlands, most precipitation occurs east of Öræfajökull, with a yearly average of over 3000 mm in many places. West of Öræfajökull, at Skaftafell for example, there is much less precipitation. In the western region of the property, precipitation is more moderate; the easterly winds there are drier, and although the southeast wind often brings rain, winds from the south and southwest are more common. In the northern region, there is much less precipitation – some areas north of the ice cap are the driest in Iceland, with an average annual precipitation of only 300–400 mm, most of it coming from the north. In the eastern region of the property, precipitation is also highest in northerly winds; but going eastwards, precipitation in easterly winds is most important (Trausti Jónsson, 2017, pers. comm.).

Precipitation is greatest in the autumn and winter, and less in the spring. Unexpectedly, the midsummer precipitation contributes proportionally more to the annual total in the area north of Vatnajökull, compared to the rest of the country. At weather stations in the highlands north of the ice cap, the July precipitation is about 10% or more of the annual total, but in most other parts of Iceland it is only 5–7%. Afternoon showers probably play a part in this. On the Vatnajökull ice cap, the average annual precipition is 4000–5000 mm (at maximum close to 8000 mm) (Guðmundsson, 2000; Crochet et al., 2007).

Next page: Dettifoss, 17 July 2013 © Snorri Baldursson.

Temperature

Although a maritime climate dominates in Iceland, seasonal fluctuations in temperature are greater away from the coast and in the highlands. The same can be said about the diurnal fluctuation in temperature: it is greatest on flat, dry areas in the highlands, and least on islands and peninsulas. The diurnal temperature fluctuation is also smaller on the glaciers than in the adjacent area. Over the high summer, in July and early August, night frosts are uncommon, but local conditions can make them more likely (Trausti Jónsson, 2017, pers. comm.).

Fig 2.40 shows the mean monthly temperatures of the last ten years for selected stations within the nominated property. Not surprisingly the lowland sites of Skaftafell in the south and Ásbyrgi in the north enjoy the mildest climate, while the highland sites at Upptyppingar in the northern central highlands and Jökulheimar west of the ice cap suffer the coldest climate. The temperature curve at Skaftafell is the flattest, with mean temperatures not going below zero for any month. Summer temperatures are similar in Skaftafell and Ásbyrgi but the winters are considerably colder at Ásbyrgi. The data span the last ten years, and it should be borne in mind that these were quite warm in a long-term context.

Wind

Although, easterly winds dominate in Iceland, the landscape determines the wind direction at a given location within the nominated property, especially in gentle wind. There is also a large difference between the coast and farther inland. True sea breeses are of little importance in the highlands north of Vatnajökull, but more significant closer to the coast. There is a great variation in the frequency of high winds. At the weather stations within the property, high winds are about twenty times more frequent in the windiest places than they are in the calmest. The likelihood of high winds is generally greatest near high mountains and in barren areas. Some locations to the south of the ice cap are well known for extraordinarily strong winds and wind gusts that sometimes distrupt traffic along the ring road south of the ice cap and damage cars and buildings.

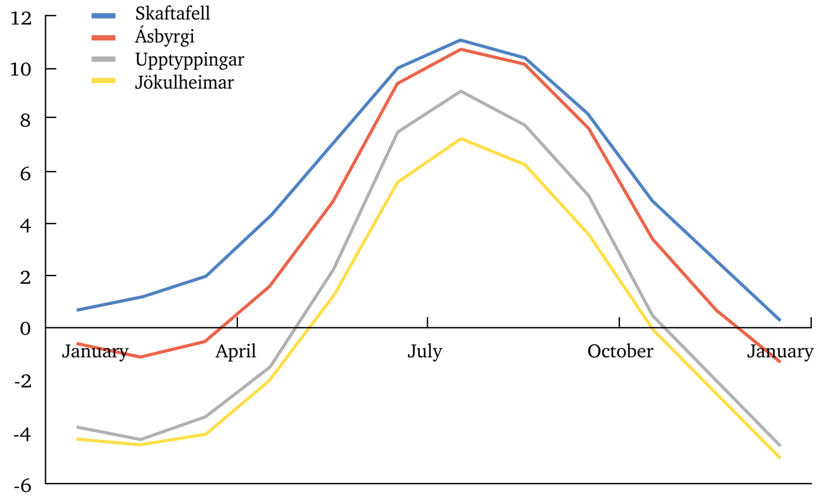


Figure 2.40.
Mean monthly temperatures at four weather stations within Vatnajökull National Park. Skaftafell and Ásbyrgi are lowland stations in the south and north, respectively. Upptyppingar and Jökulheimar are highland stations, north and west of the ice cap, respectively. Source: Icelandic Meteorological Office.

2.a (viii) Hydrology

A striking feature of the hydrology of the nominated property is the lack of surface runoff and rivers within the neovolcanic zones consisting mainly of porous lavas, hyaloclastite formations and other geologically recent volcanic products. The top sediment or soil layer, if any, is mainly sand and volcanic pumice or ash. Precipitation and meltwater percolate quickly into the permeable top layer and run underground for long distances, often along tectonic fractures, and then surface as springs and spring horizons, or enter directly into the sea. In contrast, the permeability of the older bedrock is low, causing the precipitation and meltwater to remain on the surface and collect into rivers.

Simulated average annual runoff (1 September to 31 August) for all of Iceland covering the water years 1961–1990 is estimated as 4770 m³/s (Jónsdóttir et al., 2008), which corresponds to 1460 mm/year average precipitation if evaporation is neglected. These results are consistent with precipitation modelling for the periods 1961–1990 (Crochet et al., 2007), with a simplified model for orographic precipitation, and 1981–2010, using the Harmonie meteorological model (Icelandic Meteorological Office, unoublished data), when evaporation is considered.

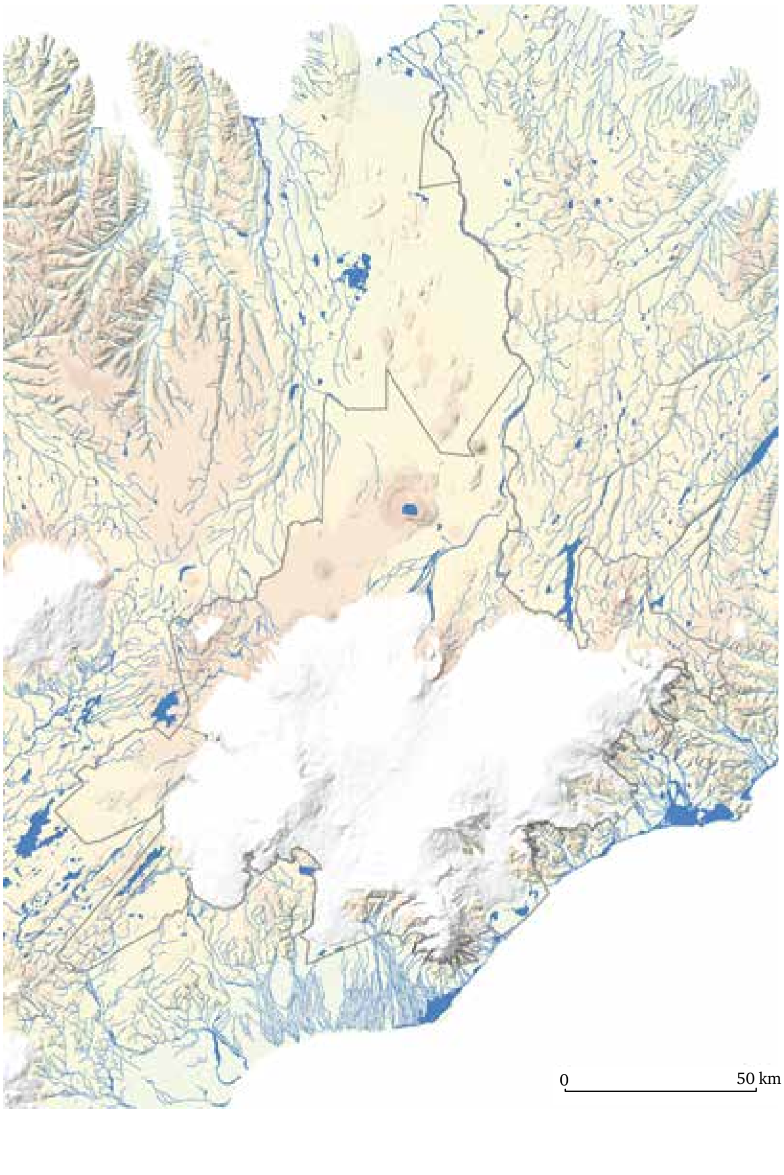


Figure 2.41.
Distribution pattern of surface runoff within the nominated property and eastern Iceland, showing clearly the "dry" neovolcanic zones where rain water percolates quickly into the ground. Source: Icelandic Meteorological Office.

Next page: Aerial view over Jökulsá á Fjöllum, close to Mt. Herðubreið, 13 August 2017 © Walter Huber.

Springs entering the riverbed of Jökulsá á FJöllum some 20 km downstream from the glacier. The red curve indicates the boundary of the new Holuhraun lava field from 2014–2015 © Oddur Sigurðsson.

Synergetic effects of geology, topography and vegetation govern the hydrology of Iceland. A map of Icelandic rivers illustrates the spatial distribution of surface runoff in the country (Fig 2.41). A striking feature is the lack of rivers in areas that lie within the neovolcanic zones where the bedrock material consists mainly of porous lavas, hyaloclastite formations and other geologically recent volcanic products. The top sediment or soil layer, if any, is mainly sand and volcanic pumice or ash. Precipitation and meltwater percolate quickly into the permeable top layer and run underground for long distances, often along tectonic fractures, and then surface as springs and spring horizons, or enter directly into the sea. In contrast, the permeability of the older bedrock is low, causing the precipitation and meltwater to run on the surface and be collected into rivers.

Within the nominated property three main types of rivers can be identified, glacial rivers, direct runoff rivers and spring fed rivers (Fig 2.42), each with distinct characteristics reflecting different geo-hydrological conditions.

Figure 2.42 illustrates the large impact of glacial melting during the spring and summer period. Virtually all the discharge at the gauging station Lónshnjúkur in Kreppa, one of two main tributaries of Jökulsá á Fjöllum, is caused by snow and glacial melting. The river responds very quickly when the melting starts in spring. Farther downstream in Jökulsá á Fjöllum, at the gauging station Upptyppingar, the discharge reflects underlying spring fed base flow for extended periods and a more damped response to snow and glacial melting. The spring fed river Svartá remains unchanged over the year while the direct runoff river Geirlandsá (Flatarhylur) responds mainly to precipitation and lacks a contribution from glacial melt.

As noted, there is a striking difference in hydrology between the active Northern Volcanic Zone, where most rain and snowmelt seeps quickly into the ground and flows as groundwater, and areas of older bedrock (Fig 2.41). In the case of Jökulsá á Fjöllum (photo to the left), the groundwater surfaces into the riverbed at around 20 km downstream of the glacier outlet. Either branch seen on the photo contains around 20 m^3/s of spring water, which is about double the consumption of water in Iceland. The groundwater

Fig 2.42.
Four distinct discharge types of rivers within the nominated property. Source: Icelandic Meteorological Office.

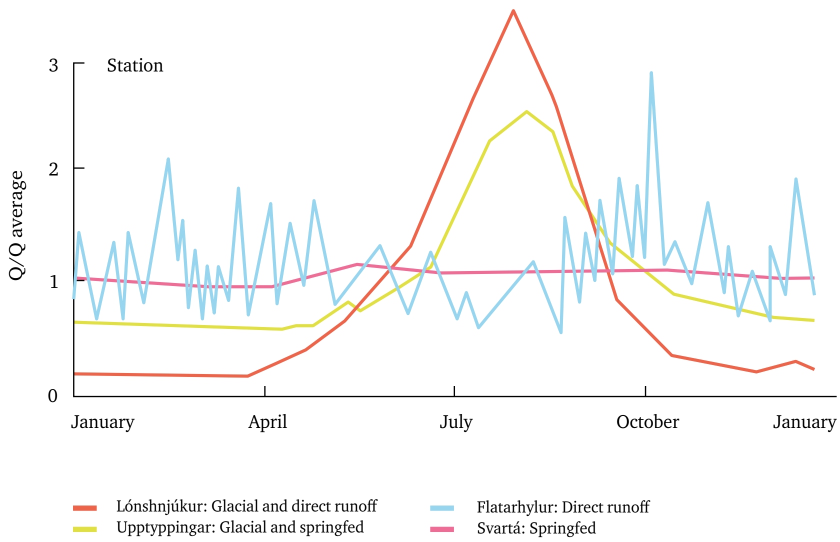


Figure 2.43.
Direction and magnitude of modelled groundwater flow (arrows) and the main spring areas (blue spots) within the northern and western parts of the nominated property, or where data is available. Source: Vatnaskil Engineering.

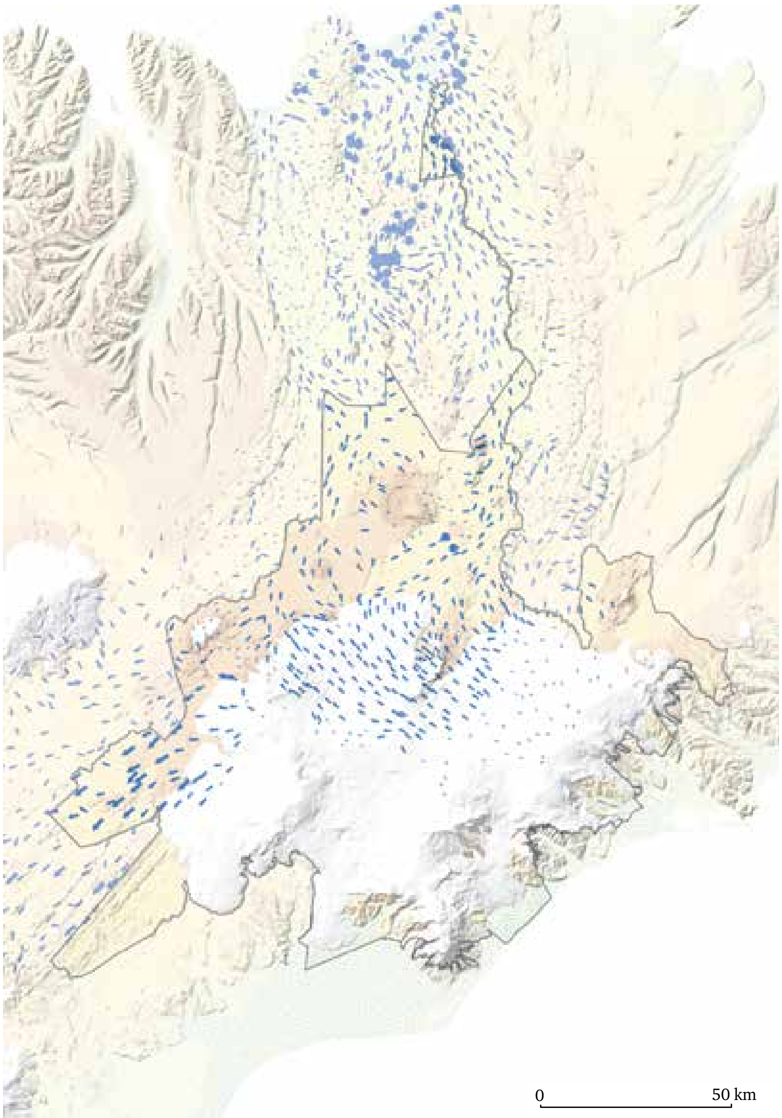
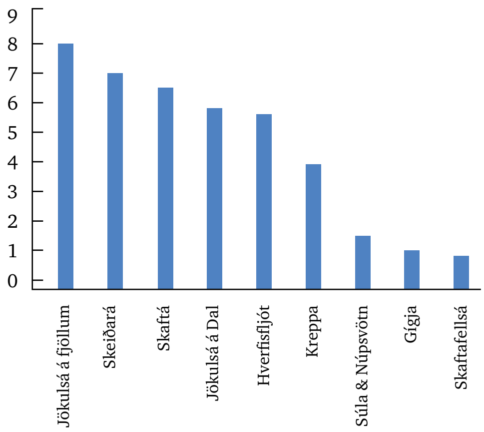


Fig 2.44.
Annual suspended-sediment load (in a million metric tons) of a few glacial rivers originating in Vatnajökull ice cap. Modified after Harðardóttir & Zóphóníasson (2017).



contribution grows to 50 m³/s just downstream of the junction and has risen to 100 m³/s before it enters the sea 160 km away. Based on model calculations, most of this groundwater originates at the northern part of Vatnajökull, and the direction of the flow is governed by the north-south oriented fissure swarms in the neovolcanic zone (Fig 2.43).

The large sandur plains in front of some of the larger outlet glaciers (Skeiðarárjökull, Dyngjujökull and Breiðamerkurjökull) bear witness to the great erosional power of the glaciers and the sediment transport of glacial rivers. Due to their heavy sediment load, glacial rivers often drift in several short-lived, braided channels over large areas where they spread and discharge their sediments. The sediment load increases in a power relationship with the discharge. Hence, the sediment discharge of one big flood can be orders of magnitude greater than that of many smaller floods. It follows that the sandur areas are composed mostly of sediments laid down during jökulhlaups rather than braided river facies. Figure 2.44 shows the amount of sediment load carried by some of the largest glacial rivers of Vatnajökull.

2.a (ix) Biota

The biota of the nominated property reflects the great variation in climate and environmental conditions, from wet to dry, lowlands to highlands. Vast fields of tephra, lava and sand, north and west of the ice cap are sparsely vegetated, with early successional species, such as snow lichens and fringe-mosses as the dominant life forms in large areas. Patches of flourishing vegetation at cold-water spring areas and "islands" of diverse flora and heat-loving microbes in geothermal areas make quite a welcome relief in these barren lands. In the north- and southeastern part, vegetation cover is more continuous, with extensive heath- and wetlands, as well as scrublands in sheltered valleys. Wildlife follows the vegetation; animals are scarce in the barren areas north and west of the ice cap, but more abundant in the heathlands of the northeast and in lowland areas to the south and north of the ice cap. Retreating glaciers leave behind denuded land that is rapidly colonised by life. The more stable ground-water environments in the fissure swarms of the neovolcanic zone are homes to endemic crustaceans and rapidly evolving salmonid fish.

Vegetation and habitat types

The nominated property encompasses some of the driest ice-free areas of the country north of the ice cap, as well as the wettest ones south and southeast of the ice cap. In ice-free areas the elevation ranges from sea level to over 1800 m and includes diverse geological formations or bedrock types, aged from a few (Holuhraun lava field 2014–2015) to millions of years.

The vegetation of the property reflects this great variation in climate and environmental conditions. The fields of tephra, lava and sand, north and west of the ice cap are mostly denuded or very

Alpine speedwell, *Veronica alpina* © Snorri Baldursson.

sparsely vegetated. Early successional species, such as snow lichens, *Stereocaulon* spp., and fringe-mosses, *Racomitrium* spp., are the dominant life forms in large areas. Patches of flourishing vegetation with diverse vascular flowering plants at Herðubreiðarlindir, Hvannalindir and other cold-water spring areas make quite a welcome relief in these barren lands. Geothermal areas, such as in Vonarskarð, are also "islands" of life and biodiversity, with a diverse flora of vascular plants, mosses and heat-loving, extremophile microbes. West and southwest of the ice cap, where precipitation is higher, mosses flourish and can, in places, constitute up to 90% of the vegetation cover.

In the northeastern part of the nominated property, outside of the neovolcanic zones, vegetation cover is more dense and continuous, with extensive heath and wetlands, including the Eyjabakkar Ramsar site. In the mountainous southeast part of the property, scrublands, forb meadows and grasslands grow in the sheltered valleys between the mountains, while the southernmost part is dominated by the vast and sparsely vegetated Skeiðarársandur outwash plain, but with a narrow band of rich vegetation at the base of the mountains. Tall birch woods can be encountered in this strip of land, in valleys and on mountain slopes, especially at Skaftafell. Rare lichen types are found in the birch woods further southeast, along with several rare species of vascular plants. Species-rich birch woodlands and forb meadows are also found in Jökulsárgljúfur canyon in the north.

In 2016, the Icelandic Institute of Natural History completed the first comprehensive description and overview of habitat types in Iceland (Ottósson et al., 2016), based on a recognised European habitat classification system (EUNIS). The size, distribution and conservation value of each habitat type was also estimated. A total of 105 habitat types was described for Iceland: 64 terrestrial ones, 17 in inland surface waters and 24 coastal habitat types. The habitat types on dry land were grouped into 12 habitat type classes.

Several Icelandic habitat types, within the EUNIS classification scheme, exist nowhere else in Europe, primarily because of Iceland's glacial and volcanic heritage. Examples of these regionally unique environments include glacial moraines and forelands, recent lava and tephra fields and geothermal areas. Although the EUNIS classification scheme could only partly be followed, all habitat types, both newly proposed Icelandic habitat types and those occurring elsewhere in Europe, were allocated places within the EUNIS scheme.

Table 2.5 and Figure 2.45 depict the habitat classes and habitat types of the nominated property. All 13 terrestrial habitat classes are present, with glaciers covering by far the largest area, or some 7997 km² in total (Vatnajökull ice cap, Tungnafellsjökull, Þrándarjökull, glaciers on Mt. Snæfell). On non-glaciated lands, two habitat classes of barren lands dominate, fell fields, moraines and sands, and lava fields, with a combined areal of 2662 and 2633 km², respectively. These classes, taken together with the glaciers and river plains (420 km²), add up to 12,987 km² of denuded or very sparsely vegetated land. Thus, some 90% of the 14,482 km² nominated property is either glacial ice or desert (Fig 2.42).

Table 2.5.
Habitat classes and habitat types of the nominated property. Both Icelandic and EUNIS numbering systems are listed, as well as the areal extent of each habitat type and its conservation value. A star (*) denotes habitat types on the Bern List of habitat types in Europe in need of protection. Source: Icelandic Institute of Natural History.

Habitat type class	Habitat type number and name	EUNIS	Areal (km²)	Conserv. value
Fell fields, moraines and sands	L1.1 Glacial moraines with very sparse or no vegetation 1	H5.2	1595.25	Low
	L1.2 Glacial moraines with very sparse or no vegetation 2	H5.2	92.71	Low
	L1.3 Oroboreal *Carex bigelowii-Racomitrium* moss-heath	E4.21	81.67	Low
	1.4 Glacial moraines with very sparse or no vegetation 3	H5.2	49.55	Low
	L1.5 Volcanic ash and lapilli fields	H6.25	842.81	Low*
	L1.6 Icelandic inland dunes	H5.341	0.30	Low
	2662.29			
Screes and cliffs	L3.1 Icelandic tallus slopes	H2.13	90.91	Medium*
	L3.2 Icelandic *Salix herbacea* screes	H2.12	11.95	Low*
	L3.3 Icelandic *Alchemilla* screes	H2.11	441.74	Low*
	544.60			
River plains	L4.1 Unvegetated or sparsely vegetated river banks	C3.6	90.79	Low
	L4.2 Icelandic braided river plains	H5.351	329.82	Medium
	420.61			
Moss lands	L5.1 Boreal moss snow land communities	E4.115	67.12	Medium*
	L5.2 Icelandic *Racomitrium ericoides* heaths	E4.26	150.76	Medium
	L5.3 Moss and lichen fjell fields	E4.25	51.23	Low
	269.11			
Lava fields	L6.1 Barren Icelandic lava fields	H6.241	2328.56	Low*
	L6.2 Icelandic lava field lichen heaths	E4.241	210.48	Medium
	L6.3 Icelandic lava field moss heaths	E4.242	41.16	Medium
	L6.4 Icelandic lava field shrub heaths	E4.243	53.04	Medium
	2633.24			
Coastal lands	L7.1 Icelandic sand beach perennial communities	B1.234	2.91	Low
	L7.3 Atlantic embryonic dunes	B1.311	0.03	Medium*
	2.94			
Wetlands	L8.1 *Philonotis-Saxifraga stellaris* springs	D2.2C12	1.29	Medium
	L8.2 Icelandic stiff sedge fens	D4.1J	42.66	Medium*
	L8.3 Cotton sedge marsh-fens	D4.261	0.64	Medium*
	L8.4 *Juncus arcticus* meadows	E3.416	7.84	Medium*
	L8.5 Boreal black sedge-brown moss fens 1	D4.162	0.08	High*
	L8.6 Boreal black sedge-brown moss fens 2	D4.162	0.68	Very high*
	L8.8 Palsa mires	D3.1	8.66	Very high*
	L8.9 Icelandic black sedge-brown moss fens	D4.163	18.84	Very high*
	L8.10 Icelandic *Carex rariflora* alpine fens	D2.2933	34.86	High
	L8.11 Common cotton grass fens	D2.26	4.08	Very high
	L8.12 Icelandic black sedge-brown moss fens	D4.163	4.12	Very high*
	L8.13 Basicline bottle sedge quaking mires	D2.332	3.01	Very high*
	L8.14 Icelandic *Carex lyngbyei* fens	D5.21B	2.19	Very high*
	128.95			

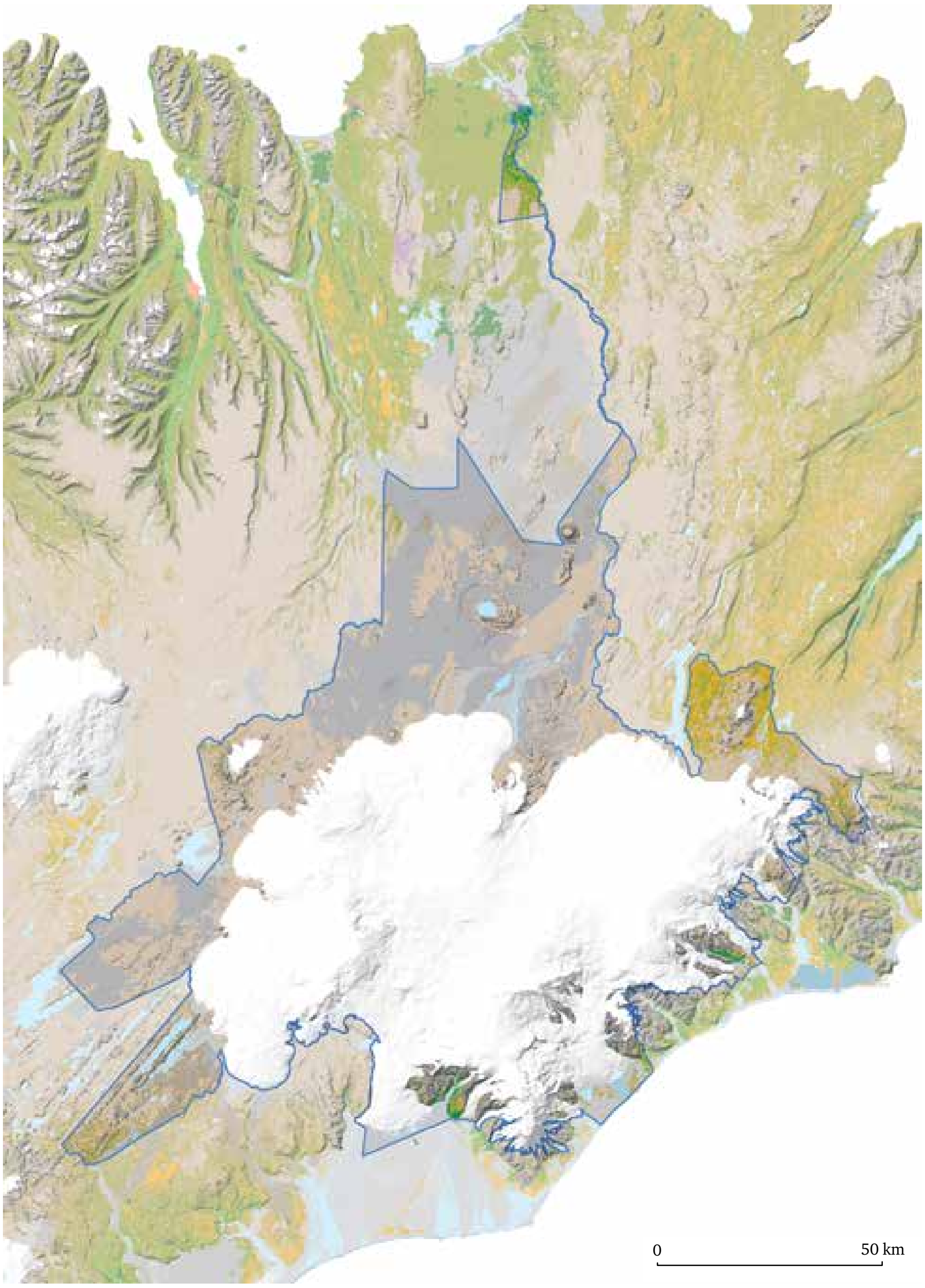
Grasslands	L9.1 Icelandic *Carex bigelowii* grasslands	E4.3C	2.22	Medium*
	L9.2 Icelandic *Nardus-Gallium* grasslands	E1.711	0.12	High*
	L9.3 Wavy hairgrass grasslands	E1.73	0.01	High
	L9.4 Boreal tufted hairgrass meadows	E3.4132	0.37	High*
	L9.5 Icelandic *Festuca* grasslands	E1.7224	6.79	High*
	L9.6 Boreo-subalpine *Agrostris* grasslands	E1.7221	1.89	High*
	L9.7 Northern boreal *Festuca* grasslands	E1.7223	0.20	Medium*
	11.59			
Heathlands	L10.1 Icelandic *Racomitrium* grass heaths	E4.28	23.26	Low
	L10.2 Arctic Dryas heaths	F2.294	2.04	Low
	L10.3 Icelandic *Carex bigelowii* heaths	E4.29	54.58	Medium
	L10.4 Icelandic *Empetrum-Thymus* grasslands	E1.2617	9.25	High*
	L10.5 Icelandic lichen-*Racomitrium* heaths	E4.27	7.85	Medium
	L10.6 North Atlantic boreo-alpine heaths	F2.255	53.67	Medium
	L10.7 Oroboreal moss-dwarf willow snowbeds	F2.112	50.09	High
	L10.8 North Atlantic *Vaccinium-Empetrum-Racomitrium* heaths	F4.211	10.94	Medium*
	L10.9 Icelandic *Salix lanata/S. phylicifolia* scrub	F2.113	24.43	Medium
	L10.10 Oroboreal willow scrub	F2.322	9.10	Very high*
Woodlands	L11 Birch woods	G1.9171	37.80	High*
	283.02			
Geothermal areas	L12.3 Geothermal alpine habitats	C2.1432	0.05	Very high
	L12.4 Icelandic solfactats/Geothermal bare grounds	H6.151	0.04	High*
	0.09			
Glaciers	L13.1 Icecaps, glaciers and unvegetated ice-dominant habitats	H4.2 & H4.3	7996.89	Na
Other land types	L14.1 Constructed, industrial and other artificial habitats	J	1.08	Na
	L14.2 Cultivated agricultural, horticultural and domestic habitats	I	0.86	Na
	L14.3 Mixed forestry plantations	G4.F	0.10	Na
Nootka lupin	L14.4 Land reclamation forb fields	L14.4	1.06	Na
Freshwater	V1 Standing waters	C1 & C3	88.72	Na
	V2 Running waters	C2	136.90	Na
Coasts	F Coastal habitats	A1 & A2	0.39	Na
	FX1.1 Lagoon	FX.1	16.91	Na
	8242.93			
Exposed aeolian soils	L2.1 Icelandic exposed andic soils	H5.7	1.59	Na

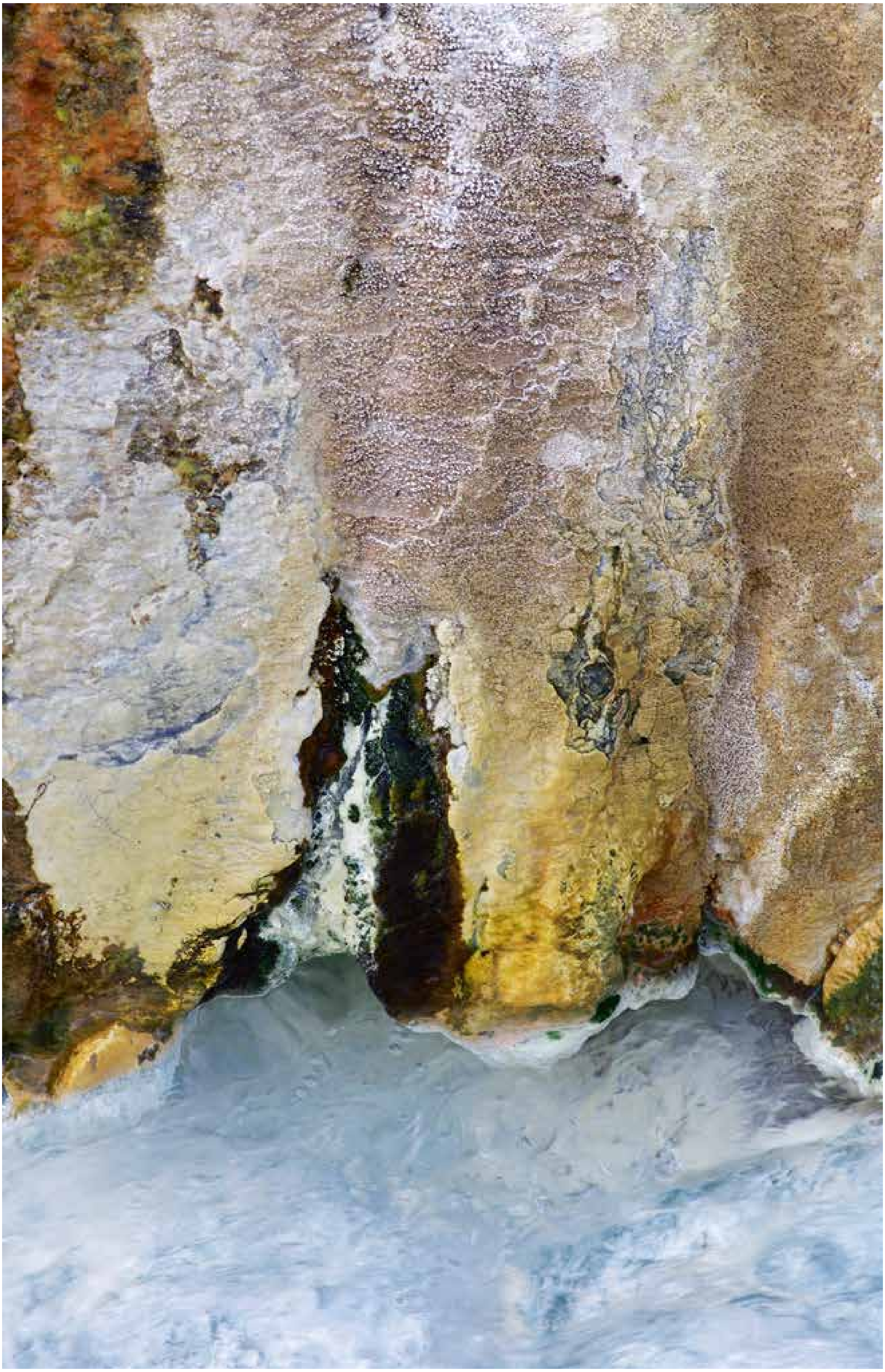
Opposite: Precipitations in a hot spring in the Vonarskarð caldera, 17 August 2011 © Snorri Baldursson.

Still, the non-glaciated part of the property contains 53 (83%) of the 64 defined terrestrial habitat types of Iceland. Mosslands and heathlands are most widespread with a combined area of 514 km². Wetlands cover 129 km² and wood- and grasslands some 49 km². Geothermal areas are the least widespread terrestrial habitat, with a combined area of only 0.09 km². Freshwater habitat classes have a combined area of some 243 km². However, within the property they have not been classified further into habitat types. Coastal lands are poorly represented, with only two out of 26 habitat types (7%) represented, and with a combined area of only 3 km².

Eight habitat types within the property are classified as having a "very high" conservation value, 12 have "high", 18 "medium" and 16 "low" conservation values (Table 2.6). Twenty-seven of the habitat types are included in the Bern Convention List of habitat types in Europe that need protection. Hence the nominated property may be considered an important sanctuary of threatened habitat types in Europe.

Figure 2.45.
Map of habitat classes of the nominated property. Refer to table 2.6 and text for explanation. Source: The Icelandic Institute of Natural History. See larger map in Appendix 1.1.





Flora

Some 344 species of vascular plants have been recorded within the nominated property (Appendix 2.2). This represents 70% of the 489 Icelandic vascular plants on record (Kristinsson, 2008). Two lowland areas of Vatnajökull National Park, Skaftafell and Jökulsárgljúfur, account for this high overall species diversity. Seven of the recorded vascular plants within the property are red listed in Iceland: The black spleenwort fern, *Asplenium trichomanes*, is considered Endangered; the green spleenwort fern, *Asplenium viride*, adder's tongue fern, *Ophioglossum azoricum*, orchid eggleaf twyblade, *Listera ovata*, true lover's knot, *Paris quadrifolia* and tufted pearlwort, *Sagina caespitose*, are classified as of Lower Risk; and the moonworth, *Botrychium simplex* var. *tenebrosum*, as Data Deficient.

Some 314 species of mosses (52%) out of a total of 606 native species have been recorded within the property (Appendix 2.3). Seven of these are red listed: *Atrichum tenellum*, as Critically Endangered; *Bryum vermigerum*, as Endangered and *Atrichum angustatum*, *Orthotrichum stramineum*, *Orthotrichum striatum* and *Schistidium venetum* as Vulnerable.

In all 287 species of lichens (38%), out of a total of 755 native species, (Appendix 2.4), have been recorded within the nominated property. Eleven of these are red listed: *Phaeorrhiza nimbosa*, *Umbilicaria virginis* and *Usnea virginis* as Endangered; *Platismatia glauca*, *Stereocaulon uliginosum* and *Usnea subfloridana* as Vulnerable; *Hypogymnia physodes*, *Hypogymnia tubulosa*, *Leciophysma finmarkicum* and *Tuckermannopsis chlorophylla* as of Lower Risk; and *Phaeophyscia endococcina* as Data Deficient.

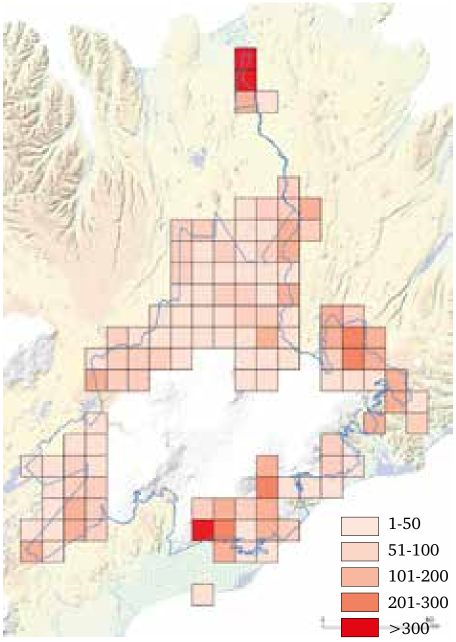


Figure 2.46.
Species richness (no. of species) of vascular plants, mosses and lichens within 10x10 grid cells of the nominated property. Source: The Icelandic Institute of Natural History.

It should be noted that sampling efforts for both mosses and lichens are much less than for the vascular plants, especially in the more remote highland areas. However, the Snæfell area in the northeastern highlands has been thoroughly surveyed relating to environmental impact assessments of the Kárahnjúkar hydropower plant and the earlier proposed Eyjabakkar power plant.

When species richness, within the classical vegetation groups of vascular plants, mosses and lichens, is plotted against the 10x10 km national grid used to survey species' numbers, the lowland areas of Skaftafell and Jökulsárgljúfur stand out as by far the most species rich, while, not surprisingly, the desert areas north and west of the glacier are species poorest (Fig 2.46).

Life in hot springs

The hot springs of the Vonarskarð caldera are habitats for unique microbial communities. As a part of an environmental assessment (Pétursdóttir et al., 2010), samples were collected from geothermal water, soil and microbial mats in the western part of the caldera in 2009. The samples were collected from different temperatures and pH, from 16–92°C and 2–7, respectively. The composition, diversity and novelty of bacteria and archaea were estimated by using culture-independent methods, based on determining sequences corresponding to the 16S rRNA gene. The sequences were classified and compared to reference sequences in a genbank that stores an enormous amount of sequence data. Those exhibiting less than 97% or 95% homology to known 16S rRNA sequences were defined as putative novel species and rare species/novel genera, respectively.

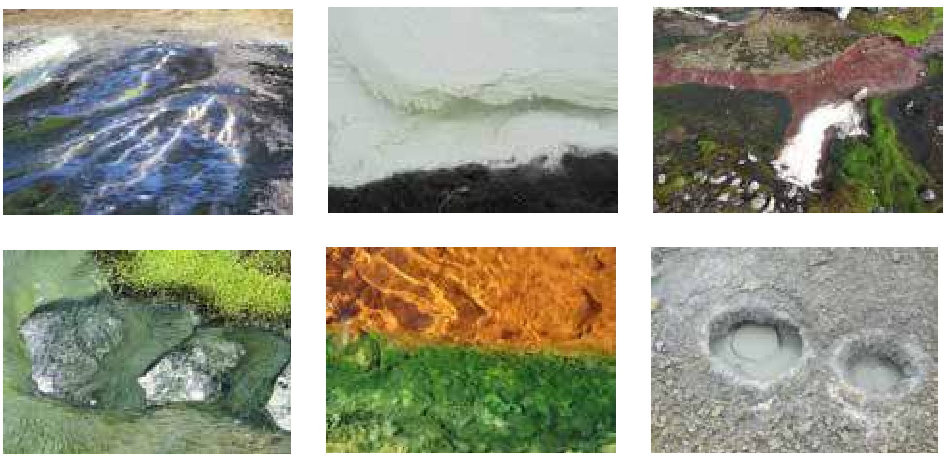
Over a thousand sequences were identified, and representatives of almost all known phyla of bacteria and archaea were detected. The estimated microbial diversity of the area was found to be high compared to that of other geothermal areas in Iceland. Many of the detected species are commonly found in geothermal areas around the world, while others represented novel groups. About 50 novel species of bacteria and 10 novel species of archaea were detected, whereof eight and five probably represent novel genera.

The microbial diversity showed distinctive patchiness. High in the Vonarskarð caldera, in hot springs of pH 2–4, the microbial diversity was low and novel groups were not identified except for an archaeon from a hot spring of 90°C and pH 2. Much higher diversity was detected in the thick mat structures observed at lower temperatures with most of the novel species found at 45–65°C. The most unusual mat encountered in Vonarskarð is a massive sulfur mat that forms in a thermal stream and extends for tens of metres. A sulfur mat of this density has not been reported before, and it is thus a subject of further studies.

The diverse physical and chemical properties of the hot springs at Vonarskarð are reflected in different microbial communities. The most common microorganisms detected in the survey were thermophilic bacteria of the phylum Aquificae. This is a well-studied group of primary producers that often form the basis of ecosystems in geothermal habitats. They can gain energy and carbon from sulfur compounds and hydrogen and from carbon dioxide, respectively. Different species of this phylum were identified in different hot springs in Vonarskarð and, remarkably, a member that probably represents a novel genus was identified. Several primary producers of archaea that likewise gain energy from inorganic chemicals were detected, belonging to either the Crenarchaeota or the Euryarchaeota.

Many of the thick mat structures in the thermal streams of Vonarskarð are green, particularly at temperatures below 40–50°C. The studied mats often contained many layers of cyanobacteria that obtain energy from sunlight. This mat ecosystem harbours highly diverse microorganisms; some other commonly detected species are bacteria that belong to the phyla of Bacteroidetes, Chloroflexi, Proteobacteria and Firmicutes.

The microbial ecosystems in the Vonarskarð area are remarkable in several respects. Firstly, because some of the prominent microbial mats observed have structures not reported from elsewhere. Secondly, because of the diverse thermal habitats that are confined to a very small area and are reflected in different community structures, and thirdly because of the novel microbial groups detected.



Diverse microbial forms of the Vonarskarð geothermal area © Snædís Björnsdóttir.

Life in subglacial lakes

Subglacial lakes beneath the Vatnajökull ice cap, Skaftárkatlar and Grímsvötn, have been studied and found to host communities of single-celled organisms, especially bacteria, that are adapted to the extreme conditions there. In fact, the first direct investigations of life in subglacial lakes were made in Iceland (Gaidos et al., 2004). The lakes are completely dark, poor in nutrients and cold (Marteinsson et al., 2012), even though they are maintained by volcanic activity that provides a heat source to melt the ice (Fig 2.27).

Intact cells, as well as cellular DNA, have been extracted from these lakes and even cultivated in the laboratory. This research has identified which kinds of microbes live in the lakes and provided information about the ways in which they are adapted to these environments, for example which sources of energy they can use (Gaidos et al., 2009; Marteinsson et al., 2013). The same volcanic activity that maintains the lakes also provides abundant sources of energy for life in the form of chemical compounds. Notable among these is hydrogen, which is produced when water reacts at high temperature with certain iron-containing minerals in volcanic rocks. Geothermal activity, combined with a lack of available oxygen and the overlying glacial ice which effectively seals the lake water from other external influences, makes hydrogen abundantly available. Some microbes can combine hydrogen with carbon dioxide, another volcanic gas that is abundant in the lakes, to produce energy for metabolisms and an organic form of carbon used in the building blocks of cells. While the end-product of many such organisms is methane, the bacteria in the Skaftárkatlar lakes appear to exclusively produce acetate, a unique feature for a lake biome.

Geothermal subglacial lakes may be appropriate analogues for the earliest habitats on Earth, at least four billion years ago. The Sun was fainter and Earth's climate may have been cooler, meaning that seas and lakes might have been ice covered. The earliest life had not yet evolved to use photosynthesis and thus there was no oxygen in the atmosphere or oceans. Like the microbes in these subglacial lakes, life would have relied on geological sources of energy such as hydrogen. As such, the Icelandic subglacial lakes may represent Earth's first "hydrogen economy". Similar scenarios may have occurred in the icy satellites of Jupiter and Saturn, including Europa and Enceladus, which are thought to contain subsurface oceans of water in contact with their rocky interiors. The Iceland subglacial lakes are a unique biome, providing opportunities to study life in extreme environments on modern Earth, life as it may have existed on early Earth, and life as it may exist elsewhere in our Solar System.

Skaftárketill Eystri (Eastern Skaftá cauldron) 10 October 2015, after jökulhlaup © Oddur Sigurðsson.

Opposite: Northern green orchid, *Platanthera hyperborea* © Snorri Baldursson.

Ecosystem development in proglacial areas and on nunataks

Proglacial areas

The first studies on primary succession in Iceland were carried out in front of Skaftafellsjökull outlet glacier by a team of Swedish biologists in the early 1960s (Lindroth, 1965; Persson, 1964). They adopted the classical chronosequence approach and Persson (1964) distinguished several seral stages, beginning with sparse pioneers, followed by heath and shrubs such as crowberry, *Empetrum nigrum*, willows, *Salix* spp., and finally birch, *Betula pubescens*, forest and woodland. Half a century later, when Persson's survey was repeated, the stages identified in 1962 had become blurred. The oldest plots had changed the least but the youngest the most, with evident convergence of successional trajectories as rates of change slowed down (Svavarsdóttir & Þórhallsdóttir, in prep.).

The proglacial fields in front of the Vatnajökull outlet glaciers can be regarded as a replicated natural experiment. Having a very similar environmental setting and climate, they offer unique opportunities of testing successional theories, e.g. the relative importance of deterministic versus stochastic factors in determining rates and directions of ecosystem change. Such a study is now in progress, comparing six glaciers (Morsárjökull, Skaftafellsjökull, Fjallsjökull, Breiðamerkurjökull, Skálafellsjökull and Svínafellsjökull eystri; Magnúsdóttir et al., in prep.). Preliminary results show marked differences in both rates and directions of succession and that this can be related to the species richness, composition and proximity of the seed source. Colonisation is extremely rapid and contrary to conventional wisdom, the pioneering plant communities (<10 years after glacial retreat) are not dominated by mosses or lichens but by vascular plants.

Top: Mountain avens, *Dryas octopedala*, tussock in the Skaftárjökull forefield © Þóra Ellen Þórhallsdóttir. Bottom: Aerial view over the braided Hverfisfljót and Djúpá rivers at Skeiðarársandur, 14 September 2014 © Snorri Baldursson.

Nunataks

Nunataks are ice-free areas surrounded by glacier. As the glacier retreats and thins, each nunatak gradually becomes larger and exposed surfaces are subjected to primary succession. Glacier forelands have been considered good sites for studying ecological succession due to their restricted size, simple ecosystems and a chronological sequence in community development (Matthews, 1992). Islands have been important in studies on community structure because of their discrete boundaries (Krebs, 2001). Nunataks have both the chronological sequence of a glacier foreland and the restricted boundaries of an island. They thus offer a unique opportunity to study primary succession and how dispersal constraints, or dispersal abilities, may affect the community assembly process.

Vatnajökull contains several nunataks (Fig 2.2). The nunataks in the outlet glacier Breiðamerkurjökull provide exceptionally good study opportunities due to accessibility and well-documented history. The Esjufjöll mountains, consisting of four mountain ridges, have been partly ice-free for at least 10,000 years (Helgi Björnsson, pers. comm.). Other nunataks have emerged within the last century, in keeping with the thinning and retreat of Vatnajökull's outlet glaciers (Einarsson, 1998). The nunatak Kárasker appeared in the 1930s (Björnsson, 1958), Bræðrasker was first seen in 1961 (Einarsson, 1998) and Maríusker emerged in 2000.

Ecosystem development on Skeiðarársandur sandur plain

With an area of 1000 km², Skeiðarársandur is probably the world's largest sandur, or outwash plain, in front of an active glacier. A small part of it are contained within the nominated property (Fig 1.3). For the first approximately four centuries of human habitation in Iceland, the plain was partly vegetated and supported many prosperous farms. The region was devastated by the 1362 eruption in Öræfajökull but some farms were rebuilt on the plain. As the Little Ice Age progressed, Skeiðarársandur was increasingly subjected to large jökulhlaups, triggered by geothermal melting of glacier ice and subglacial eruptions in Vatnajökull. In the 19th century, there were at least ten such outburst floods, the largest covering virtually the whole plain. By the end of the 19th century, the sandur was an exceptionally barren wasteland. In the first detailed map of the region, surveyed in 1904, only five tiny patches with continuous vegetation are shown, totalling <1 km² (Þórhallsdóttir & Svavarsdóttir, submitted).

Several changes have combined to transform environmental conditions on Skeiðarársandur. Skeiðarárjökull glacier has retreated behind its large Little Ice Age moraines, thereby decoupling floodwater from the plain. Water now first collects in the proglacial depression, depositing sediment and icebergs, and only has an outlet through a few gaps in the moraines. There was a quiescent period in Grímsvötn volcano from 1938–1996 with few and mostly small events and as Skeiðarárjökull becomes thinner, the jökulhlaups become smaller, on average. Compared with the late Little Ice Age jökulhlaups, the post-1938 floods have been fewer, smaller and with a greatly reduced destructive power. The largest 20th century flood, in 1996, caused by the Gjálp eruption (Box p. 87), occurred in November when the ground was frozen. Thus, it only had very local impacts on the vegetation of the sandur plain (Svavarsdóttir & Thórhallsdóttir, pers. observ.). Together with a warming climate, these radical changes in the disturbance regime have greatly ameliorated conditions on Skeiðarársandur. Although the flat and largely featureless sandur appears homogeneous to the human eye, present rates and directions of vegetation succession vary greatly across the 1000 km² region.

Most of Skeiðarársandur remains very sparsely vegetated. Over 70% of the area between Gígjukvísl and the old Skeiðará-water course (ca. 400 km²) has less than 10% vegetation based on a 2002 satellite image (Kofler, 2004) and on repeated recording of species cover in 40 systematically placed plots on the upper part of the plain (25x25 m; Svavarsdóttir & Þórhallsdóttir, 2004–2017, unpublished data). On bare ground, grains <2 cm in diameter dominated >90% of all plots. After the Grímsvötn eruption in 2011, moss cover decline was observed in some plots due to tephra deposition.

Since the early 1970s, continuous vegetation has primarily developed in three areas: across the uppermost part of the sandur plain, on a long NE-SW oriented tongue in the central part and in coastal areas east from the mouth of Gígjukvísl (Fig 2.47).

In the uppermost zone, between the Little Ice Age moraines and the national highway, moss now has a largely continuous cover in about two-thirds of the area between Gígjukvísl and the old Skeiðará river course (Fig 2.47). Over 90 vascular plant species have been recorded. Mountain birch, the only forest-forming species in Iceland, colonised this zone late in the 20th century, probably mostly around or after 1990 (Marteinsdóttir et al., 2007; Heidl, 2009). Its distribution has since expanded greatly and was in 2016 at least 34 km² (Madrigal et al., unpublished data). In the absence of catastrophic events, one of the largest natural birch woodlands in Iceland will develop on Skeiðarársandur over the coming decades.

Figure 2.47.
Infra-red (SENTINEL–2/ ESA) satellite image of Skeiðarársandur taken 6 September 2017. Source: National Land Survey of Iceland.

The first written record of vegetation on Breiðamerkurjökull's nunataks dates from a Danish excursion that crossed Vatnajökull in 1912 and visited Esjufjöll (Geirdal, 2012), but it listed only a few plant species. Systematic listing of vascular plant species started later, when the Björnsson brothers from the farm Kvísker made repeated excursions to the nunataks in 1933, 1943, 1950 and 1951, publishing their observations in Icelandic journals (Björnsson, 1951b; Björnsson, 1958; Björnsson, 1979). In 1960, botanist Eyþór Einarsson installed permanent study plots on two of the nunataks, Bræðrasker and Kárasker, which were regularly surveyed until 1997 (Einarsson, 1998). In 2003, Einarsson's study was extended with permanent study plots installed on Maríusker and Skálabjörg in Esjufjöll (Sigurðsson et al., 2005), and studies on invertebrate communities were added there later (Ingimarsdóttir, 2012).

The flora of the nunataks is rich in species, and on the oldest and largest nunataks of Esjufjöll, the total number of vascular plant species is 100, which is approximately one-fifth of the native vascular plant flora of Iceland. These nunatak communities represent some of the very few vegetated areas in Iceland that have never been influenced by human land use or grazing of domestic animals. Interestingly, some plant species, such as the alpine lady fern, *Athyrium distentifolium*, which are otherwise mostly restricted to North Iceland, are found on Breiðamerkurjökull's nunataks.

Top: The furrow spider, *Larinioides patagiatus*. Bottom: The antler moth, *Cerapteryx graminis* © Snorri Baldursson.

In Esjufjöll more than 70 species of lichens have been found. Most of them are common in Iceland, but a few rare species are found, such as *Umbilicaria virginis*, which has only been found at two other locations.

The Björnsson brothers were also keen bird watchers and published a comprehensive overview of the bird fauna of the nunataks in Breiðamerkurjökull (Ólafsson & Björsson, 1986). They listed six species which have nested on the larger nunataks: rock ptarmigan, *Lagopus muta*, parasitic jaeger, *Stercorarius parasiticus*, the great black-backed gull, *Larus marinus* (one record), the white wagtail, *Motacilla alba*, the northern wheatear, *Oenanthe oenanthe*, and the most common of the six, the snow bunting, *Plectrophenax nivalis*. In 2011, a new breeding bird was found on the Skálabjörg nunatak, the golden plover, *Pluvialis apricaria*.

Invertebrates have been collected from the Breiðamerkurjökull nunataks multiple times (Björnsson, 1951a; Ingimarsdóttir, 2012). The nunatak invertebrate fauna is rich and varied, with around 180 invertebrate species identified from the Esjufjöll mountains alone. These include common Icelandic species, as well as high Arctic ones and vagrant species from Europe. The spider *Collinsia spitsbergensis* is most common in the high Arctic but rare in Iceland (Agnarsson, 1996; Marusik, 2015). The same applies for a hoverfly, *Eupeodes rufipunctatus*, which outside of Iceland is found in Greenland, Canada and the USA (Böcher et al., 2015). Vagrants include the silver Y moth, *Autographa gamma*, and the hoverflies *Episyrphus balteatus* and *Eupeodes corollae*. Common Icelandic invertebrates include species that disperse easily, like flies and spiders, but also ones that are not considered good dispersers, such as the snail, *Vitrina pellucida*, and the earthworm, *Dendrobaena octaedra*, which are found on older parts of Esjufjöll.

Animal life in the nominated property

The Arctic fox, *Alopex lagopus*, is the only native mammal within the nominated property and Iceland (Box p. 142). Introduced mammals are the field or wood mouse, *Apodemus sylvaticus*, and the reindeer, *Rangifer tarandus*. A large reindeer herd breeds and grazes in the heathlands around Mt. Snæfell, while spending the winters in the lowlands at the southeast edge of the property. American mink, *Mustela vison*, is found in the lowland areas of the south and north. The Norwegian rat, *Rattus norwegicus*, and the house mouse, *Mus musculus*, may be encountered close to human dwellings.

Birds are the most conspicuous wildlife in Iceland and in the nominated property. In the highland areas to the north and west of the ice cap, bird life is scattered, with most common species being

Invertebrates come firsts

To study the invertebrate dispersal and colonisation, a thorough sampling was performed in 2008, on four of the Breiðamerkurjökull nunataks: Skálabjörg in Esjufjöll, Kárasker, Bræðrasker and Maríusker. Two other nunataks in southwest Vatnajökull were also visited in 2009, Vöttur in Skeiðarárjökull and Húsbóndi (Ingimarsdóttir, 2012).

The results showed that many invertebrate species were found on these nunataks within only a few years from deglaciation (Table 2.6). As on other new landforms, surface-active predators and detritivores dominate the first stages of colonisation and precede the establishment of vascular plants (Thornton & New, 1988; Kaufmann, 2001; Hodkinson et al., 2004; Ingimarsdóttir et al., 2012; Ingimarsdóttir et al., 2013).

On the nunataks, the first colonisers consist of windborne spiders, collembolans and mites (Ingimarsdóttir et al., 2013), and their main food source is allochthonous, that is not originating from the nunataks themselves but from external sources (Ingimarsdóttir et al., 2014). Around 25 years after deglaciation, a vegetation cover had developed on all the nunataks, although there were large differences between them. The presence of vegetation allows more invertebrate species, such as herbivores and their predators to establish (Ingimarsdóttir et al., 2013).

The conclusion is that nunatak colonisation of small windborne or actively dispersing invertebrates happens at the same rate as on any other type of new land (Ingimarsdóttir et al., 2012; Ingimarsdóttir et al., 2013). However, the isolation by the glacier decreases the colonisation rate of large, passively dispersing invertebrates. For example, beetles and harvestmen were rare or absent on the young nunataks but were present on the older Esjufjöll mountains (Ingimarsdóttir et al., 2013). On glacier forelands, beetles and harvestmen are among the first colonisers (Kaufmann, 2001; Gobbi et al., 2006; Gobbi et al., 2011).

Table 2.6.
Number of invertebrate species found on the Breiðamerkurjökull nunataks in 2008. The focus was on young land (<100 years from emergence) so only a small part of Skálabjörg in Esjufjöll was sampled (Ingimarsdóttir, 2012).

Nunatak	Years since nunatak emergence	No. of invertebrate species in 2008 survey
Maríusker	ca. 8	>40
Bræðrasker	ca. 47	>60
Kárasker	ca. 70	>75
Skálabjörg, Esjufjöll (the youngest part <100 years old)	ca. 10,000	>100

Great skua, *Stercorarius skua*
© Daniél Bergmann.

snow bunting, northern wheatear and purple sandpiper, *Calidris maritima* in dry areas, and e.g. long-tailed duck, *Clangula hyemalis*, dunlin, *Calidris alpina*, red-necked phalarope, *Phalaropus lobatus* and the common loon, *Gavia immer*, in wetter areas.

A large population of the pink-footed goose, *Anser brachyrhyncus*, breeds in the heathlands around Mt. Snæfell; the neighbouring Eyjabakkar wetlands are an internationally recognised Ramsar site as a moulting area for the species. The area around Mt. Snæfell is also an important hunting area for rock ptarmigans, *Lagopus muta*. A comparatively high concentration of gyrfalcons, *Falco rusticolus*, nests in the Jökulsárgljúfur canyon and neighbouring areas where it feeds mostly on ptarmigans.

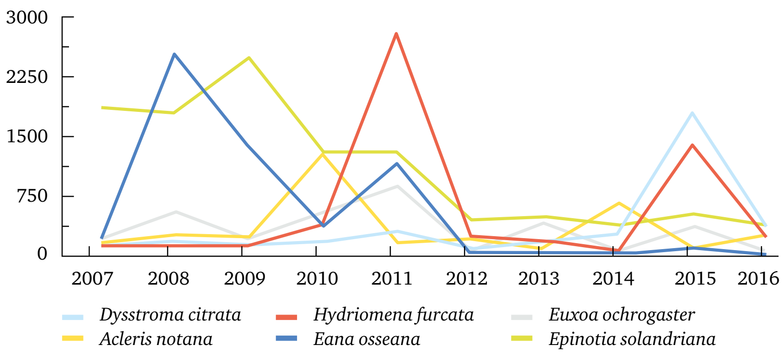
The thin strip of lowland plains south of the ice cap is a very important staging area for migratory birds in spring, and popular with birdwatchers seeking vagrant species. Breiðamerkursandur is an internationally important nesting area for the great skua, *Stercorarius skua*, with 2820 pairs in 1985 and, since the late 20th century, for the growing breeding population of the barnacle goose, *Branta leucopsis*, in Iceland. In 2017, 967 pairs of this species bred at Breiðamerkursandur (Box p. 146).

Rivers and lakes contain Arctic charr, *Salvelinus alpinus*, populations, which are exploited. No important salmon rivers are within the borders of the nominated property. In recent years, there has been an increased focus on the groundwater and spring fauna in the neovolcanic zone, including within the nominated property, following the discovery of two endemic groundwater amphipod species (Kristjánsson & Svavarsson, 2004; Svavarsson & Kristjánsson, 2006; Box p. 149).

Moths in Jökulsárgljúfur canyon

The Northeast Iceland Nature Research Centre has monitored moths during the summer months of June, July and August since 2007, using light traps. The project is part of a nation-wide monitoring network run by the Icelandic Institute of Natural History. The traps are emptied once a week and the yield identified to species. Altogether, 44 species of moths have been trapped. Most of these occur only rarely, but a few species are consistently present although their abundance fluctuates quite wildly between months and years (Fig 2.48). In most years at least one species gains dominance, but in some years, i.e. 2012–2014 and 2016, the overall abundance of moths is low.

Figure 2.48.
The number of six species of moths trapped in light traps at Vesturdalur in Jökulsárgljúfur canyon during a 10-year period from 2007–2016. Source: East Iceland Nature Research Centre.



Terrestrial invertebrates are poorly studied within the nominated property, preventing any meaningful summary. A few areas have been surveyed concerning the Plan for Nature Protection and Energy Utilisation and the habitat classification of Iceland (Magnússon et al., 2009). These include the area around Lakagígar in the southwest where some 190 species of insects and spiders were identified or inferred, including two globally rare species, the dipteran, *Allodia embla*, and the spider, *Islandiana princeps*. Another well-surveyed area is the Esjufjöll nunataks where some 180 species have been identified (see p. 137).

In general, both native as well as vagrant species are most numerous in the southeast part of the property. There, *Carabus problematicus*, the largest beetle in Iceland is found at the foot of the mountains.

Terrestrial vertebrates

Reindeer bull, *Rangifer tarandus*, in Kringilsárrani © Skarphéðinn Þórisson.

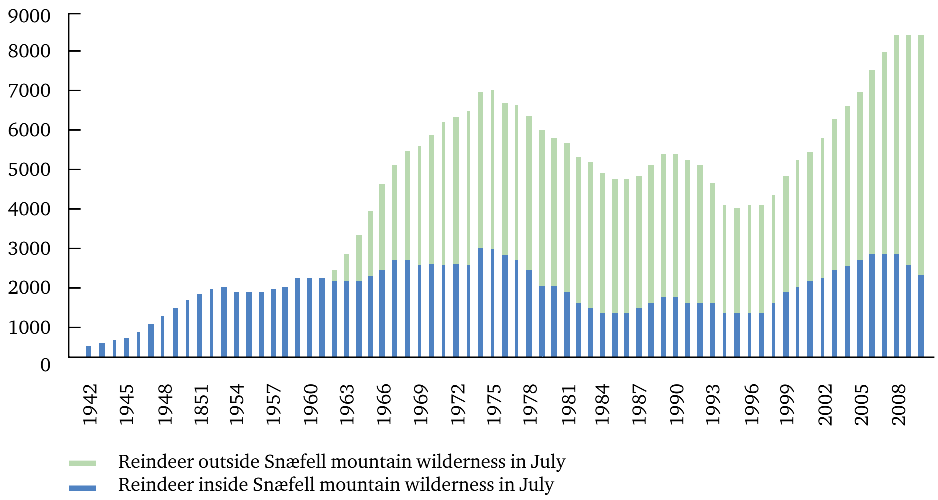
<u>Reindeer</u>

Reindeer are the only wild ungulates roaming the property. They have been living in East Iceland since 1787 when 35 semi-domesticated animals arrived to Vopnafjörður from Avjovarre in Kautokeino, Finland. They soon became feral and their numbers increased quickly, so that farmers started complaining of reindeer spoiling sheep grazing areas and eating Icelandic moss, *Cetraria islandica*, in competition with humans (Valtýsson, 1945).

It appears that the main home of the reindeer in the 19th century was the highland plateau around Mt. Snæfell inside Vatnajökull National Park, i.e. where the Fljótsdalur herd roams today during summer (Þórisson & Ágústsdóttir, 2014). The population fluctuated through time, but decreased markedly in the late 19th and early 20th centuries. The cause is believed to have been overgrazing in winter pastures, combined with harsh winters. By 1939, only a small herd persisted in Kringilsárrani at the northeast corner of Vatnajökull glacier (Valtýsson, 1945). The population gradually grew in numbers during the latter part of the 20th century, spending summers close to Vatnajökull glacier, migrating east and north in autumn and descending to lower grounds in winter.

The estimated size of the reindeer population today (summer 2017) is some 6400 individuals. The population is divided into eight herds. The biggest herd is the Snæfell herd, the traditional

Figure 2.49.
Average number of reindeer within and outside the Mt. Snæfell wilderness area in the years 1940–2016.



A few characteristic animals of the nominated property. Top: Reindeer, *Rangifer tarandus* © Skarphéðinn Þórisson; Middle: Whooper swan, *Cygnus Cygnus* © Þorvarður Árnason. Bottom: Barnacle goose, *Branta leucopsis* © Skarphéðinn Þórisson.

A few characteristic animals of the nominated property, cont. Top: Rock ptarmigan, *Lagopus muta* © Ólafur Nielsen. Middle: Pink-footed goose, *Anser brachyrhynchus* © Skarphéðinn Þórisson. Bottom: Arctic fox (white morph), *Vulpes lagopus* © Skarphéðinn Þórisson.

homerange of the reindeer, estimated to be 2900 animals in July 2017. This herd utilises the highland plateau to the northeast of Vatnajökull and is divided by the glacial river Jökulsá á Dal into two sub-herds: the Norðurheiði herd (1250 animals) north and west of Jökulsá á Dal and the Fljótsdalur herd (1650 animals) which roams the heathlands around Mt. Snæfell within the nominated property.

In general, hunting of reindeer is allowed from July 15th (bulls) and 1st of August (cows). Within Vatnajökull National Park, reindeer are protected in two areas, in the immediate vicinity of Mt. Snæfell and in the Kringilsárrani area (Fig 4.1). In other areas of the park, reindeer hunting is allowed from 15th September. This late date safeguards the calves from losing their mothers too soon and guarantees peaceful hiking for visitors to the park.

Arctic fox (brown morph)
© Skarphéðinn Þórisson.

Arctic fox

The distribution and density of the Arctic fox within Vatnajökull National Park have never been estimated, but hunting statistics can be used to assess the local population. These indicate the highest densities of foxes in the vegetated highland areas and oases of the park, especially in the northeastern highlands around Mt. Snæfell and Eyjabakkar, where birdlife is the richest. Geese carrion is e.g. commonly found amongst food remains at fox dens (Hersteinsson & Macdonald, 1996). The rock ptarmigan is a non-migrant bird in all vegetated areas of Iceland and a common prey species for the Arctic fox. The number of ptarmigans within the nominated property is unknown, but the high density of falcon territories found there

The first settler

The Arctic fox is the only native terrestrial mammal in Iceland. Genetic studies indicate almost complete isolation of the population for thousands of years, perhaps since the end of the last ice age (Dalén et al., 2005), apart from occasional visits from east Greenland via sea ice, during cold phases of the Medieval Period (Mellows et al., 2012). The oldest remains of foxes found in Iceland are 3500 years old (Hersteinsson et al., 2007). Arctic foxes are widely distributed on the island but the density is highest in coastal areas (Hersteinsson, 1992). Two distinct ecotypes have been described: “coastal” with a diet that is mainly sea-derived, and “inland” foxes that largely prey on rock ptarmigans and pink-footed geese (Angerbjörn et al., 1994; Hersteinsson & Macdonald, 1996). Arctic foxes come in two main colour morphs, dark brown and white. A clear majority of the coastal foxes are of the brown morph type but 60–70% of the inland foxes are white (Hersteinsson, 2004). Arctic foxes in Vatnajökull National Park are mostly of the inland ecotype. The Icelandic Arctic fox population was large in the 1950s with declining numbers through the cold spell of the 1960s and 1970s to as little as 1000 individuals in 1980. Since then, the population has risen considerably reaching a peak of 10,000–11,000 individuals in 2007–2008 (Hersteinsson, 2010) but then declining by approximately 25% through 2010 (Unnsteinsdóttir, 2014). The increase of the Arctic fox population has been correlated to growth of bird populations, especially the pink-footed goose (Pálsson et al., 2016) resulting in increased carrying capacity for inland fox ecotypes (Unnsteinsdóttir et al., 2016).

(see p. 144–145) indicates that they are likely to be available in some abundance. An increasing number of carcasses of the Snæfell reindeer herd are found annually (Þórisson & Þórarinsdóttir, 2017) and could be important as a winter food resource for foxes in the area. Arctic foxes were abundant in Jökulsárgljúfur canyon in the past (Gunnlaugsson, 1955) and this is still the case, according to hunting statistics.

Most likely, the local population of Arctic foxes within the nominated property grew in numbers after the 1980s as elsewhere in Iceland (Box, p 142). The locations of known fox dens suggest habitat selection in association with food resources, as suggested by Jepsen et al. (2002). Mapping of the annual occupancy rate would be useful while evaluating population density and favourable habitat sites for the species in Iceland.

The wood mouse

The wood mouse is the only rodent found in the wild in Iceland. The species is widespread in all regions and can easily survive where there are enough edible seeds and/or invertebrates (Unnsteinsdóttir, 2014). Neither distribution nor density of the wood mouse is known within the Vatnajökull National Park. However, it is said that wood mice regularly visit huts and cabins for food and shelter (Stefánsson & Þórisson, 2010). The distribution history of the species is unknown but it has been reported that there were no wood mice in Skaftafell until the mid-20th century, probably due to geographical barriers such as glacial rivers and large areas of barren sands (Skírnisson, 2004).

Pink-footed goose, *Anser brachyrhynchus* © Skarphéðinn Þórisson.

Pink-footed goose

The pink-footed goose is the most conspicuous breeding bird in the eastern part of the nominated property. The main breeding area is within the Vesturöræfi wilderness west of Mt. Snæfell. However, the bird is a recent breeder in the area, with the first nest found as late as 1963, near the Sauðá river (Skarphéðinsson & Þórisson, 2001). In 1981, 76 nests were found, all on the riverbanks of the Jökulsá á Brú and Sauðá rivers. As the number of nests increased, the birds dispersed all over the Vesturöræfi area (600–700 m elevation). The number of nests has fluctuated between years, with winter snow cover and timing of the spring melt apparently the most important factors in determining breeding success. A peak number was reached in 2013: 1292 nests, or 37 nests/km².

On the eastern side of Mt. Snæfell lays the RAMSAR site "Snæfell and Eyjabakkar Area" (265 km²), a major moulting ground for the non-breeding Iceland-Greenland pink-footed goose population. The Eyjabakkar wetlands are situated on the sandur plain formed by the river Jökulsá í Fljótsdal where it flows through the depression to the north of Eyjabakkajökull glacier. Small ponds and lakes, sedge and sandy fens, palsa mires, moist sedge and moss heath are the main habitat types. The moulting flocks of the pink-footed goose within the Eyjabakkar area have been counted in July most years since 1979 (Fig 2.50). The flocks were most numerous in the late 20th century with a peak of some 13,000 birds (6% of the population) in 1991. The moulting flocks then declined in size and were at their minimum (2000–4000 birds) in the period around the construction and startup of the Kárahnjúkar hydropower plant.

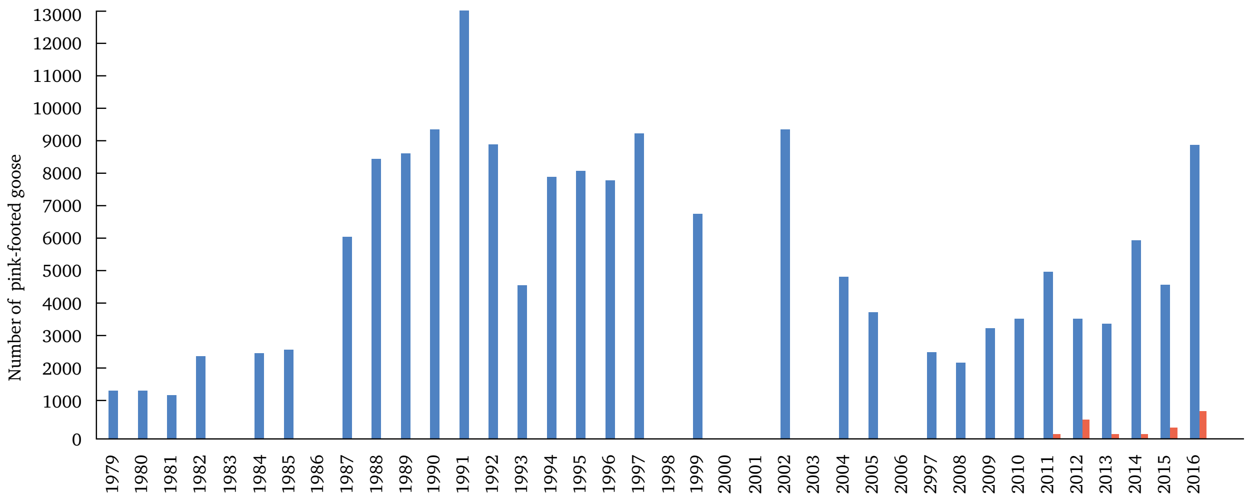


Figure 2.50.
The number of moulting pink-footed geese within the Eyjabakkar RAMSAR site, from 1979 to 2016, based on aerial counts in July. Blue columns represent adult birds and red columns young birds hatched the same spring. From Stefánsson & Þórisson (2017).

Since 2010, the number of moulting geese at Eyjabakkar has been on the rise again and was 9000 in the summer of 2016 (Stefánsson & Þórisson, 2017).

The oldest record of pink-footed goose moulting at Eyjabakkar dates to 1397; one of the benefits of the church in Hallormsstaður was hunting moulting geese in the Eyjabakkar area. The collection of goose feathers at moulting areas close to Mt. Snæfell is also mentioned in descriptions of the benefits of the church at Valþjófsstaður in 1830 (Árnason, 1840). Moulting and flightless geese were hunted by clubbing, after first herding them into stone fences. However, no remains of such stone fences are known today in the Eyjabakkar area.

In the Krepputunga region, further west, the main breeding area of the pink-footed goose is at Hvannalindir. In 1981, 184 nests were counted (Skarphéðinsson, 1983). The colony at Hvannalindir occupies the highest breeding ground of all known pink-footed goose colonies in Iceland, 710 m above sea level. The Hvannalindir area is closed to visitors until 24th June when the last eggs have hatched.

Pink-footed goose hunting is allowed within the nominated property, outside the strictly protected area of Mt. Snæfell. When a late spring melt delays the breeding in the area, the start of the hunt within Vatnajökull National Park is postponed by ten days (Stefánsson & Þórisson, 2014).

Gyrfalcon and rock ptarmigan

The close predator-prey relationship between the gyrfalcon and the ptarmigans has long been noted by biologists. Gyrfalcons and rock ptarmigans are both resident in Iceland. The rock ptarmigan is a widespread and common breeding bird, and in peak years the population numbers one to five million birds in autumn (Nielsen et al., 2004). The gyrfalcon is also widespread in Iceland, but the population is small (estimated 300–500 breeding pairs; Icelandic Institute of Natural History, unpublished data).

The gyrfalcon in Iceland is a rock ptarmigan specialist, and the ptarmigan is the main food of the falcon in all years and during all seasons (Nielsen, 2011). What the gyrfalcon takes of other prey very much depends on the status of the ptarmigan population, not on the numbers of the alternative prey. Rock ptarmigan is especially important as food during March through mid-June, and late

July into mid-October. The spring and early summer predation is directed at adult males but the late summer and autumn predation is directed first at adult females and then juvenile birds (Nielsen, 2003). Although a ptarmigan specialist, the gyrfalcon is a powerful predator of several other birds and mammals, and it is versatile with respect to the size of potential prey.

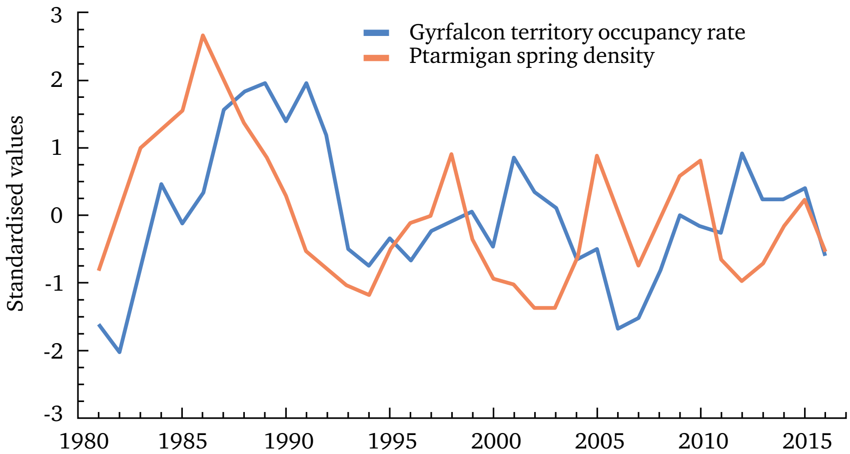
Many populations of ptarmigans have cyclic population dynamics, characterised by regular cyclic changes of numbers. The length of the cycle differs, but it is 10–12 years in Iceland (Nielsen and Pétursson, 1995). The difference in spring numbers between high and low years is commonly three- to fivefold but can be up to twenty- to thirtyfold (Nielsen, 1999; Icelandic Institute of Natural History, unpublished data).

Rock ptarmigan, *Lagopus muta*
© Daníel Bergmann.

The predator-prey relationship of the gyrfalcon and the rock ptarmigan has been studied in northeast Iceland since 1981 (Nielsen, 1999, 2011). This study has provided the longest existing time series that describe the interaction of these charismatic species. The study area covers 5300 km² and within this area a total of 83 gyrfalcon territories are known, and they are visited every year to determine occupancy. The rock ptarmigan is very common within the gyrfalcon study area, and territorial males are counted each spring on six plots to monitor population change. The gyrfalcon shows both a functional and a numerical response to changes in ptarmigan numbers (Nielsen, 1999). The functional response is slightly concave but shows a high importance of ptarmigan in falcon diet across all ptarmigan densities observed. The numerical response shows that gyrfalcon numbers track ptarmigan numbers, but with a time lag; gyrfalcons peaking two to four years after the peak in ptarmigan numbers (Fig 2.51).

The Jökulsárgljúfur canyon is within the gyrfalcon-ptarmigan study area in northeast Iceland. Within the canyon are nine known gyrfalcon territories that have been visited every year to record occupancy, chick production and food habits. The number of occupied territories has fluctuated from 4 to 9. The quality of the territories, or their attractiveness to the falcons, differs; six of the territories are occupied in most years but three intermittently. The falcons within the park rely on the rock ptarmigan as food during the breeding season when ptarmigans make up as much as 84% of the prey eaten. The most popular alternative prey is whimbrel, *Numenius phaeopus*, puffin, *Fratercula arctica*, and widgeon, *Anas penelope*. It is interesting to observe that some of the pairs will hunt

Figure 2.51.
The relationship between the rock ptarmigan, *Lagopus muta*, spring population index and occupancy rate of gyrfalcon, *Falco rusticolus*, territories in northeast Iceland 1981–2016. Values were standardised to 0 mean and unit variance. Based on Nielsen, 1999a; Nielsen, 2011; Icelandic Institute of Natural History, unpublished data.



puffin out on the ocean in late summer. The heathlands on both sides of the canyon are a prime rock ptarmigan breeding habitat.

The biology and interaction of the gyrfalcon and the rock ptarmigan are a fascinating topic to explore and have been used in nature interpretation and education activities by the staff of Vatnajökull National Park. The educational programme has been run in cooperation with the Gyrfalcon Education Centre, which has its domicile at the main office and visitor centre of Vatnajökull National Park in Ásbyrgi. The unique situation within the Jökulsárgljúfur canyon, with respect to how common and accessible these iconic species are, should allow for developing this idea further.

Barnacle geese on Skúmey

The island Skúmey in the northwestern part of the Jökulsárlón lagoon at Breiðamerkursandur measures roughly 10 ha. The island first appeared from under the Breiðamerkurjökull outlet glacier in 1978–1979 and was fully revealed in 2000.

The barnacle goose breeds mainly on islands in the North Atlantic. The species consist of three main populations that breed respectively in eastern Greenland, on Svalbard, Norway, and Novaya Zemlya, Russia. For decades, barnacle goose in Iceland were exclusively passing migrants, in spring and autumn, travelling between Greenland and the wintering areas in the British Isles. The first records of stray barnacle geese nests in Iceland are from the 1970s. However, they did not become established as a breeding population until a few pairs began nesting on Breiðamerkursandur in 1988. Since then, the population has grown rapidly and spread widely in the area, including to Skúmey island.

The rapid population growth is demonstrated by the fact that in 2009, only some 40 nests were found in the entire Breiðamerkursandur area. In 2014, 361 nests were found on Skúmey island alone, excluding non-breeders, and in 2017, the number of nests had risen to 967 on the island. This amounts to a 267% increase in three years. The density of nests rose during the same period from roughly 36 nests/ha in 2014 to 97 nests/ha in 2017. Barnacle geese are not known to breed in such a high density elsewhere in the world. In addition, the fecundity of the geese rose from an average of 3 eggs to 4 eggs per nest (Ævarsdóttir 2017, unpublished data). The island of Skúmey now holds by far the largest breeding colony of barnacle geese in Iceland and is thus an extremely important habitat for this new and charismatic species.

Barnacle goose, *Branta leucopsis* © Daníel Bergmann.

Freshwater life with focus on spring fed systems

The young rock formations of the neovolcanic zones are porous, so rainwater and snowmelt seep into the ground until they reach impermeable older bedrock whence it flows on as groundwater. Further downstream the groundwater re-emerges at the surface as springs and spring-fed rivers or lakes (Kjartansson, 1945) (see Fig 2.43). Some of the glacial rivers also disappear into the porous surface, adding to the groundwater flow. As a result, many of the largest cold spring systems on Earth are found in Iceland (Óskarsdóttir et al., 2011). Furthermore, many warm to hot springs can be found throughout Iceland, especially within the neovolcanic zone where recent magmatic activity provides an accessible heat source. Spring-fed water systems commonly display stable physical conditions, e.g. temperature, pH, conductivity and discharge (Kjartansson, 1945; Sigurðsson, 1990; Petersen et al., 1995). This stability may be important for the local adaptation of organisms.

Biology of cold springs

Cold water springs in the Icelandic highlands are home to a diverse fauna of invertebrates. Fish, especially Arctic charr, are also common (Kristjánsson et al., 2012). Other fish species in springs are three-spine stickleback, *Gasterosteus aculeatus*, and brown trout, *Salmo trutta*. Brown trout in spring fed systems is more common further downstream of the source region, where it can reach exceptionally large sizes such as in the Mývatn/Laxá system (Guðbergsson & Antonsson, 1996).

In spring fed systems, the dipteran family Chironomidae is the dominant invertebrate taxon and commonly makes up well over 50% of the number of invertebrates found in cold springs (Ólafsson et al., 2010). Other insect taxa, such as other dipterans and Trichoptera, can be abundant, along with crustaceans, e.g. Cladocera, Copepoda and Ostracoda (Ólafsson et al., 2010; Govoni, 2011).

The spring type – limnocrene (pond forming) or rheocrene (stream forming) – seems to be a key variable in determining the invertebrate communities present. Other key factors are e.g. the temperature and pH of the water. Increased pH has been positively correlated to the number of crustaceans in springs. Often the fauna of warm springs in the highlands, e.g. within the Vonarskarð caldera, resembles lowland systems, and some invertebrate taxa, common in lowland freshwater systems, for instance *Cricotopus syslvestris*, exist in the highlands only in warm springs.

Since 2015, Kreiling et al. have visited 49 springs in Iceland, mostly within the neovolcanic zone of the northern highlands. Freshwater springs in these remote areas of the country can be seen as "ecological islands" with remarkably high invertebrate diversity (Kreiling, unpublished data). These springs might thus be considered hot spots of biodiversity, and awareness of these special habitats needs to be promoted.

As in the open springs, the most commonly found taxon in subterranean groundwater systems is Chironomidae, but other taxa, e.g. Ostracoda, Copepoda and Oligochaeta, have commonly been observed. It is also clear that Arctic charr migrate into the groundwater parts of springs, probably to spawn, but likely as well to forage (Kristjánsson et al., 2012). Charr have been found to migrate underground in lava caves (Leblanc et al., personal communications) and according to local farmers, charr quickly colonise newly dug, waterfilled holes close to the springs they inhabit.

Repeated evolution of small benthic Arctic charr

An example of adaptations towards spring- and groundwater habitats can be seen in the evolution of small benthic Arctic charr (Fig 2.52) within the neovolcanic zones of the nominated property.

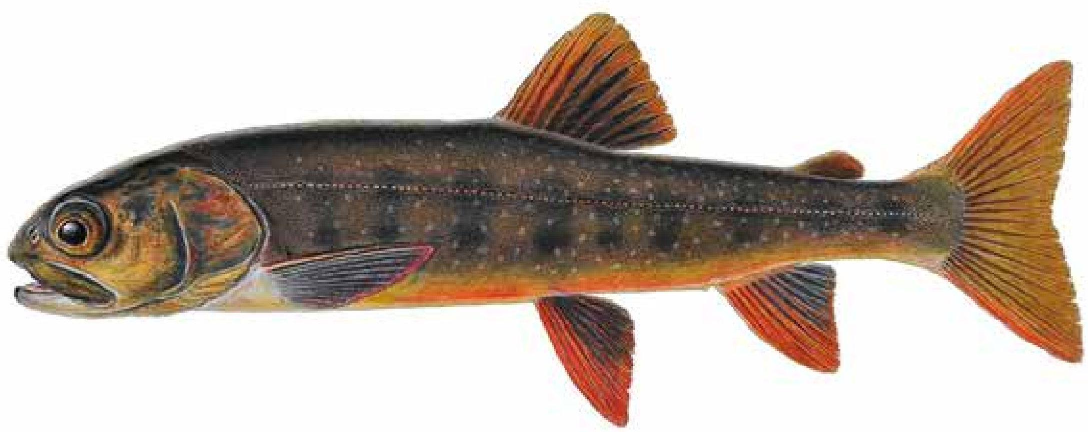
The spring-dwelling small Arctic charr are similar in morphology across different locations (Kristjánsson et al., 2012), but have evolved independently from the "regular" charr morph in each region (Kapralova et al., 2011). They are much smaller than normal charr, mature fish are only 10 –15 cm long, and have retained juvenile characteristics, such as a blunt head and parr marks (Kristjánsson et al., 2012). This is an indication that their parallel evolution has taken place through paedomorphosis (acceleration of sexual maturation relative to the rest of development).

The small benthic charr show clear adaptations to living in the spatially restricting lava spring habitats, where these fish must be able to hide in holes and crevices within the lava. The diversity of the fish across habitats is related to the type of spring they are found in. In limnocrene springs (pond forming) the fish are phenotypically different from those living in rheocrene springs (stream forming). The latter have a thicker body, a different head shape, and a less subterminal mouth than the former. The diet of the fish reflects these morphological differences, with rheocrene charr consuming a higher proportion of chironomid larvae, as well as taking prey from the surface, while the limocrene charr have a more diverse diet and a higher proportion of crustaceans (Kristjánsson et al., 2012).

Such repeated phenotypic evolution across a high number of locations is uncommon worldwide and provides great opportunity for further studies.

The diversity of freshwater habitats within the neovolcanic zones of Iceland and the nominated property is in many ways unique in the world. The occurrence of numerous geographically isolated spring habitats that provide the home to the small benthic morph of Arctic charr allows for powerful comparative research of independent habitats and/or populations. This makes it possible to ask important questions regarding the origin and maintenance of biological diversity at various levels, from intraspecific diversity to diversity of ecosystems. Furthermore, the variable temperatures

Figure 2.52.
Small benthic Arctic charr, *Salvelinus alpinus*, as found within the neovolcanic zones of the nominated property. Illustration by Paul Vecsei for Dr. Jim Reist, Fisheries and Oceans Canada.



found in Icelandic freshwater springs provide the opportunity to study how temperature shapes ecosystems, which is an important question considering global warming. These types of freshwater springs (both cold and warm) are to a large extent unique to Iceland. They are vulnerable to anthropogenic influences and increasingly disturbed in areas that are not legally protected such as Vatnajökull National Park.

Surviving the ice age in subglacial refugia

In 1998 and 2001, two endemic species of amphipods were found in Icelandic springs. *Crymostygius thingvallensis* (Fig 2.53, left) was discovered in Lake Þingvallavatn in SW Iceland (Kristjánsson & Svavarsson, 2004) and later found in one other place, in Herðubreiðarlindir within the nominated property (Egilsdóttir & Kristjánsson, 2008). The species represents a new family of amphipods, Crymostygidae, endemic to Iceland (Kristjánsson & Svavarsson, 2004). The other species, *Crangonyx islandicus* (Fig 2.53, right), was found in the same spring in Þingvallavatn as *C. thingvallensis* (Svavarsson & Kristjánsson, 2006), but has since been found to be widely distributed within the neovolcanic zones, including within the nominated property (Kristjánsson & Svavarsson, 2007).

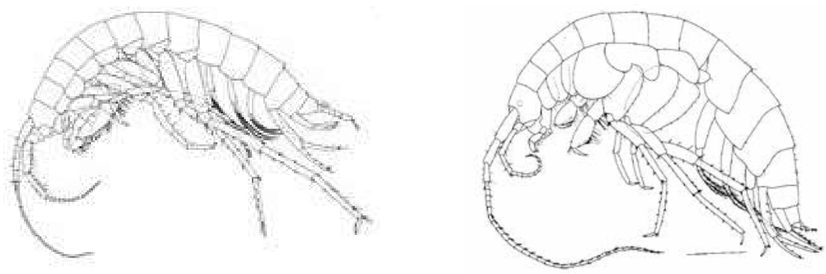


Figure 2.53.
The endemic groundwater amphipods; *Crymostygius thingvallensis* (left) and *Crangonyx islandicus* (right). Kristjánsson & Svavarsson, 2004; Svavarsson & Kristjánsson, 2006.

Population genetic studies have found strong evidence for the survival of these amphipod species in subglacial refugia during the last glacial maximum, and most likely during the entire ice age (Kornobis et al., 2010). Furthermore, studies indicate that these refugia were primarily in the fissure swarms of the nominated property. Potential refugia have been identified, e.g. in the area around the Laki craters and near Mt. Herðubreið. Amphipod populations there are characterised by a higher molecular diversity, in comparison to amphipods found in locations closer to the shore (Kornobis et al., 2010). The endemic amphipods of the neovolcanic zones represent the first known animal species worldwide to survive glaciation in refugia under the ice shield of the ice age.

The above-mentioned amphipods are not the only organisms suspected to have survived in subglacial refugia within the nominated property. Recently many Ciliata species have been found associated with the amphipods (Guðmundsdóttir et al., in review), as well as several species of bacteria, some of which are likely to represent the food source or symbionts of the Ciliata (Guðmundsdóttir et al., in prep). Genetic analysis has revealed two main groups of bacteria, Halomonas and Shewanella, which are known to be chemotrophic, and which may obtain chemical energy from basaltic rocks (Guðmundsdóttir et al., in prep). This may explain how the amphipods managed to survive in the subglacial refugia, and indicates that groundwater food webs in Iceland might be, at least partially, chemotrophic.

2.a (x) Cultural Heritage

No signs of permanent residence have been found in the highland area of Vatnajökull National Park, but at Hvannalindir and Herðubreiðarlindir there are important remains of the dwellings of outlaws, who lived there in secret. Hence, most archaeological features in the highlands are transport related or related to sheep herding. The lowland environs of Jökulsárgljúfur canyon in the north and Skaftafell in the south comprise rich cultural landscapes and extensive ruins of ancient farmsteads and shielings. However, at present, there are no working farms within the nominated property. The settlements closest to the nominated property, especially to the south, have repeatedly been exposed to major natural hazards, and have shown a remarkable resilience and adaptability in very challenging conditions.

The nominated property extends over a vast area, and within it is a diverse cultural heritage. The character of the archaeological features in the property is regionally varied, and reflects the natural environment and landscape. Stretching almost from coast to coast, the property includes vegetated farmland in the north around Ásbyrgi and Jökulsárgljúfur, and south of the ice cap at Skaftafell. In these areas, the lives of previous generations can be traced from the Settlement period until the present. A considerable number of farm mounds, farmsteads and diverse features connected to agriculture and survival in previous centuries exist, and church ruins can be found beneath the turf, as well as heathen and Christian graves.

Over a millennium, the human settlements in the neighbourhood of Vatnajökull, especially south of the ice cap, have been uniquely exposed to natural hazards. Destruction of farmlands and buildings has commonly been caused by changing glaciers and glacial rivers, jökulhlaups, tephra falls and pyroclastic density currents following subglacial eruptions (Þórarinsson, 1957, 1974b; Jónsson, 2004; Ives, 1991, 2007). Also, the settlements south of the ice cap were among the most isolated in the country until the glacial rivers were bridged in the late 20th century. Many examples exist of the adaption of the settlements to challenging conditions. The history of the settlements and their interaction with the natural environment is an interesting subject of study for the many visitors to Vatnajökull National Park, adding to the pleasure gained from studying its geological, glaciological and biological nature.

Registration of archaeological features

Comprehensive registration is a premise for both protection and promotion of the cultural elements of Vatnajökull National Park. Some progress has been made in registering archaeological features, but it is still a long way from being a complete index of all cultural heritage in the area. The process of registering archaeological sites can be divided in three: preliminary appraisal, onsite registration and analysis/report writing. An appraisal involves consulting key sources such as place name registers, land registers and field maps, looking for indications of significant sites. Various other sources may be consulted, e.g. regional-interest publications; *Diplomatarium Islandicum* – a collection of pre-1570 documents; and the Journal of the Icelandic Archaeological Society. A good overview of the number of archaeological remains in each area can be gained in this way. The onsite registration process begins with a visit to a site identified in the appraisal. The archaeological features found there are geographically located and surveyed using GPS; they are also photographed and described in words. The onsite registration usually adds significantly to the known archaeological features, because only a fraction of archaeological remains is mentioned in written sources. The final stage of registration is data analysis and the publication of a report with descriptions of the features, photographs and maps.

Already, documentary sources have been consulted for heritage sites in most of the nominated property (Vésteinsson, 1996). However, the status of archaeological site registration is quite different. Systematic onsite registration has only taken place in the environs of Ásbyrgi, Jökulsárgljúfur and Skaftafell, and very little has been done in the central highlands. The Cultural Heritage Agency of Iceland has established rules and standards for the registration of archaeological sites, allowing for the surveying and mapping of sites. Only a fraction of the available field registers meets the requirements for surveying and mapping, even though the submitted work is good in other respects.

Cultural heritage within the nominated property

Based on the current status of archaeological site registration, four areas within the porperty can be identified that are particularly noteworthy regarding cultural heritage. They are Herðubreiðarlindir and Hvannalindir in the central highlands and the areas in the extreme north and south of the nominated property.

At both Hvannalindir and Herðubreiðarlindir there are ruins of the dwellings of outlaws, and both places are associated with Fjalla-Eyvindur. Eyvindur “of the mountains” Jónsson (1714–abt.1783) was born in southwest Iceland and became a legendary figure after evading the authorities and surviving for many years in the highlands. The ruins at Hvannalindir are much more extensive than those at Herðubreiðarlindir, and testify to having been built for a longer-term occupation. Hvannalindir, one of the remotest areas of Iceland, is an oasis of green in an otherwise barren landscape. The outlaws’ ruins were found in 1880, about 50 years after a local

Ranger shows the ruins of the outlaw Fjalla-Eyvindur at Hvannalindir © Snorri Baldursson.

farmer first explored the area. There are ruins of a small farmhouse, two outhouses and a small sheepfold. The outlaws' ruins at Hvannalindir are protected and listed archaeological remains, and it has been argued that the outlaw couple Fjalla-Eyvindur and Halla lived there for up to a decade in the late 18th century (Briem, 1983). The workmanship of the ruins is believed to be like Fjalla-Eyvindur's work in other parts of the country; they were recently carbon dated, and the result is compatible with this idea.

At Herðubreiðarlindir there is a small hut, built from stones against a natural rock wall and on top of a spring that could be accessed by lifting a slab from the floor. Other manmade structures are known, just a few hundred metres away on the edge of the lava field: a stone-built shelter that was another dwelling, and ruins that might have been used to house sheep (Briem, 1983); but these are all still unregistered. Oral sources report that Fjalla-Eyvindur lived alone in the hut at Herðubreiðarlindir in the winter of 1772, after having escaped custody on his own. North of Herðubreiðarlindir, on the east side of Mt. Miðfell and overlooking the river Jökulsá á Fjöllum, is the herders' hut known as Tumbi, well built from stones and with an intact roof.

There are extensive and ancient ruins in the environs of Ásbyrgi and Jökulsárgljúfur (Ólafsson et al., 2008). The estate Ás is mentioned in Landnámabók (the Book of Settlements). It was an ancient manor with two farmsteads, as well as a church that had fallen into disuse by 1816, and a churchyard.

Many deserted farms and shielings are known on the Ás estate and within the borders of the property in these areas. They are: Gilsbakki, Geithús, Hvammssel, Rauðhólasel, Fornasel and Víðrasel. Most of the ruins of these old farms, and their outhouses and walled homefields, can be easily seen in the surrounding area, arranged up to 15 km southwards from Ás's homefield. The only one of these farms that was inhabited into the 20th century was Svínadalur in Jökulsárgljufur canyon, and it was abandoned in 1947. Svínadalur was uninhabited in 1712 when Árni Magnússon and Páll Vídalín compiled their Jarðabók or land register, but it was inhabited

Sel, one of three former homesteads at Skaftafell. The old turf house is now maintained as cultural heritage by the Cultural Heritage Agency of Iceland © Snorri Baldursson.

again later. Extensive heritage remains are in Svínadalur, including a large farm mound, remains of a chapel and substantial ruins of numerous outhouses and a walled homefield (Ólafsson et al., 2008). In 1919, human remains were found south and west of the homefield in Svínadalur. Kristján Eldjárn believed that it was a heathen burial site and that there were possibly more, undiscovered, heathen graves (Eldjárn, 2016).

At Skaftafell, there are many archaeological features and a rich cultural landscape. In the recent archaeological register for the area, over 160 archaeological sites are identified, and attention is drawn to the rapid growth of the birch woodland, and that if action is not taken the human landscape will be enveloped within a few decades (Lárusdóttir & Heiðarsdóttir, 2014). Remains of old structures are still visible on the surface at 80 sites, and the distribution of features is densest around the four farmsteads.

The Skaftafell farmsteads have migrated to higher ground over the centuries. It is believed that the original farmstead stood on the coastal plain of Skeiðarársandur, but it was moved because of encroachment by the Skeiðará glacial river (Lárusdóttir & Heiðarsdóttir, 2014) and no traces of it remain. Initially it was moved up to Gömlutún (Old Meadow), where signs of habitation can still be seen. The old Skaftafell farm stood in Gömlutún until almost the middle of the 19th century, and there is an important cluster of remains there. The farm property was divided in three when the farmstead at Gömlutún was abandoned due to encroachment and erosion. The farmsteads Hæðir, Bölti and Sel were built instead, on even higher ground, and around them are also many old remains. The farmhouses and outhouses have been rebuilt at Sel, and a smithy and sheepshed restored at Bölti, so these old structures are still protected by roofs. Away from the farmsteads, most of the archaeological sites are connected to grazing: round sheep folds and sheepsheds in the outfields (Lárusdóttir & Heiðarsdóttir, 2014) and examples of drystone walls and grass-covered ruins are widespread.

Some important archaeological sites have not yet been located at Skaftafell. Part of the Skaftafell estate belonged in medieval times to the farmstead and church land Jökulfell. That farm had already been abandoned when Ísleifur Einarsson's Jarðabók or land register was compiled in 1709, but its ruins could still be seen until about 1800. Today its exact location is not known, and probably the ruins are now under gravel and sand from the nearby glacial river Morsá (Lárusdóttir & Heiðarsdóttir, 2014). It is also unknown where on the Skaftafell estate the farm Freysnes stood; it was abandoned before 1362. In the Commonwealth Era (c. 930–1262) a spring Assembly was held at Skaftafell, but the location of Skaftafellsþing has been forgotten, and there seem to be no visible signs of it now (Lárusdóttir & Heiðarsdóttir, 2014).

Human struggle with the elements

The entire district around Öræfajökull was devastated in the 1362 eruption and further damage was done to the remaining settlement in a second major eruption in 1727 (Þórarinsson, 1958; Höskuldsson & Þórðarson, 2007; Roberts & Guðmundsson, 2015), as well as by numerous jökulhlaups in Skeiðará river (Þórarinsson, 1974a). The remaining farms in the district, at Skaftafell, Svínafell, Hof, Fagurhólsmýri, Hnappafell and Kvísker, are clustered at sheltered locations between the main paths of jökulhlaups in the area and are a testament to the struggle of the inhabitants with natural hazards through the centuries (Jónsson, 2004; Ives, 1991, 2007).

As stated above, the settlements to the south of Vatnajökull were among the most inaccessible in Iceland. Bridges over the rivers of Skeiðarársandur sandur plain were built as recently as 1974, the bridge over Jökulsá at Breiðamerkursandur in 1967, and the bridges over Hornafjarðarfljót, farther to the east, in 1961. Other rivers such as Kolgríma, Heinabergsá, Hólmsá and Jökulsá í Lóni were also often difficult to cross. Before the advent of bridges, ferries were operated on some of the rivers, but horses were the main means of crossing for centuries; the southeast coast has very few harbours. Not only were the settlements isolated from the rest of the country, but also among themselves. Crossing the rivers on horseback demanded skill of both horses and riders. Hence, farmers in the area trained their horses especially for this purpose. Dramatic descriptions of travels over the rivers on horseback feature in the literature, for example in a famous essay Vatnadagurinn mikli (The great day of fording, 1943) by Þórbergur Þórðarson (1888–1974), one of the leading novelists in Iceland in the 20th century.

Top: The bridge over Heinabergsvötn was built in the 1940s, but shortly afterwards the river moved to the west © Snævarr Guðmundsson. Bottom: The remains of the Gígja bridge stand now as a memorial to the 1996 Gjálp jökulhlaup, 30 December 2017 © Hrafnhildur Ævarsdóttir.

Maintaining road connection over glacial rivers is challenging, even with modern technology, due to the migration of river paths and because of occasional jökulhlaups. A couple of bridges have been left standing on dry land after the river changed course due to the retreat of the glacier terminus, providing an interesting demonstration of the challenge in question. Several bridges have, furthermore, been damaged or destroyed by jökulhlaups, such as after the Gjálp eruption in 1996. Dramatic evidence of the destructive power of this event is provided by the twisted steel beam from the bridge over Skeiðará, exhibited at a rest area by road 1, close to Skaftafell.

East of Öræfajökull, the Breiðamerkurjökull outlet glacier advanced over settled areas, mainly in the 17th and 18th centuries (Þórarinsson, 1974b; Jónsson, 2004), including farms established by the earliest generations of settlers of Iceland. Some of these former farmlands have again become ice-free as a result of the retreat of the glacier since the end of the 19th century and are now among Iceland's most popular tourist destinations.

Still farther east, erosion by glacier rivers has greatly affected hay fields and other vegetated areas, particularly near the rivers Steinavötn, Heinabergsá and Hornafjarðarfljót where jökulhlaups from ice-dammed lakes were an increasing problem for the settlements during the Little Ice Age (Jónsson, 2004, and references therein). By Hólmsá, eastward migration of the glacial river in the proglacial terrain due to terminus retreat in the early 20th century endangered the settlement. The danger was averted in the 1930s thanks to a great effort by the farmers of the area who built dams and dug channels to contain the river (Jónsson, 2004). Large dams for diverting and containing the glacial rivers have since been constructed. Extensive areas, formerly devastated by glacial river erosion, have also been successfully revegetated (Jónsson, 2004), the Skógey area by Höfn in Hornafjörður being a particularly good example.

2.b History and Development

Iceland probably first began to develop about 25 million years ago with the oldest surface rocks in West and East Iceland dated at 17 million years BP. The oldest rocks within the nominated property are ca. 10 million years old and the youngest, Holuhraun lava, less than three years old at the time of writing. Most likely, the Vatnajökull ice cap disappeared in the early Holocene and began to form again around 4000 BP, reaching its maximum size at the end of the 19th century. The record of scientific research and endeavours is strong and fruitful. Further, the nominated property is the venue of some of the largest natural disasters in the history of Iceland, providing many tales of human struggle against the elements.

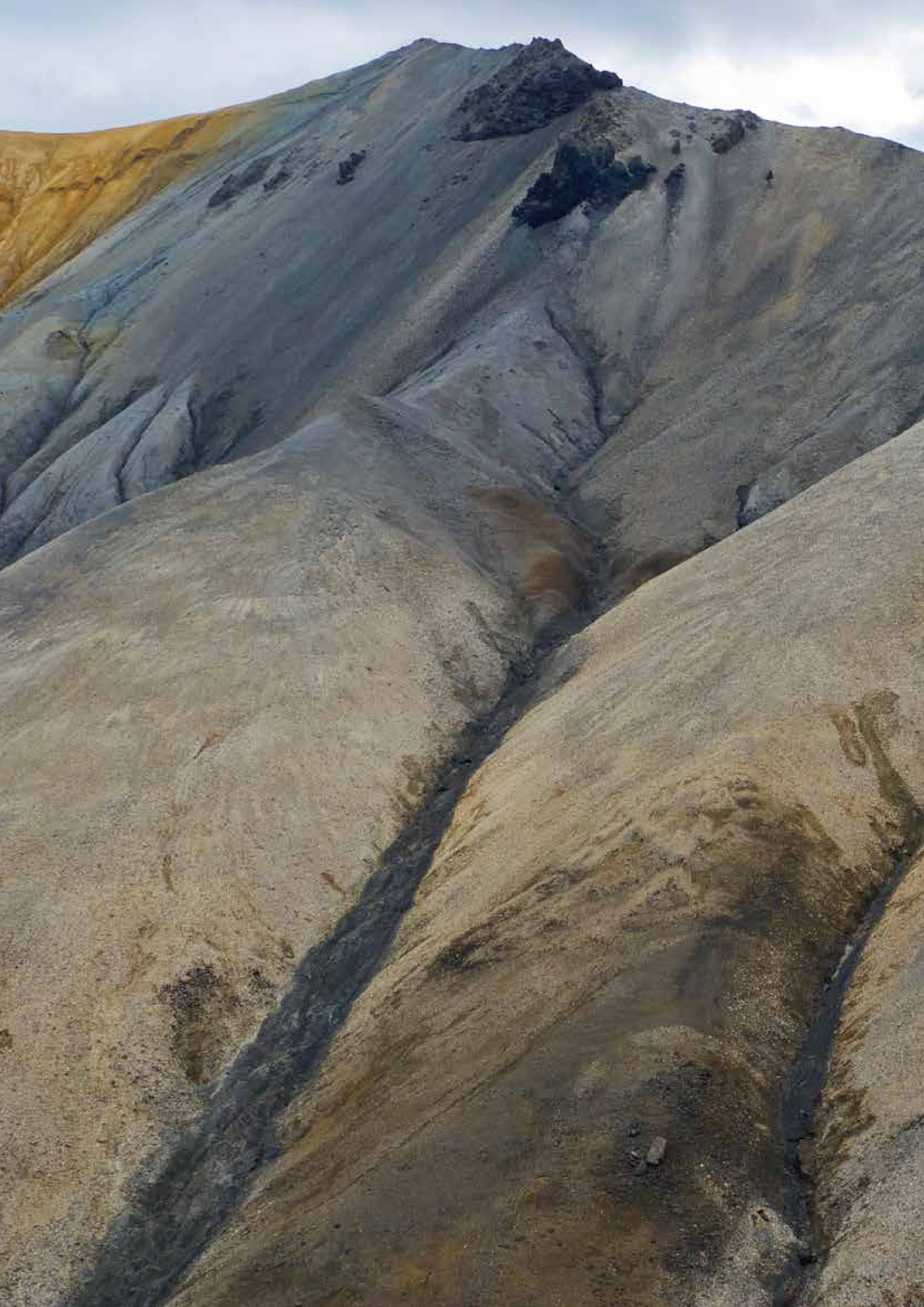
2.b (i) The creation and growth of Iceland

Opening of the North Atlantic began about 55–60 million years ago, with massive basaltic volcanism, evident on both sides of the Atlantic. Divergence of the North American plate and the Eurasian plate since that time has formed the ocean floor in the North Atlantic, with the Mid-Atlantic Ridge marking the current plate boundary. The history of spreading is well documented by regular magnetic lineaments on the ocean floor both south and north of Iceland, with magnetic observations from ocean floor south of Iceland being used in the early development of the ideas of plate tectonics. Iceland probably first began to develop as a land mass about 25 million years ago, when the westward drifting Mid-Atlantic Ridge encountered a static mantle plume providing a generous source of magma that ever since has been building the country. However, the oldest dated surface rocks in Iceland are about 17 million years old, found in West and East Iceland furthest away from the present plate boundary. The youngest rocks in Iceland and the highest altitude occurrences are within the neovolcanic zone that traverses Iceland, including the nominated property.

Iceland, one of the most thoroughly studied volcanic hotspots, has been suggested to be the manifestation of an upwelling mantle plume (Morgan, 1971). Excessive mantle upwelling under central Iceland is reflected in anomalously low seismic velocities, initially recognised by Tryggvason (1964), and first mapped out in a pioneering seismic tomography study by Tryggvason et al. (1983) which imaged deep subsurface features. Data from a network of broadband seismic stations operated in Iceland in 1993–1996 then allowed Wolfe et al. (1997) to resolve these low velocity seismic anomalies much further. They found low velocities of both P- and S-waves extending from a depth of 100 km to at least 400 km beneath central Iceland, and concluded that Iceland is underlain by a hot, narrow plume of upwelling mantle with a radius of approximately 150 km.

A study by Allen et al. (2002a, 2002b) used a combination of seismic body wave and surface wave data. Their favoured model for S-wave velocity is shown in Fig 2.54. It shows a cylindrical low-velocity anomaly extending from the maximum depth of resolution at 400 km up toward the surface, where it spreads out beneath the lithosphere. The results are interpreted as a vertical plume conduit at a depth of 400 to ca. 200 km and a horizontal plume head above

Next page: Mt. Göngubrún in Vonarskarð © Snorri Baldursson.



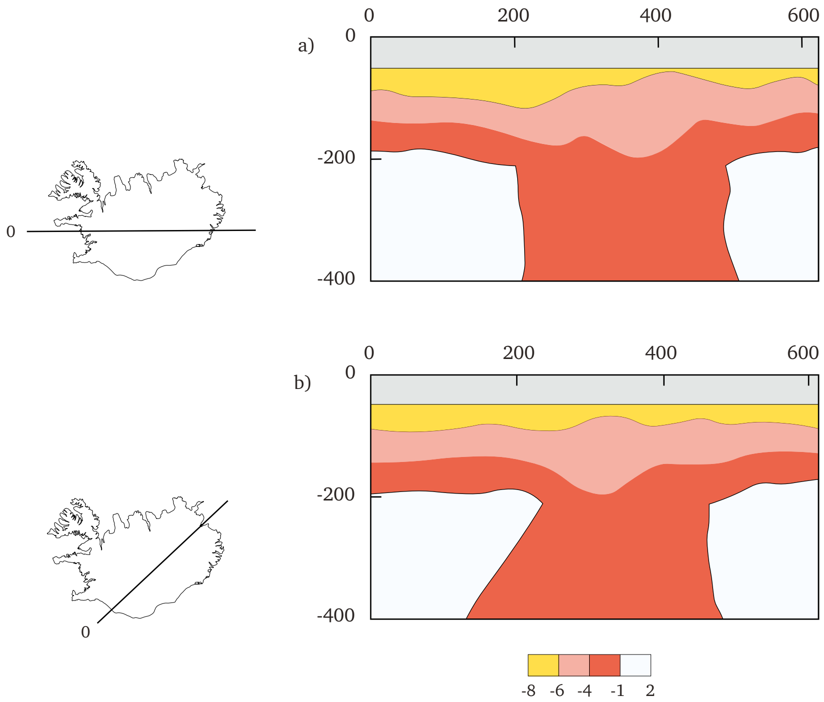


Figure 2.54.
Vertical cross sections through a mantle S-velocity model. Reconstructured after Allen et al. (2002a).

200 km. Multiple studies of seismic wave velocities show that a plume like structure is well resolved in the uppermost few hundred kilometres under Iceland, with a centre under northwestern Vatnajökull. This accords well with the idea of a mantle plume under Iceland, as initially suggested by Morgan (1971).

An alternative model, attributes enhanced magmatism in the Iceland region to high local mantle fertility which leads to anomalously large volumes of melt on this part of the ridge (e.g. Foulger & Anderson, 2005; Foulger et al., 2005), rather than a deep-seated mantle plume. The source of the high local mantle fertility in this model is subducted ocean crust associated with the Caledonian collision around 440–400 million years ago, when an earlier ocean in the North Atlantic region closed. However, in this model there is also excessive production of magma under central Iceland.

The excessive magmatism at the Iceland hotspot is also witnessed in crustal thickness, as the crust is formed from magma extracted out of the mantle of the Earth. The crustal thickness in Iceland as revealed by seismic studies of Allen et al. (2002a) is shown in Fig 2.55. The centre of this activity is often called the Iceland hotspot.

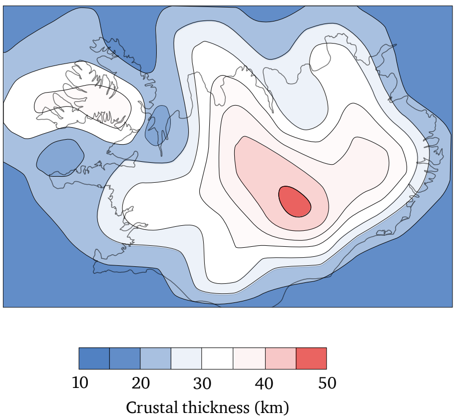


Figure 2.55.
Crustal thickness model for Iceland. Reconstructed after Allen et al. (2002b).

The North Atlantic area is dominated by the Iceland mantle plume and the excessive magmatic activity that has built up the country. Many of the characteristics of the North Atlantic can be attributed to the interaction of this mantle plume with the Mid-Atlantic Ridge, as reviewed by Ito et al. (2003), for example. On land in Iceland, the plate-spreading pattern is more complicated because of the plume-ridge interaction, and the relative motion between the central axis of the plate boundary and the excessive mantle upwelling. If the centre of the mantle plume is regarded as fixed over millions of years, the plate boundary system drifts gradually westwards relative to it. When the central axis (the rift zone) has drifted sufficiently far from the focus of mantle upwelling, a rift jump occurs and a new segment of a spreading zone opens above the centre of mantle upwelling.

This has occurred several times since the formation of Iceland.

As a result, the plate spreading history in Iceland is complex, with extinct rifts towards the west of the present spreading axis. Plate divergence north of Vatnajökull is currently fully accommodated by spreading across a single rift zone, the Northern Volcanic Zone (Drouin et al., 2017). The volcanic rift zone southwest of Vatnajökull is called the Eastern Volcanic Zone, to distinguish it from the overlapping Western Volcanic Zone, which is located further towards the west. Following rift jumps, it is inferred that activity began in the Northern Volcanic Zone about 6–7 million years ago and in the Eastern Volcanic Zone about 2–3 million years ago (Sæmundsson, 1979). Although the zone of plate spreading and rifting is continuous under Vatnajökull, these two zones are of different age and somewhat different character, and a transition between the Eastern and Northern Volcanic Zones is inferred beneath the ice cap.

2.b (ii) Formation of the Vatnajökull ice cap and its history

Vatnajökull is not a remnant of the Weichselian ice sheet that covered the entire country during the last glacial maximum. The deglaciation following this glacial period began about 15,000 BP (Norðdahl & Pétursson, 2005). The most continuous data set to shed light on the Holocene development of Vatnajökull is the sedimentary record from lake Lögurinn, which receives meltwater from Eyjabakkajökull outlet glacier. By about 9000 BP, no meltwater originating from the ice cap was entering this lake.

The warmest period of the Holocene, called the Holocene Thermal Maximum, began around 8000–7000 BP and lasted until 5000 BP (Striberger et al., 2011; Geirsdóttir et al., 2013). During this period, the Weichselian ice sheet disappeared and probably only small glaciers were found on the highest mountains. The return of glacial meltwater to Lögurinn (signifying the return of Eyjabakkajökull) is dated to ca. 4400 BP (Striberger et al., 2011), which is in accordance with other data from Iceland, indicating a decline in summer temperatures starting ca. 5000 BP (Geirsdóttir et al., 2013). Glaciers began expanding in the highlands approximately 3000–4000 BP. From the sediment record of Lögurinn, it has been inferred that Eyjabakkajökull had reached a considerable size around 2200 BP. Similarly,

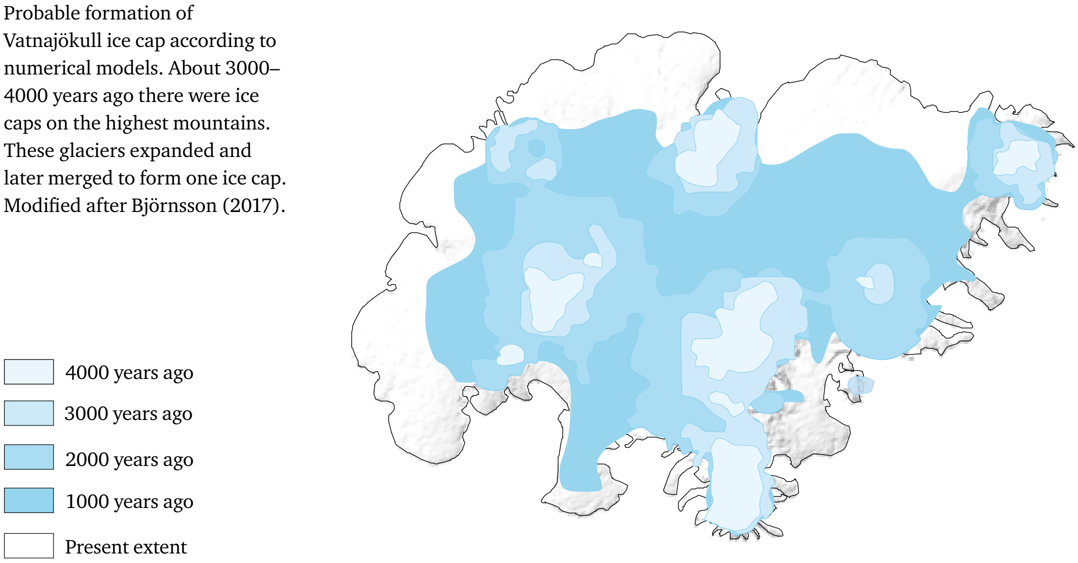


Figure 2.56.
Probable formation of Vatnajökull ice cap according to numerical models. About 3000–4000 years ago there were ice caps on the highest mountains. These glaciers expanded and later merged to form one ice cap. Modified after Björnsson (2017).

tree logs found in the forefield of Fláajökull are dated to about 2100 BP (Jónsson et al., 2016) and in the forefield of Skaftafellsjökull dated to 2000 BP (Ives, 2007), indicating that the valleys had been ice-free and that the glaciers probably started to reform at that time.

Vatnajökull began to take on its modern form when glaciers from mountain ranges at elevations between 1200 and 2000 m coalesced. This stage was probably reached 1000–1500 years ago according to numerical models (Björnsson, 2017). By the time of the Settlement, around 874 AD, all the glaciers had coalesced into one continuous ice cap (Fig 2.56). The step-wise cooling in the latter part of the Holocene culminated in the Little Ice Age. However, the outlet glaciers of southeast Vatnajökull did not reach the lowlands until the 17th and 18th centuries. By the end of the 19th century, the ice cap had reached its maximum Holocene size. Soon after that the outlet glaciers started receding, marking the end of the Little Ice Age.

History of subglacial eruptions and tephrachronology

Knowledge of the eruptive history of subglacial volcanoes within the Vatnajökull ice cap (Table 2.8) is primarily derived from tephrachronology and from contemporary accounts (Larsen, 2002; Þórdarson & Höskuldsson, 2008). The tephrachronology has been established through soil sections outside of the ice cap (Óladóttir et al., 2011) and reinforced through studies of tephra horizons in the outlet glaciers of the ice cap (Larsen et al., 1998).

Table 2.8.
Known subglacial eruptions within the Vatnajökull ice cap since 1300 AD. For Bárðarbunga and Grímsvötn the eruptions are grouped into intervals, for Öræfajökull the known year of eruption is indicated (Jakobsson & Guðmundsson, 2008; Larsen et al., 1998; Þórarinsson, 1974a; Thórðarson & Larsen, 2007).

Volcanic system	Interval	Number of eruptions
Bárðarbunga	1300–1500	3
	1501–1700	0
	1701–1800	10
	1801–2000	2
Grímsvötn	1301–1400	8
	1401–1500	7
	1501–1600	3
	1601–1700	13
	1701–1800	8
	1801–1900	11
	1901–2011	9
Öræfajökull	1362	1
	1727	1

In historic times (since 874), 60% of all eruptions in Iceland have been subglacial, and 80% of these have occurred within the nominated property (Larsen, 2002; Thórðarson & Höskuldsson, 2008; Thórðarson & Larsen, 2007). Subglacial eruptions occur every 10 years on average. The activity appears periodic with a recurrence interval of some 60–80 years (Larsen et al., 1998). The largest subglacial eruption in historic times was the 1362 Öræfajökull eruption, producing some 10 km³ of tephra that devastated the county of Öræfi (then named Litla-Hérað) to the south of the volcano. The Öræfajökull event was up to four orders of magnitude larger than the smallest known events that rarely result in tephra fall outside of the ice cap (Larsen, 2002).

The size of a subglacial eruption can't be deduced from the subsequent tephra layer as minor tephra layers may be associated with relatively large events. For example, in the 1996 Gjálp eruption (Box p. 64), tephra fall was confined to Vatnajökull and is therefore not recorded in soil sections. It is estimated that only about one in five Grímsvötn eruptions deposit tephra outside of the glacier. For this reason, the frequency of volcanic eruptions in Iceland, particularly subglacial ones, will always be underestimated (Larsen & Eiríksson, 2008).

A recent study aimed at resolving this problem and estimating the number of eruptive events within the ice cap during the Holocene, compared the number of tephra layers in the ice with tephra layers in soil sections from the surrounding area (Óladóttir et al., 2011). The resulting estimate was that the central volcanoes of Grímsvötn, Bárðarbunga and Kverkfjöll have erupted approximately 960 times during the last 8000 years. Grímsvötn is responsible for an estimated 540 eruptions, Bárðarbunga for some 350 and Kverkfjöll 70, none during historic times (Óladóttir et al., 2011). The study found that there was a marked low in subglacial volcanic activity between 5000 and 2000 years ago.

Eruptive history of Grímsvötn

The Grímsvötn system is estimated to have erupted between 50–55km³ of magma during the Holocene (Jakobsson, 1979). The volume of magma produced in the ice-free region of the system is 21.5 km³, of which 15.1 km³ (65%) were erupted by the Laki fissures in 1783–1784. On average, Grímsvötn has erupted 6–11 times per century, and is therefore Iceland's most active volcanic system (Óladóttir et al., 2011). In historic times, only the Katla volcanic system has erupted more volume, mostly during the Eldgjá 939 AD eruption (Thórðarson & Larsen, 2007).

Three types of Grímsvötn eruptions can be distinguished, i.e. subglacial eruptions within the Grímsvötn calderas, subglacial eruptions outside of the calderas and finally subaerial eruptions on the fissure swarm.

Small to medium sized (<0.1 km³ of material) explosive basalt eruptions within the main Grímsvötn caldera have been most common; all recent eruptions (1998, 2004 and 2011) have occurred at the southern rim of the caldera fault (Guðmundsson et al., 2013; Guðmundsson & Larsen, 2015; Jude-Eton et al., 2012). These events quickly melt their way through the ice and progress from subglacial eruption to a subaerial phreatomagmatic eruption. Melting through the overlying 50–200 m thick ice takes minutes to one or two hours (Guðmundsson & Larsen, 2015). Most of the erupted material is deposited onto the Vatnajökull ice cap and the craters formed are short lived (Guðmundsson et al., 2013). Tephra production is primarily phreatomagmatic, and typical plume heights are around 10 km (Guðmundsson et al., 2013).

Subglacial eruptions outside of the principal Grímsvötn caldera seem to occur one or two times per century and tend to be larger than the ones within the caldera. Two eruptions of this type are known from the 20th century north of Grímsvötn, in 1938 and 1996. They melt their way through thick ice and are a potential source for large jökulhlaups (Guðmundsson et al., 2013, 1997). The best-known event of this type is the 1996 Gjálp eruption (Box p. 64). Subglacial eruptions to the south of the Grímsvötn caldera and around Þórðarhyrna are known (1903) or inferred (1887) (Grönvold & Jóhannesson, 1984). Eruptions in this part of the volcanic system are also inferred in 1887 and 1753. The 1753 event was followed by jökulhlaups in the rivers Djúpá, Hverfisfljót and Skaftá (Þórarinsson, 1974a).

During the Holocene, there have been at least four (possibly six) subaearial eruptions on the ca. 100 km long and 15 km wide volcanic fissure swarm of the Grímsvötn volcanic system to the southwest, including the Lambavatnsgígar cone row north of Mt. Laki (Guðmundsson et al., 2013). However, the Laki eruption 1783–1784 (Box p. 65) is the only historical event. Others are known from their eruptive vents and lava flows.

Eruptive history of Bárðarbunga

During the Holocene, the Bárðarbunga/Veiðivötn volcanic system has been the second or third most active in Iceland, with 14% of all events in terms of frequency (Thórðarson & Larsen, 2007). Most volcanic events occur in the subglacial central volcano Bárðarbunga with an inferred 350 events during the Holocene (Larsen & Guðmundsson, 2015; Óladóttir et al., 2011).

There are 22 confirmed Holocene eruptions on the ice-free part of the system (Larsen & Guðmundsson, 2015; Óladóttir et al., 2011) and these are some of the largest in Iceland. Namely, the formation of the Þjórsá lava around 8500 years ago, the Vatnaöldur eruption in around 870 and the 1477 Veiðivötn eruption. The Þjórsá lava (mostly outside the nominated property) is approximately 950 km² in area and 21 km³ in volume, and presumed to be the largest Holocene lava flow on Earth formed in one eruptive episode (Fig 2.57; Hjartarson, 1988). The ca. 870 Vatnaöldur eruption (vents outside the nominated property), on the other hand, produced some five km³ of highly fragmented tephra, which is found in soils in large parts of Iceland.

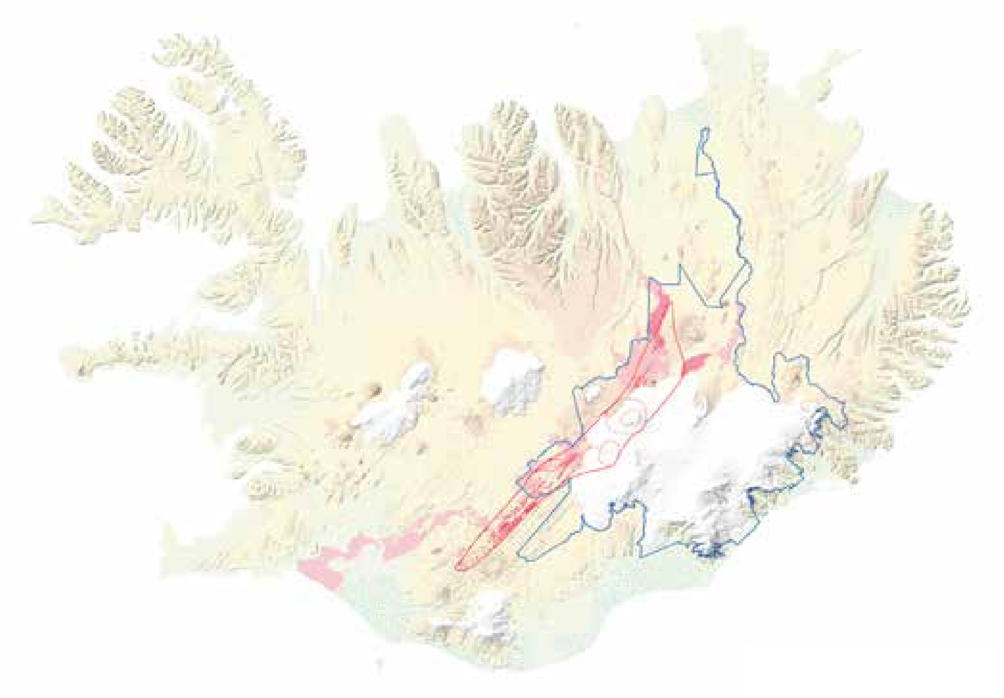


Figure 2.57.
Holocene lava flows from the Bárðarbunga/Veiðivötn volcanic system. From Jóhannesson & Sæmundsson (1998).

Vatnajökull National Park boundary
Caldera
Central volcanoe
Volcanic sysetm
Historic lavas, <1100 years.
Prehistoric lavas, 1100–11,500 years.

The Little Ice Age in written documents

The cool and fluctuating climate of the Little Ice Age in Iceland is clearly evidenced in written documents as early as the 13th century (Þórarinsson, 1960; Ogilvie, 2005), and in the sea-ice annals since the 1600s (Bergþórsson, 1969; Ogilvie, 2010; Ogilvie & Jónsson, 2001). In Konungs Skuggsjá (King's Mirror) from the middle of the 13th century (Lárusson, 1955), glaciers and glacial rivers are described and their existence explained by their geographical location close to cold ice-covered Greenland. Þórarinsson (1960) infers that this is most likely the oldest climatological explanation of glaciers found in the literature. Permanently frozen glaciers on high mountains are mentioned in Guðmundar Saga Biskups Arasonar, written around 1350 (Kristjánsson, 2002). Descriptions of advancing glaciers due to a colder climate are found in the treatise of bishop Oddur Einarsson from 1590 (Einarsson, 1971). But the written accounts describing the deteriorating climate and advancing glaciers in Iceland only become prolific and detailed around 1700 (e.g. Þórarinsson, 1943; Ogilvie, 2005).

The eruption coincided with the colonisation of the country. Hence the tephra layer has been termed the "settlement layer" and is an important chronostratigraphic marker in Iceland (Larsen, 1984). The 1477 Veiðivötn eruption (vents outside the nominated property) produced some 10 km³ of tephra and sizable lava flows. Tephra from this eruption fell mostly to the northeast, where it had, and continues to have, a huge environmental impact (Box p. 42).

The youngest fissure eruptions of the system created the 1862 Tröllahraun lava field (28 km² in area and 0.3 km³ in volume) on the southern fissure swarm, just west of Hamarinn and Sylgjujökull within the property (Þórarinsson & Sigvaldason, 1972), and the 2014–2015 Holuhraun lava field (Box p. 36).

Glacier variations during the Little Ice Age (ca. 1450–1900)
Terrestrial records around Iceland indicate that the transition into the Little Ice Age occurred in two steps with initial summer cooling 1250–1300 AD, and a more severe drop in summer temperatures between 1450 and 1500 AD (e.g. Geirsdóttir et al., 2009, 2013; Axford et al., 2011; Striberger et al., 2010, 2012; Larsen et al., 2011, 2013; Knudsen et al., 2012). Records of widespread glacier advances demonstrate the Little Ice Age cooling in Iceland. Most glaciers reached their Holocene maximum extent in either the 18th or 19th century, and some advanced during both periods (e.g. Þórarinsson, 1943; Guðmundsson, 1997; Evans et al., 1999; Sigurðsson, 2005; McKinzey et al., 2014; Kirkbride & Dugmore, 2008; Björnsson, 2009; Geirsdóttir et al., 2009; Larsen et al., 2011).

Historical documents are very important for inferring glacier advances, as methods to date glacier moraines, e.g. by means of lichenometry, have proved to be inconsistent (e.g. Decaulne, 2016). The Little Ice Age terminal (outermost) moraines in the forefield of the outlet glaciers of southern Vatnajökull have been dated to the 18th or the 19th century by lichenometry and a few by tephrochronology (Hannesdóttir et al. 2015a; Decaulne, 2016).

Rest in Morsárdalur valley, Skaftafell, around 1938, Morsárjökull in the background © Ingólfur Ísólfsson.

The first descriptions of the Little Ice Age glacier margins in Iceland were obtained in the inhabited regions south of Vatnajökull ice cap. The local accounts and the writings of naturalists and travellers provided information about the extent of the outlet glaciers at their most advanced positions. Descriptions of damaged pastures, hayfields and houses due to glacial rivers and advancing glaciers, along with difficult access to grazing areas, are prominent in the written records. Historical records detail how the outlet glaciers advanced in the late 17th century and reached far out on the lowlands in the mid-18th century.

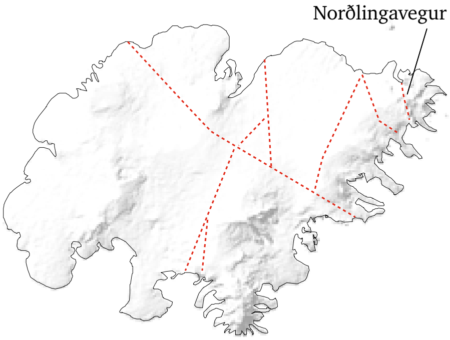


Figure 2.58.
Suggested mountain routes between settlements south and north of the ice cap from the time of settlement until the end of the 16th century. From Þórarinsson (1974b).

Routes across Vatnajökull were in previous centuries used for travelling between different parts of the country (Fig 2.58). Some mountain routes between farms and settlements became impassable due to advancing glaciers during the Little Ice Age. One of those routes, known as Norðlingavegur, lay from Fljótsdalur northeast of the ice cap to Lón in the southeast. Farmers and migratory workers from north Iceland crossed the ice cap for the fishing season on the southeast coast, whereas workers in the south would head for the northern highlands to collect grasses and herbs or to find summer grazing for horses. There are also indications of a route between Skaftafell, south of the ice cap, and Möðrudalur á Fjöllum in the northern highlands, which was abandoned well before 1700.

Many photographs of Vatnajökull from the late 19th and early 20th century have been preserved (Ponzi, 2004; Archives of the National Land Survey of Iceland; Reykjavík Museum of Photography; National Museum of Iceland) and a collection has been made available on the website of the Iceland Glaciological Society. The photographs provide valuable information on glacier extent. Through analysis of repeat photography to deduce glacier changes, they clearly illustrate the magnitude of the pronounced changes of the last 120 years.

The oldest photographs of Vatnajökull were taken by Frederick W.W. Howell (1857–1901) in 1891 and during the surveying work of the Danish General Staff in the first years of the 20th century. These first photographs were taken at the height of the Little Ice Ace, thus providing good evidence of the extent of the outlet glaciers at the time. Howell took some unique oblique photographs of Kotárjökull outlet glacier that have been used to calculate the surface lowering of the glacier since the end of the 19th century (Guðmundsson et al., 2012). Howell's photograph of Kvíárjökull from the same year shows that the glacier almost reached the crest of the moraines, in accordance with descriptions of ice-blocks rolling down the moraine wall in the 1870s to 1890s (Björnsson 1998).

Glacier variations since the end of the 19th century

Since the end of the Little Ice Age, the ice cap has lost some 400 km³ of ice, mainly in response to climate warming caused by changes in atmospheric and oceanic circulation around Iceland in the early part of the 20th century and global anthropogenic warming after the middle of the century (Björnsson et al., 2013 and references therein). Most termini of the outlet glaciers have retreated several kilometres since then, although several surging outlets have temporarily advanced in the 20th century. Recent studies on the changes of the non-surging southern outlet glaciers of Vatnajökull since the end of the 19th century (Guðmundsson, 2017; Hannesdóttir et al., 2015a, 2015b) have provided new quantitative estimates of glacial mass loss. The general response of the southern outlets of Vatnajökull to the warming climate of the 20th century is quite similar, but their individual dynamics differ (Fig 2.60).

The response of Vatnajökull's outlet glaciers to climate change and mass balance depends on their size and shape, but most of them react within a few years by adjusting the position of their snout.

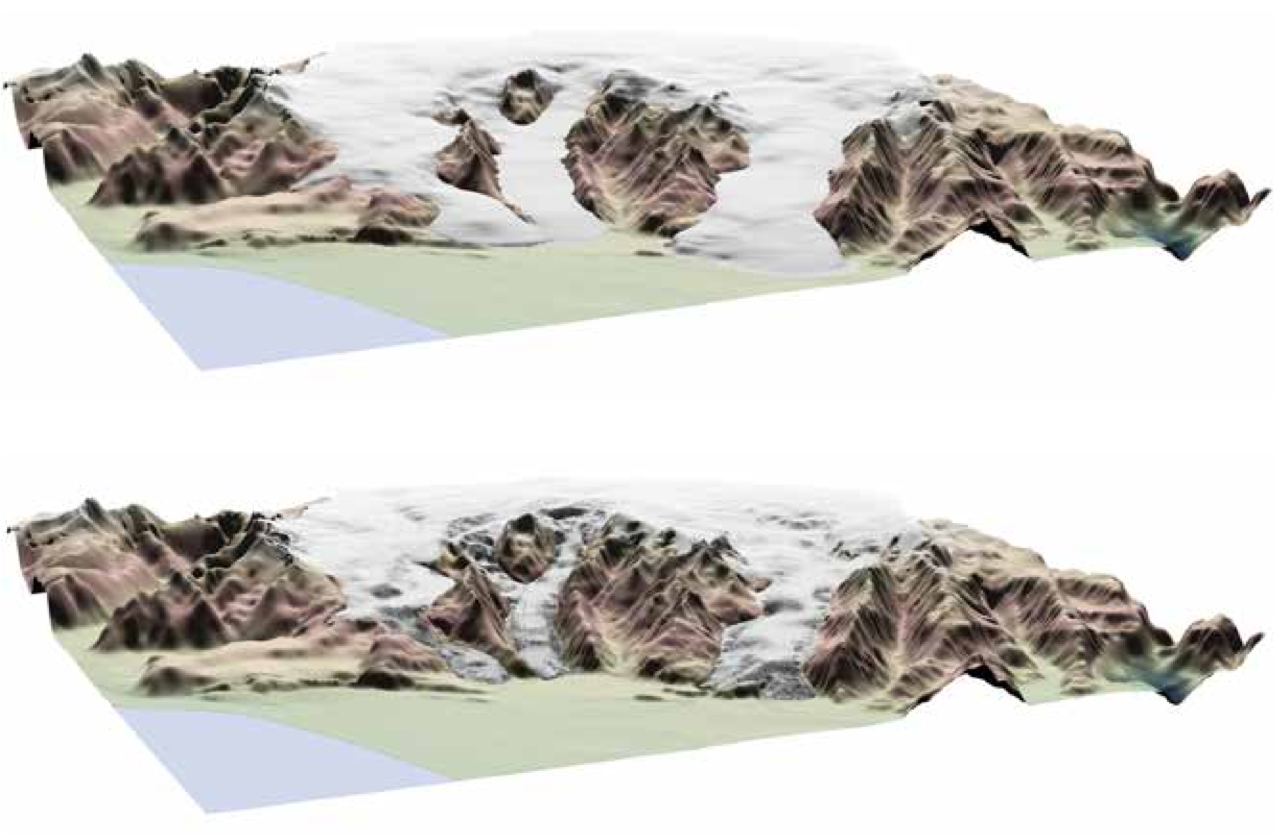


Figure 2.59.
Top: Reconstructed surface geometry of Skálafellsjökull, Heinabergsjökull and Fláajökull around 1900, based on glacial geomorphological data and oldest maps. Bottom: The same glaciers in 2010, based on a lidar DEM. Hrafnhildur Hannesdóttir, unpublished data.

Old and new photographs demonstrating glacier retreat. Top left: Kotárjökull and Rótarfjallsjökull (outlets of Öræfajökull) in 1891 © Frederick W.W. Howell. Top right: Kotárgil from ca. the same location in 2011 © Snævarr Guðmundsson. Middle left: In 1935, Breiðamerkurjökull and Fjallsjökull closed off Mt. Breiðamerkurfjall as seen from Breiðamerkursandur © Helgi Arason. Middle right: Mt. Breiðamerkurfjall from ca. the same location in 2015 © Snævarr Guðmundsson. Bottom left: Kotárjökull in 1925 © Ólafur Magnússon. Bottom right: Kotárjökull from ca. the same location in 2012 © Aron Reynisson.

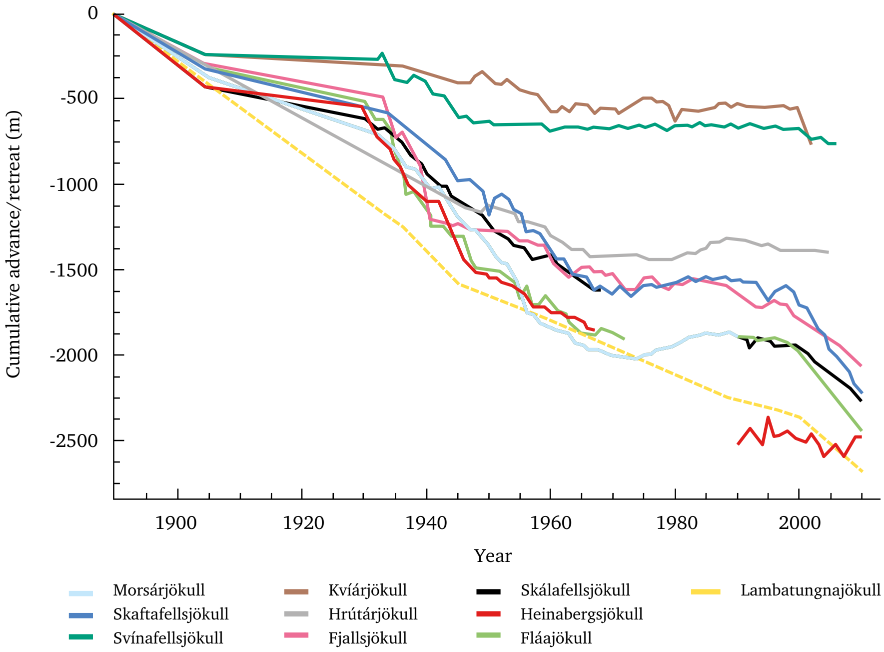
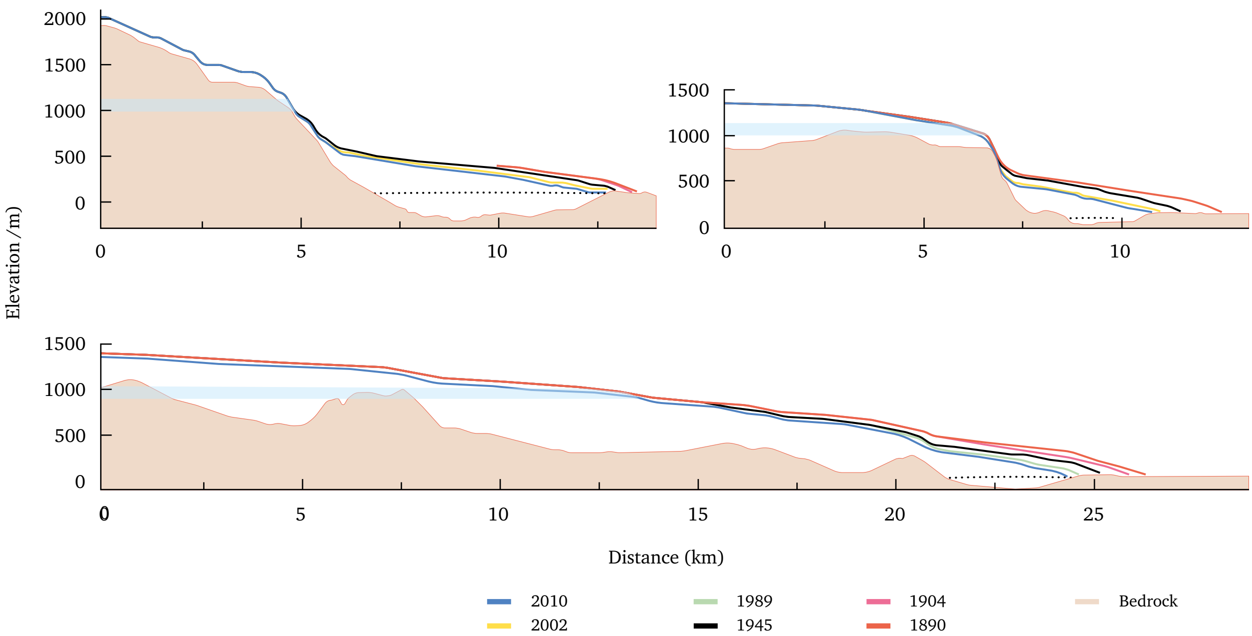


Figure 2.60.
Cumulative frontal variations of a few south-flowing outlet glaciers relative to the ca. 1890 terminus position determined from the terminal Little Ice Age moraines. The retreat until 1932, when measurements of volunteers of the Icelandic Glaciological Society started, is hypothesised, while the position in 1904 is known from the maps of the Danish General Staff. From Hannesdóttir et al. (2015b).

The glacier will then continue to retreat or advance for many years or decades until the adjustment to the change in climate has been completed. Short and steep valley glaciers complete their adjustment within a decade or two, but larger and less steep glaciers have a much longer response time.

The southern outlet glaciers of Vatnajökull have lost between 15 and 50% of their 1890 volume, the difference attributed to their variable hypsometry, i.e. their basal topography, and the presence of proglacial lakes that enhance melting at the terminus (Figs 2.60–2.63). The different response of glaciers experiencing similar climatic forcing underlines the importance of using a large sample of glaciers when interpreting the climate signal. The varied responses show that frontal variations and area changes only provide limited information on the glacier response, as some glaciers have experienced rapid downwasting but little retreat (Hannesdóttir et al., 2015b).

Figure 2.61.
Longitudinal profiles of three south-flowing outlet glaciers, showing ice thickness and location of the termini at different times. The average equilibrium line altitude, derived from the MODIS images, is shown with a light blue horizontal band. From Hannesdóttir et al. (2015b).



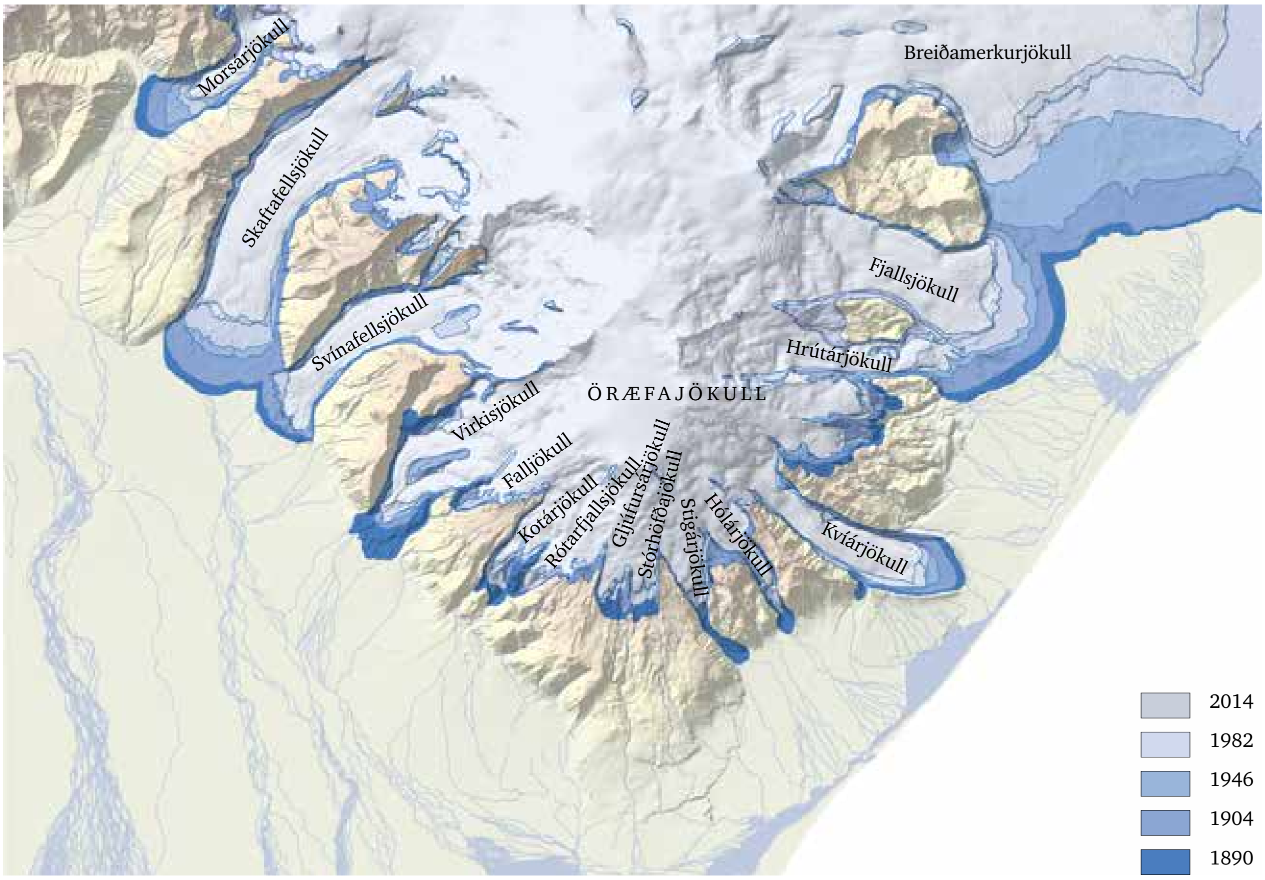


Figure 2.62.
The extent of the outlet glaciers of Öræfajökull and neighbouring glaciers at different times since the maximum of the Little Ice Age ca. 1890. Based on Hannesdóttir et al., 2015a, 2015b; Guðmundsson et al., 2017 and unpublished data.

Outlook

Many modelling studies have been carried out for Vatnajökull to assess the ice cap's sensitivity to climate change and to predict its future (e.g. Marshall et al., 2005; Flowers et al., 2005; Aðalgeirsdóttir et al., 2006, 2011; Hannesdóttir et al., 2015c). Vatnajökull is sensitive to small, sustained temperature shifts and the maritime situation of the ice cap makes it one of the most sensitive glaciers in the world (de Woul & Hock, 2005). The dynamic nature of the ice cap, with frequent surges, jökulhlaups, and geothermal and volcanic activity, make it difficult to simulate. The outlet glaciers of southern Vatnajökull are more vulnerable to climate warming than the outlet glaciers to the north and west because the southern ice margin reaches down to lower elevations.

The future of the glaciers and ice caps in all of Iceland, as well as within the nominated property, is dependent on their elevation range and the future climate. It has been estimated that annual mean temperatures in Iceland will increase by ca. 2°C during the 21st century, and that the climate may continue to warm during the following century (Gosseling, 2017). Given this magnitude of warming, glacier models indicate that after 200 years there will only be small ice caps on the highest mountains of Vatnajökull, i.e. on Öræfajökull and in the highlands between Grímsvötn, Bárðarbunga and the Kverkfjöll mountains (Jóhannesson et al., 2011b; Aðalgeirsdóttir et al., 2011). Vatnajökull could lose a quarter of its current volume within the next fifty years, though its northern part will survive a bit longer (Fig 2.64). The total runoff from the ice cap will increase over the same period, and remain higher than today well into the 22nd century, until the ice reservoir has been substantially depleted (Jóhannesson et al., 2007).

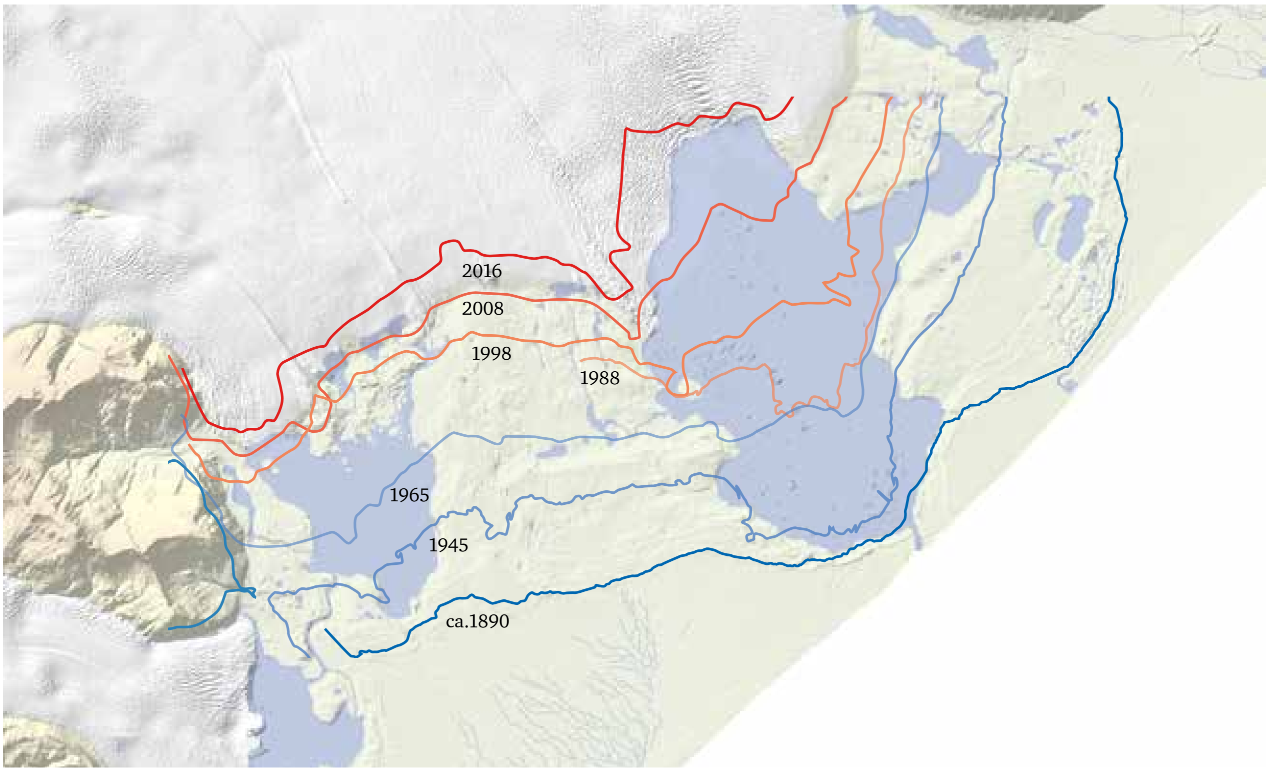
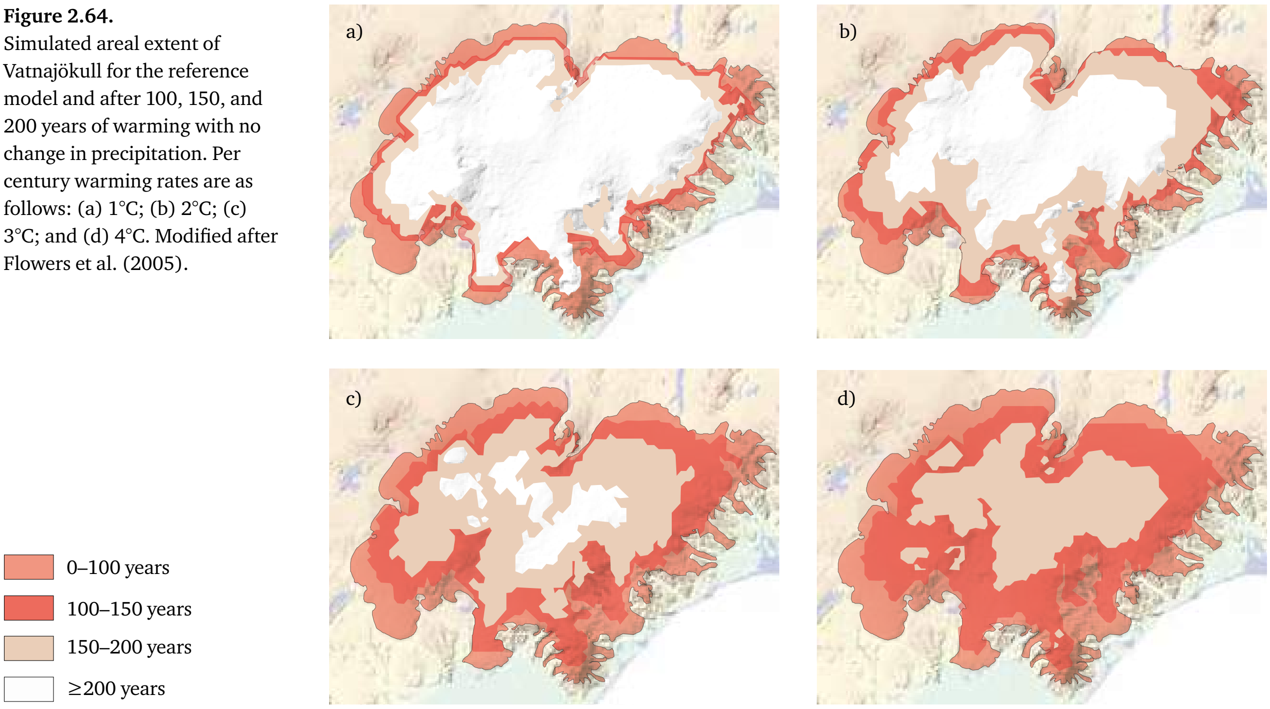


Figure 2.63.
The terminus of Breiðamerkurjökull outlet glacier at various times since 1890 and the increasing size of Jökulsárlón glacial lake. The glacier outlines are based on old maps, aerial photographs (National Land Survey of Iceland) and satellite images. Since 1890, the glacier has retreated more than 7–8 km. Image: Earth Science Institute, University of Iceland.

The retreat and thinning of the ice cap will continue to have various and significant effects on glacial river outlets, subglacial water flow paths, the ice and water divides, on the size of jökulhlaups, surges and volcanic activity, the last due to unloading of the crust (Aðalgeirsdóttir et al., 2005, 2006, 2011; Flowers et al., 2005; Marshall et al., 2005; Jóhannesson et al., 2007, 2011; Árnadóttir et al., 2009; Magnússon et al., 2012; Schmidt et al., 2013). Jökulhlaups from ice-dammed lakes will likely become more frequent and less powerful as the ice dams grow thinner, and new lakes might form or expand at other locations, particularly proglacial lakes that are currently forming at many sites. Water divides may move several kilometres, and the sources of rivers at the glacier margin will migrate. At some of the outlet glaciers, runoff may be diverted from one river basin to another by only moderate retreat of the glacier, as took place in 2009 when Skeiðará river diverted into the river channel of Gígja. Glacier models indicate that only small glaciers will remain at highest locations by year 2150-2220 (Aðalgeirsdóttir et al., 2006; Björnsson 2017). The southern and eastern outlet glaciers are sensitive to changes in temperature, and recent modelling studies indicate that a warming of 2-3 °C by 2100, which some forecasts predict, will result in a >50–80% decrease in ice volume of some of these outlets (Hannesdóttir et al., 2015a).

The southern outlet glaciers of Vatnajökull, especially Breiðamerkurjökull, will probably experience the most dramatic geometric response over the coming decades (e.g. Björnsson et al. 2001, Aðalgeirsdóttir et al., 2006; Flowers et al., 2006; et al., 2007; Björnsson 2017). Jökulsárlón proglacial lake will expand rapidly as the glacier terminus breaks up and retreats several kilometres, until the lake reaches to Esjufjöll mountains. A lake will form at the snout of Skeiðarárjökull. However, Skeiðarárjökull may be expected to survive longer than Breiðamerkurjökull since it receives ice from a higher elevation (Björnsson, 2017).

Figure 2.64.
Simulated areal extent of Vatnajökull for the reference model and after 100, 150, and 200 years of warming with no change in precipitation. Per century warming rates are as follows: (a) 1°C; (b) 2°C; (c) 3°C; and (d) 4°C. Modified after Flowers et al. (2005).



As the ice cap thins and retreats, the underlying crust rebounds at an accelerating rate (Auriac et al., 2013). The uplift rate is most rapid closest to the glacier margin. Measurements show an uplift rate of 40 mm per year at Jökulheimar at the western margin of the ice cap, compared with a current rate of 15 mm per year at Höfn in Hornafjörður (Ófeigsson and Zonetti unpubl. data; Friðriksdóttir, 2014). If Vatnajökull were to disappear completely, the total uplift would be more than 100 m near the centre, and approximately 50 m close to the ice margin, occurring over a time scale of a few centuries. The removal of the ice load could lead to enhanced magma generation and increased volcanic activity (e.g. Pagli and Sigmundsson, 2008).

Fláajökull outlet glacier and its forefield showing the retreat since 1890 © Snævarr Guðmundsson.

2.b (iii) A brief history of glacial research

“Icelanders are shown to have had a greater knowledge and experience of glaciers than most nations, from the time of settlement through to the 18th century, and they were sometimes pioneers in glaciological studies” (Björnsson, 2017, p. 129).

Nowhere in Iceland has the relationship between man, glaciers and rivers been as intimate as near Vatnajökull. However, knowledge on the ice cap did not advance much in the “dark ages” from approximately the 12th century through the 18th century, as most Icelanders were afraid of exploring glaciers and the uninhabited central highlands (Björnsson, 2017).

Sigurður Þorsteinsson, accompanied by another local, set off from Skaftafell and reached the summit of the ice cap of probably Öræfajökull in the spring of 1795. Other than that, few accounts exist of expeditions onto Vatnajökull before the end of the 19th century, when there was an increase in the number of ascents. Although these were mainly done for pleasure, the explorers wrote diaries, which included descriptions of the location and shapes of mountains, routes taken, the sources and outlets of glacial rivers, and the termini of the glaciers. William Lord Watts (1850–1921) was one of these adventurers, who ascended Vatnajökull three times, successfully crossing it on the final trip in 1875. He described how the ice cap had an influence on the climate of northern Iceland by shielding it from the moisture borne by southerly winds.

At the end of the 19th century and beginning of the 20th, many European scientists were doing research in the forefields of the outlet glaciers of Vatnajökull, including studies of the formation of outwash plains from glaciofluvial deposits. Research on the ice cap itself began in the 1920s, including descriptions of its main features and characteristics. The 1934 eruption of Grímsvötn led the way into glacial research in Iceland; several expeditions were made to investigate the volcano after this eruption.

The Grímsvötn lake system is first depicted on a map from 1721, but its correct location did not appear until 1777. The people of Skaftafell county seemed to have always held the opinion that Grímsvötn was a volcanic centre within Vatnajökull itself, although Sveinn Pálsson (1762–1840) and Þorvaldur Thoroddsen (1855–1921) confused it with Grænalón. In the late summer of 1919, two Swedish students, Wadell and Ygberg, were exploring Vatnajökull and came across a vast crater in the ice, at the bottom of which lay a lake – Grímsvötn. They named the crater Svíagígur (Swedish Crater), measured its size and sketched an important map of the crater, believing it to be at least 7.5 km long and 5 km broad, with a surface area of 37.5 km². Grímsvötn has been part of the history of glacial research in Iceland ever since, and expeditions, led by Guðmundur Einarsson from Miðdalur (1895–1963), were made to investigate the eruption site after the 1934 eruption (Björnsson, 2017).

Glaciers in Iceland had visibly retreated during the first three decades of the 20th century, and an international committee on glaciological research suggested regular measurements of glacial terminus variations. Jón Eyþórsson (1895–1968) at the Icelandic Meteorological Institute initiated annual measurements of glacial changes. The Icelandic Glaciological Society soon became involved and funds were raised for the project. The first measurements were carried out at

Early pioneers of glaciological research (Björnsson, 2017)

Physician and headmaster Þórður Þorkelsson Vídalín (1662–1742) was the first Icelander to make serious scientific observations about glaciers. Vídalín's treatise on the ice mountains of Iceland from 1695, is the most instructive work ever produced about glaciers by the end of the 17th century. Vídalín noticed that glaciers changed shape because they moved, grew larger due to accumulation of snow during winter, and shrank due to melting in the summer.

Árni Magnússon's (1663–1730) most important contribution to glaciology was his description of jökulhlaups from glacially dammed marginal lakes. A description of such an event had not previously been recorded anywhere in the world.

Eggert Ólafsson (1726–1768) and Bjarni Pálsson (1719–1779) wrote a travelogue based on their expeditions all around Iceland (although they seldom entered the highlands) during the summers of 1750–1757. They recorded information about the glaciers' locations, size and local conditions. Ólafsson believed that outlet glaciers only existed in south and southeast Iceland. Ólafsson and Pálsson were pioneers of glacial exploration, and by climbing mountains and glaciers they helped to overcome superstition and much of the fear that many Icelanders held for the highlands.

Sveinn Pálsson's (1762–1840) "Treatise on Glaciers" was a high point in Icelandic glaciology. He improved knowledge of the glaciers of Iceland, their topography, classification, formation, and movements, and the interaction between glaciers and local communities. He noted that all glaciers formed as annual layers of snow, which settle on top of each other, and the thickness is limited due to summer melting. Pálsson's descriptions of glacial surges are unique in the history of glaciology. He noted that surges are mostly in the broad and lobate glaciers such as Breiðamerkurjökull and Skeiðarárjökull. Pálsson distinguished between jökulhlaups that emerged from glacially-dammed lakes and those originating from the meltwater of a subglacial geothermal area or volcanic eruption.

Knowledge of the location and size of glaciers increased tremendously through the work of Björn Gunnlaugsson (1788–1876), who surveyed and mapped Iceland in the years 1831–1844, resulting in the 1848 map of Iceland.

Þorvaldur Thoroddsen (1855–1921) made numerous trips to Vatnajökull, and no Icelander had previously spent such a long time on the ice cap. Thoroddsen described the prevalent climatic conditions and pointed out that the existence of very large glaciers in Iceland was due to high levels of precipitation and cool summers. He measured and compiled a map of the snowline over a wide area of Iceland, drawing attention to how variable it could be from year to year.

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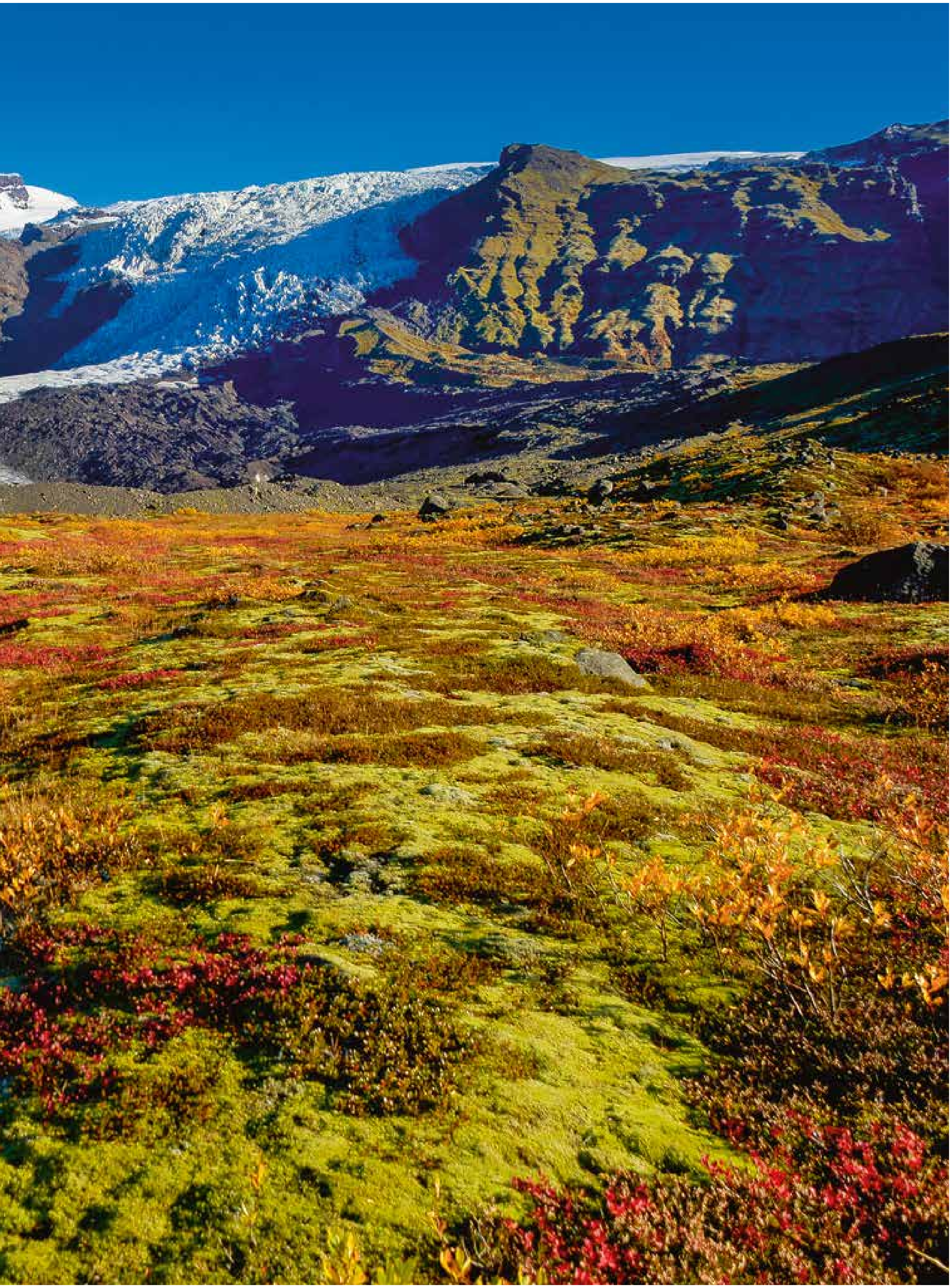
five of the outlet glaciers of southeast Vatnajökull.

The Swede Hans Ahlmann (1889–1974) introduced the systematic research of the relationship between mass balance and weather conditions around the North Atlantic. Together with Jón Eyþórsson and Sigurður Þórarinsson (1912–1983), he led the Swedish-Icelandic expedition onto Vatnajökull in 1936–1938, the largest glacial research expedition and project in Iceland until the 1970s (Ahlmann & Þórarinsson, 1943). Vatnajökull was a good candidate for the mass balance and ice flow measurements, being in a maritime climate,

Next page: Autumn at Falljökull outlet glacier, 10 October 2012



with high precipitation and summer ablation. A detailed analysis to understand the relative roles of accumulation and melting in the total mass balance of the glacier was carried out, and a relationship between the climate and the advance and retreat of the glaciers was established. Since the 1960s, research has been conducted concerning the mass balance, accumulation and ablation, ice volume and areal changes, and runoff into glacial rivers from the ice cap.

Recent research

Regular mass balance monitoring of Vatnajökull during glaciological field campaigns has been ongoing since 1990/1991 (Björnsson et al., 2013). Automatic weather stations have been operating on the ice cap since 1994, and they measure temperature, relative humidity, wind speed, wind direction at two metres above the surface and radiation components (e.g. Guðmundsson et al., 2009). The subglacial topography is known from radio-echo sounding measurements, which started in the 1950s and are still carried out. High-resolution maps detail previously unknown landscapes and formations including the geometry of volcanic systems (Magnússon et al., 2012; Björnsson, 2017). Surface velocities have been measured for selected outlet glaciers during the summer using GPS instruments, and velocity maps have been compiled from satellite data (e.g. Magnússon et al., 2005, 2007; Nagler et al., 2012; Voytenko et al., 2015).

Reconstruction of former glacier extent and glacier surface maps at different times has been done using various data sources (e.g. Björnsson, 2017; Hannesdóttir et al., 2015a, 2015b; Guðmundsson et al., 2012, 2017). Volunteers from the Icelandic Glaciological Society have carried out systematic monitoring of glacial snouts of most of the outlet glaciers of Vatnajökull. Several modelling studies on the response of the ice cap to climate change have been conducted (Aðalgeirsdóttir et al., 2005, 2006, 2011; Flowers et al., 2005; Marshall et al., 2005; Hannesdóttir et al., 2015c). New high-resolution digital elevation models (DEMs) from lidar measurements have revealed important information about the glacial surface (Icelandic Meteorological Office and Institute of Earth Sciences, 2013), portraying accurate outlines of ice cauldrons and facilitating delineation of individual catchment areas, and are useful for studies of ice volume change, jökulhlaups and mapping of crevasses to name a few (e.g. Jóhannesson et al., 2013). Most recently, accurate DEMs derived from satellite measurements have revolutionised studies of glacier changes, providing information about surface elevation variations and ice velocities over large areas several times per year.

Calving events into Jökulsárlón have been monitored and the influence that the salty ocean waters entering the lagoon have on melting (Landl et al., 2003; Jónsson, 2016). Several investigators have studied the influence of volcanic ash and dust from the sandur plains on the mass balance of the ice cap (Möller et al., 2014; Dragosics et al., 2016a; Wittman et al., 2017; Schmidt et al., 2017). Regular monitoring of the lake level of Grímsvötn is done, both by field measurements and by using remote sensing data and the height of the ice surface at the Skaftárkatlar subglacial lakes is measured with GPS equipment, to foresee jökulhlaups into Skeiðará and Skaftá rivers (e.g. Etienne et al., 2006; Björnsson & Pálsson, 2008).

2.b (iv) Major historic eruptions and their impact on society

The nominated property has been the venue of a few of the largest and most devastating volcanic eruptions in the history of Iceland, and some even in the recent history of the Earth. In this section the societal impacts of four eruptions, Eldgjá 934–939, Öræfajökull 1362, Laki 1783–1784 and Askja 1875, will be highlighted.

Eldgjá 934–939

Iceland had just been colonised by the time the massive Eldgjá eruption occurred. Its effects on the early settlement in Iceland must have been devastating. Scarce records show that the Eldgjá lava advanced over large areas of productive farmland and forced many settlers from their lands, especially within the districts of Álftaver and Síða. The lava also forced the Skaftá river into a new course. The tephra fallout from Eldgjá devastated the summer grazing commons of Álftaversafréttur to such an extent that it has not yet fully recovered (Larsen, 2000).

The Eldgjá event is probably the largest volcanic-pollution event in recent history, exceeding the Laki 1783–1784 and Tambora 1815 events by a factor of two (Oppenheimer, 2003; Thórðarson et al., 2001). It pumped approximately 200 million tons of SO_2 into the atmosphere, where it may have spread out over much of the northern hemisphere and produced acidic haze. Historical accounts indicate that the eruption had a significant effect on weather patterns in Europe and the Middle East for several years (Oman et al., 2006). However, the human health impacts of Eldgjá may not have surpassed that of Laki (see below) or the eruption in Tambora 1815, as it probably was a prolonged event with sulfur emissions drawn out over several years.

Öræfajökull 1362

The 1362 eruption of Öræfajökull was the first post-settlement event of this large central volcano. The eruptive vents were buried under the thick glacier that covers its summit region. In the early explosive phases, the eruptive plume partly collapsed and caused pyroclastic density currents to flow down the volcano and its slopes. The combination of meltwater, ice and the hot mixture of gas, ash and pumice produced a mixture of jökulhlaups, pyroclastic density currents and tephra fall on the surrounding lowlands (Þórarinsson, 1958).

At the time of the eruption the district around the volcano was called Litla-Hérað (the Small District) – the name implies prosperity at the time (Guðmundsson, 1998). The direct impacts of the eruption were destruction of farmland and an assumed toll on human lives and life stock; some have estimated that 250–400 people perished (Imsland, 2005). Archaeological excavations of two farms in the district, Bær and Gröf, show that they were abandoned; human belongings had been removed and no human remains were found (Einarsson, 2005; Gestsson, 1959). This, however, does not prove that the inhabitants escaped the consequences of the dramatic event, only that they had time to evacuate the house. The current name for the district is Öræfi (Wasteland), and historic records imply that

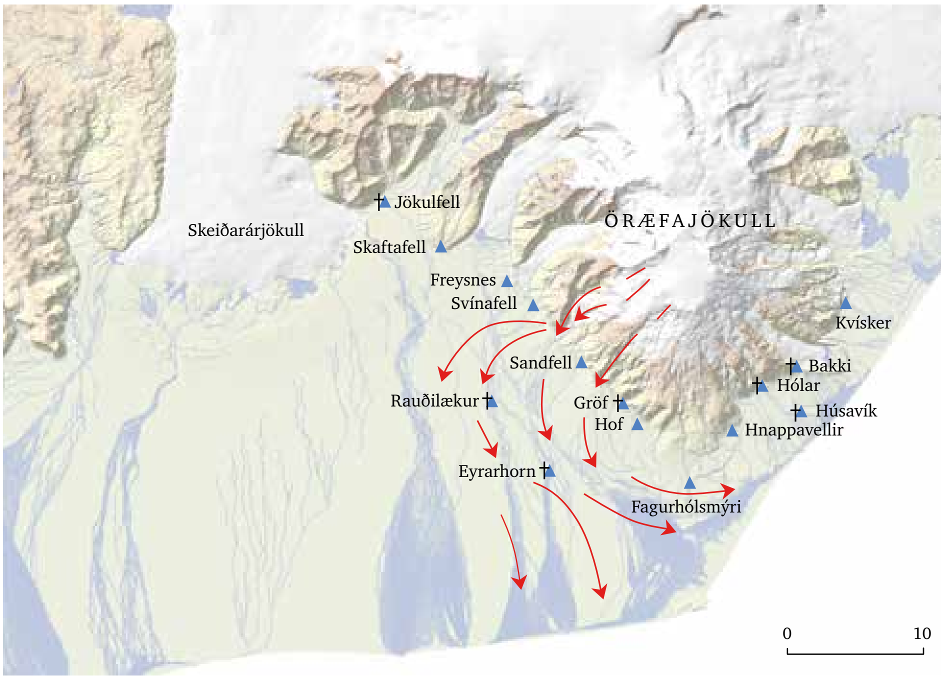


Figure 2.65.
The estimated source and direction of the jökulhlaups from the volcano. Reconstructed by Guðmundsson et al. (2016), after Þórarinsson (1958).

the area was uninhabitable for decades after the event (Björnsson, 1982). Total devastation by volcanic eruption, as in the case of the 1362 Öræfajökull event, is a singular event for Iceland. The environmental impacts can still be felt in the district of Öræfi.

The size of the jökulhlaups (Fig 2.65) that tumbled down the Öræfajökull volcano is estimated at 100,000 m^3s^{-1}, which is twice that of the recent Gjálp jökulhlaup (Box p. 87). The jökulhlaups carried so much mud and other debris that up to 50-m deep coastal waters became dry land (Þórarinsson, 1958). Tephra fallout from the eruption was mostly towards the southeast – out to sea – and thus had minimal impact in other areas of Iceland (Fig 2.66). However, the regions to the east of Öræfi suffered from the tephra fall and were partly devastated (Þórarinsson, 1958).

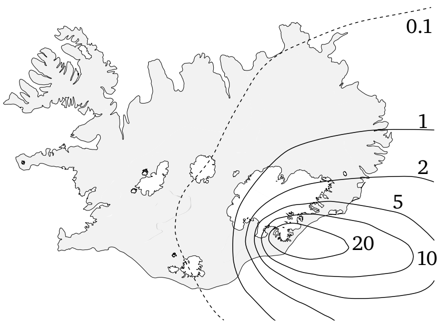


Figure 2.66.
Isopach map of the tephra fall from the 1362 Öræfajökull eruption, showing the thickness of the tephra in cm. From Þórarinsson (1958).

Laki (Skaftá fires) 1783–1784

There is a wealth of contemporary information available for the Laki eruption of 1783–1784, primarily due to the accounts of the Reverend Jón Steingrímsson (Steingrímsson, 1788), who wrote: "Before this volcanic fire and countrywide pestilence descended, the land was bounteous and prosperous; although this was surpassed in the last year, and never in recent years had there been such an amazing flowering and fruiting of everything, with the best weather, on land and at sea."

As the above quotation describes, Vestur-Skaftafellssýsla was a very prosperous county, and never more so than in the spring of 1783 when on 8 June the eruption broke out with a pitch-black eruption cloud rising into the sky to the north and spreading southwards over Síðumannaafréttur commons. This day marked the beginning of Móðuharðindi, the Haze Famine, Iceland's greatest natural catastrophe.

The gas emissions from the eruptive vents were so great that the radiation from the Sun was substantially reduced, and it appeared to be blood red. Lava flowed down the Skaftá and Hverfisfljót river canyons onto the lowlands below where it spread out in two great lobes on the coastal plains, destroying 21 farms (Fig 2.12, p. 69).

The eruption gradually faded out and ended on 7 February 1784.

The environmental impacts of the Laki eruption were enormous. Although the lava flows covered precious agricultural land and destroyed over 20 farms, no lives were lost directly because of falling tephra or flowing lava. The most serious consequences of the eruption came from poisonous volcanic gasses (Fig 2.67). An estimated 120 million tons of sulfur dioxide (SO_2) ascended into the stratosphere where it reacted with water vapour to form sulfuric acid aerosols, which were spread by a jet stream across the entire northern hemisphere. The amount of sulfur dioxide emitted in each of the ten eruptive episodes at Laki was of a similar magnitude to that released by the 1991 Pinatubo eruption in the Philippines. The sulfurous haze remained over the northern hemisphere until the spring of 1784, and this is among the top few eruptions affecting climate in the Holocene (Self et al., 1996; Thórðarson & Self, 2003).

Locally, acid rain that accompanied the haze burned holes in northern dock leaves and chemically burned the skin of people and animals. People complained of weakness and breathing difficulties, eye irritation and rapid heartbeat. Haze greatly reduced plant growth, and grass withered in meadows and pastureland. Fluoride poisoning, manifesting as distorted teeth and bone deformities in limbs, plagued the livestock, and within a year well over half of all livestock in Iceland had perished. Subsequently, people died in their thousands from starvation and deprivation. The collapse of the livestock, coupled with an unusually cold summer and winter, was the principal cause of the Haze Famine, in which a fifth of the population died, about 10,000 people in total (Steingrímsson 1788; Gunnlaugsson et al., 1984).

The haze from the Laki eruption lay across the whole of Europe and beyond. Jet streams at the top of the troposphere carried it onwards, east across Eurasia, then over the polar region and on to North America. At its maximum extent, the haze formed a continuous cloud over the northern hemisphere between the 30° and 90° lines of latitude. As the haze descended into the lower tropo-

Figure 2.67.
Location map of Lakagígar (Laki cone row), Skaftáreldahraun lava flow field and the Grímsvötn central volcano. The dotted line is the 0.5 cm isopachyte – connecting places where the tephra layer was 0.5 cm thick. The part of the country in which more than 60% of the livestock died, mainly from fluoride poisoning, is shown in dark green. Modified after Thórðarson & Self (2003).

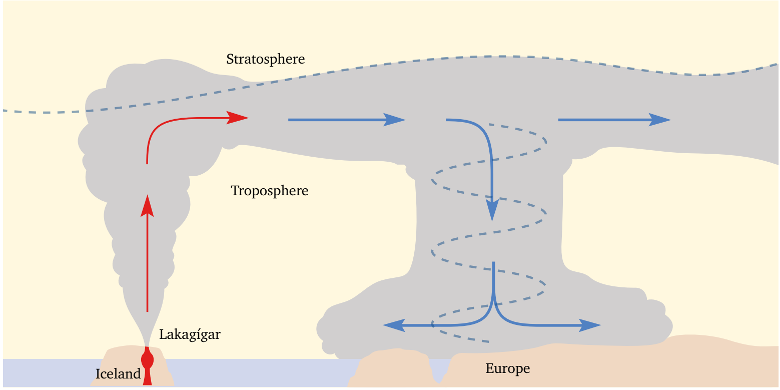


Figure 2.68.
Schematic cross section showing transport of the Laki volcanic haze, from Iceland to Europe and how it was pulled downwards to spread as a dry fog. Modified after Thórðarson & Self, 2003.

sphere it created the infamous "dry fog", which lay like a blue curse across mainland Europe with all the associated pollution (Fig 2.68; Thórðarson & Self, 2003).

In the European annuls, 1783 is known as *annus mirabilis*, the year of awe, because of the many and extraordinary events that took place that year. Particularly astonishing was the strange haze or dry fog that filled the air from June until October. Breathing problems afflicted many and are described in contemporary records (Oman et al., 2006). Another consequence of the dry fog was acid rain, which in total is thought to have been the equivalent of over a ton of sulfuric acid on each square kilometre of land in areas where the haze was most dense. The sulfurous rain caused considerable damage to vegetation and crops all over Europe and stunted the growth of trees in Scandinavia and Alaska.

The Laki eruption had a far-reaching effect on the weather. Available data and mathematical modelling indicate that the haze lowered the mean annual temperature in the northern hemisphere by over 1°C for one to three years (Oman et al., 2006). Contemporary sources show that the influence on weather was neither uniform nor evenly distributed. For instance, in central Europe the late summer was good and produced record grape harvests, while in east Europe the weather was changeable and cold, with midsummer snow in Poland and Russia. Severe droughts hit North Africa, India and the Yangtze province of China, with accompanying famines, while crops failed to grow in Japan due to an unusually cold and wet summer (Jacoby et al., 1999; Thórðarson & Self, 2003). The winter of 1783–1784 was one of the hardest ever recorded in Europe and North America (Thórðarson & Self, 2003). The harbours and waterways around Chesapeake Bay, for example, were closed for a long time due to ice, and a skim of ice was seen on the Mississippi in New Orleans on 13–19 February. Each of these is a singular event in North American weather history.

Askja 1875

Askja lies deep in the central highlands, far away from inhabited areas. The area was poorly explored up until the 1800s, primarily due to inaccessibility but also due to the prevailing belief that outlaws inhabited the area; for instance, geothermal steam was thought to result from their activities (Hallgrímsson, 1970).

The 1875 Askja eruption was a major tephra-producing eruption and the only historic example worldwide of a phreatoplinian eruption, i.e. when silicic magma interacts violently with abundant

Next page: Grímsvötn ash plume on 21 May 2011 © Þórdís Högnadóttir.

water in a caldera lake (Carey et al., 2010; Self & Sparks, 1978). This eruption is furthermore the third largest explosive eruption in the written history of Iceland, after the 1104 Hekla eruption and 1362 Öræfajökull eruption. The tephra production shifted between phases of subplinian, phreatoplinian and Plinian activity, resulting in tephra deposition to the northeast of Askja and all the way to Scandinavia and northern Europe (Carey et al., 2010). Contemporary accounts report total darkness during the most intense tephra fallout, and that fields and grassland turned grey or became totally buried. Later the ash and tephra were suspended in the air, and blown by wind to affect a much wider area than the initial tephra fall sector (Hallgrímsson, 1970). Where the most intense tephra fallout occurred, vegetation in the highland grazing areas was buried and livestock needed to be transported to other regions.

In total, 18 farms were abandoned in Jökuldalur and on Jökuldalsheiði to the east of the volcano. Some were abandoned for only a year or so, others to this day. Already in 1875, people from the Eastfjords began to emigrate to North America, and the emigration continued for several years. It is estimated that some 500 people from East Iceland emigrated because of the tephra fallout from the 1875 Askja eruption, which is said to have been a primary event triggering the exodus of Icelanders to Canada in the late 19th century (Hallgrímsson, 1970).

3. Justification for Inscription

It is the coexistence and active interaction of a divergent tectonic plate boundary, a mantle plume and a large ice cap that gives the nominated property its Outstanding Universal Value. Iceland is the only place, possibly with the exception of Antarctica, where all these Earth processes are currently interacting. Together they create a dynamically evolving and easily accessible natural environment that is exceptionally diverse, globally unique and scientifically fascinating.

3. Justification for Inscription

3.1.a Brief Synthesis

The Vatnajökull National Park property, a total of 14,482 km² (1.48 million ha), comprises the whole of Vatnajökull National Park, plus two contiguous protected areas, Herðubreiðarlindir and Lónsöræfi Nature Reserves. At its heart lies the Vatnajökull ice cap, covering 7800 km² of the mountainous southeast Iceland. To the south of the ice cap the property extends to the coast, and both here and north of Vatnajökull there are numerous outlet glaciers.

Iceland is currently the only part of the active spreading zone of the Mid-Atlantic Ridge exposed above sea level. The Eurasian and North American tectonic plates on either side of the ridge are moving apart by an average of 19 mm each year. The spread is accommodated in rift zones, two of which, the Eastern and Northern Volcanic Zones, pass through the nominated property. Iceland probably first began to develop as a land mass about 25 million years ago, when the westward drifting Mid-Atlantic Ridge encountered the Icelandic mantle plume, providing a generous source of magma that ever since has been contributing to the build-up of the country. The drift of the plate boundary relative to the mantle plume has now positioned the latter beneath the Bárðarbunga central volcano in the northwestern part of the property.

Vatnajökull National Park, like all of Iceland, has a volcanic origin and contains ten central volcanoes, eight of which are subglacial. Two of the latter are among the four most active in Iceland. Most of the property's bedrock is basaltic in composition, the oldest being erupted some ten million years ago and the most recent in 2015. Outside of the ice cap, the terrain varies from flat lava flows and sediments to mountains, including tuyas and tindar (ridges) of brown hyaloclastites, known by their Icelandic name móberg. The tuyas and tindar were erupted in fissure eruptions beneath ice age glaciers, when Iceland was partially or totally covered by sheets of ice, and the latter occur nowhere else in the world in such numbers. However, during interglacial periods the same types of eruptions have produced cone rows and lava shields of the Icelandic type. Few if any areas in the world provide, side by side, the opportunity to study landforms created by similar eruptions under either thick ice or air. Subglacial eruptions in Vatnajökull can also trigger sudden outbursts of meltwater, a flood that is internationally known as jökulhlaup. These and the many glacial rivers have created vast outwash plains to the south and north of the ice cap, known internationally by their Icelandic name sandur.

The nominated property comprises an entire geological system where magma and the lithosphere are incessantly interacting with the cryosphere, hydrosphere and atmosphere. Thus, the interplay of volcanism, air and glaciers, past or present, is continually working to create extremely dynamic and diverse geological processes and landforms, many of which are currently underrepresented or not found on the World Heritage List. It was here that the phrase "Fire and Ice" was coined. The property contains a large ice cap, tectonic zones and fissure swarms, lava shields and tuyas, tindar and cone rows, clusters of rootless craters, numerous outlet glaciers, nunataks, subglacial- as well as proglacial lakes, glacier forefields, geothermal areas, highland deserts, sandur plains and river canyons. Vatnajökull National Park is one of the best places on Earth to experience the ongoing development of a variety of landforms and some of them serve as analogues for volcanic landforms on Mars.

The Vatnajökull ice cap began to form from coalescing mountain glaciers some 4000–5000 years ago, at the end of the Holocene Thermal Maximum. The ice cap grew markedly during the Little Ice Age (ca. 1450–1900), reaching its greatest extent by the end of the 18th century. In recent years its retreat has become greatly accelerated in response to global warming making the property a prime locality for exploring the impacts of climate change on world glaciers and the various landforms left when they retreat.

The biota of the nominated property reflects its dynamic geology. There are moulting and breeding grounds of birds of world importance, as well as vast desert-like areas where vegetation is fighting a tough battle. The fissure swarms of the rift zones hold endemic groundwater amphipods that are believed to have survived the entire ice age under thick sheets of ice. The geothermal areas contain thermophilic microbes that thrive in even the hottest water and single-celled organisms also prosper in the inhospitable environment of subglacial lakes that may replicate conditions on early Earth and the icy satellites of Jupiter and Saturn.

Over a millennium, the human settlements south of the Vatnajökull ice cap have had to adjust to natural hazards and changing environments as glaciers advance and retreat, glacial rivers flood and subglacial volcanoes erupt, devastating homes and farmlands. The resilience, adaptability and ingenuity of the residents over the ages are an endless source of admiration and wonder.

With its extensive areas of pristine wilderness and fascinating geology, we intend to maintain and manage the Vatnajökull National Park nominated property to ensure that it can be enjoyed by current and upcoming world generations. The park's very character as a dynamic Earth system means that its nature and landscapes may change significantly – even in the next few years or decades – from what is presented here, but this makes the property even more interesting and valuable as a global natural laboratory.

3.1.b Criteria under which Inscription is Proposed (and Justification for Inscription)

Vatnajökull National Park is proposed for inscription on the World Heritage List under Criterion (viii) of the Operational Guidelines for the Implementation of the World Heritage Convention (2017). Thus, the nominated property shall:

> *Be outstanding examples representing major stages of earth's history, including the record of life, significant ongoing geological processes in the development of landforms, or significant geomorphic or physiogeographic features.*

In 2005, the IUCN published a thematic report on the role of the World Heritage Convention in recognising and protecting geological and geomorphological heritage within the global framework

Next page: One of the Laki craters from air, 27 August 2011 © Walter Huber.

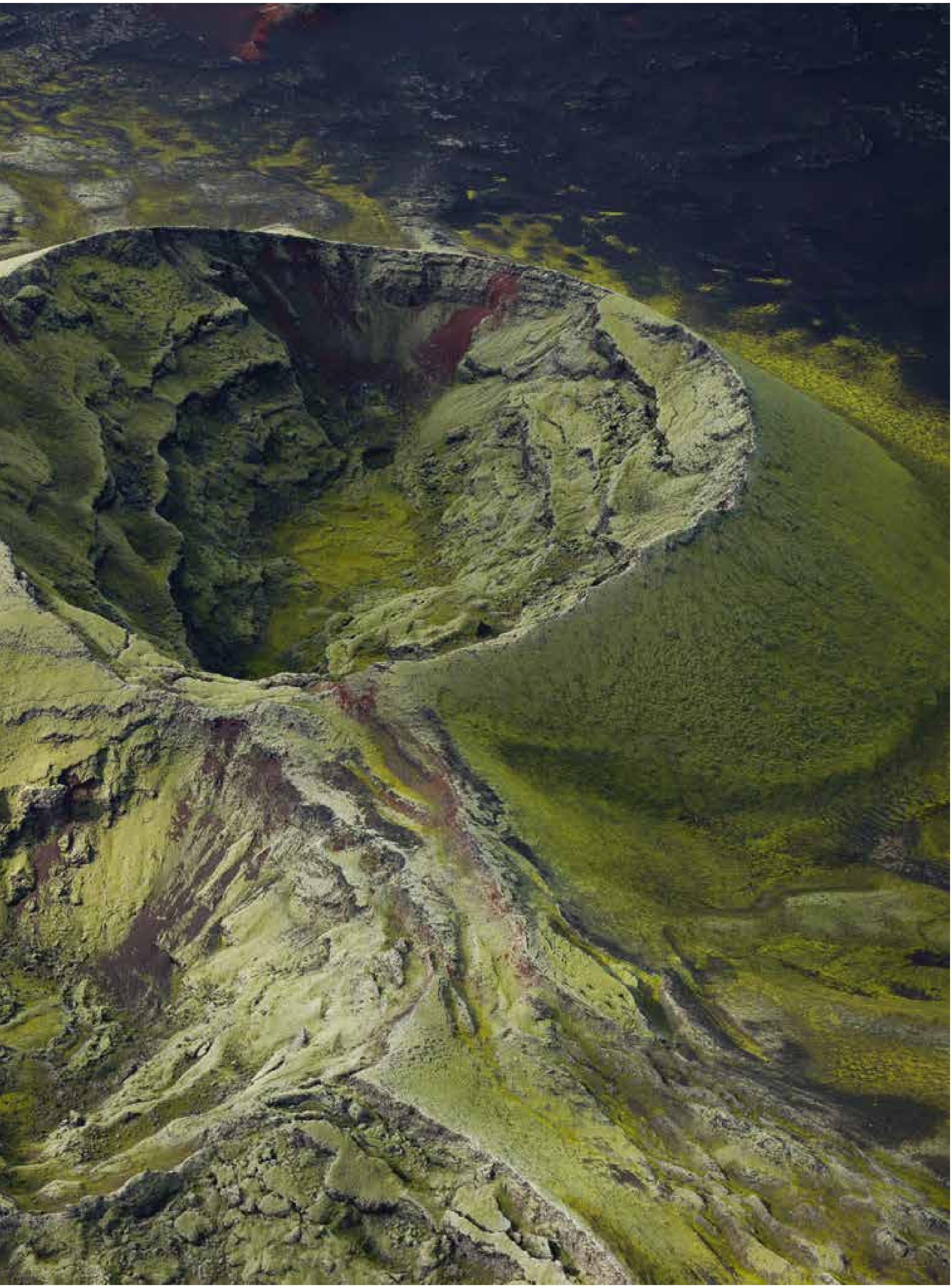


Figure 3.1.
Schematic drawing of the geological history and proposed geological future of the Icelandic Earth system. Illustration modified after Benjamin van Wyk de Vries.

as dictated by Criterion (viii) (Dingwall et al., 2005). The report examines the four natural elements, inherent in this criterion, i.e. Earth's history, the record of life, ongoing geological processes and significant geomorphic or physiographic features. Three of these are highly relevant for the nomination of Vatnajökull National Park:

Earth's history
The IUCN thematic report suggests that relevant World Heritage sites that meet this part of Criterion (viii) could include universally outstanding examples of crustal dynamics and tectonism, volcanoes, plate movements, continental movement and rift valley development.

The existence of Iceland, and its short geological history, is intimately linked to two major geophysical processes: the separation of tectonic plates through oceanic spreading at the surface of the Earth, and the mechanism of a mantle plume that originates deep within it (Fig 3.1).

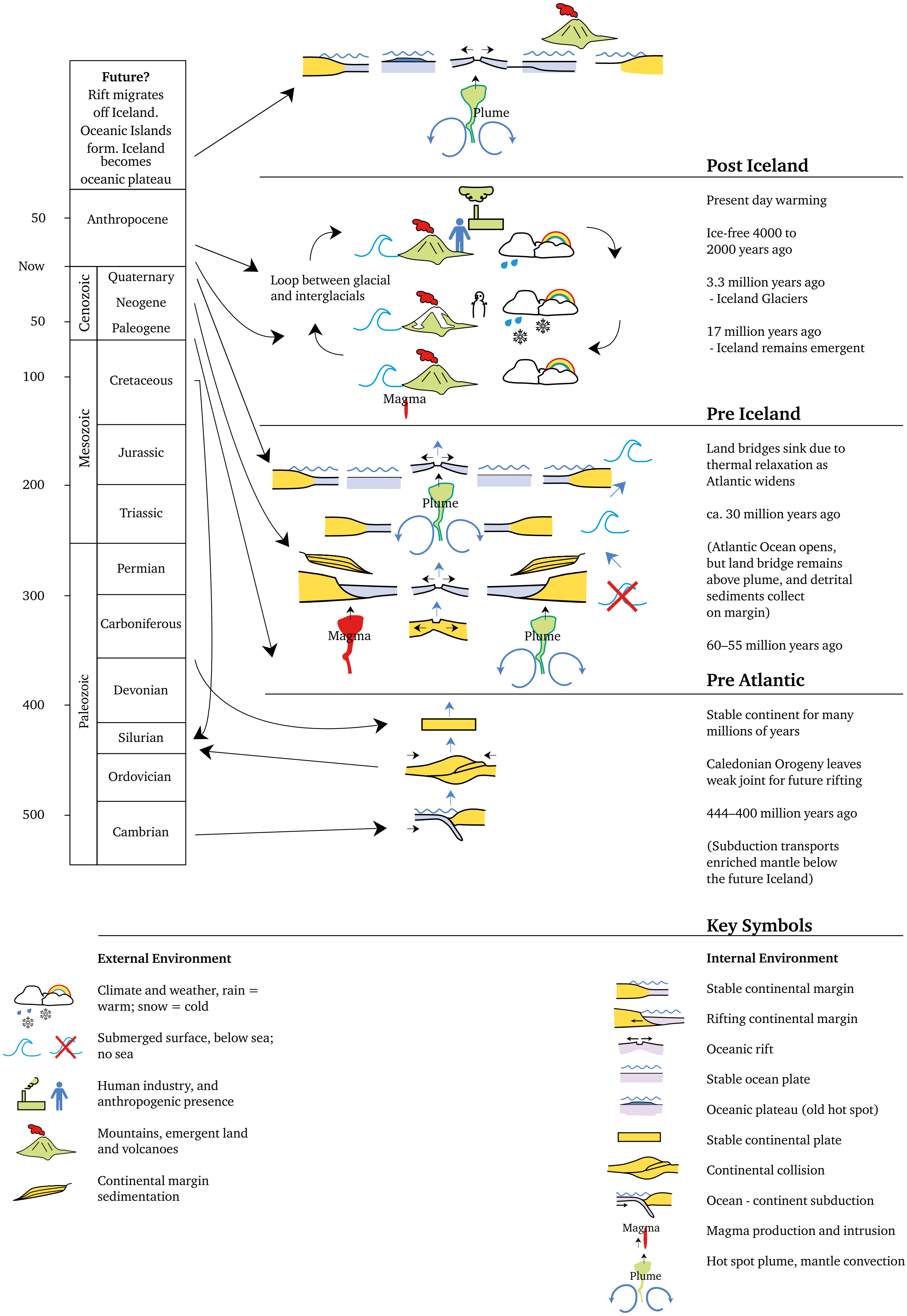
Some 55–60 million years ago the supercontinent Laurasia began to break up, giving birth to the North Atlantic Ocean and two separate continents, North America and Eurasia. These continents have been drifting slowly apart ever since, through a process called seafloor spreading. The Mid-Atlantic Ridge marks the boundary where active rift or seafloor spreading is taking place. When break up began, a static mantle plume, a hot and highly viscous anomaly that rises slowly from depths of 400–700 km within the Earth's mantle, was located some distance to the west of the plate boundary, probably under the middle of Greenland. However, as the boundary moves slowly northwest relative to the mantle plume – leaving a trace in the form of basaltic outcrops and submarine ridges – the two processes were destined to meet. This meeting, marking the foundation of Iceland, took place some 25 million years ago followed by a dramatic increase in volcanic activity.

Mid-ocean ridges are found in all the major oceans of the Earth, and normally they do not build up above sea level. However, in Ieland the Mid-Atlantic Ridge does because of the added activity of a mantle plume. As this anomalously hot material approaches the surface, parts of it melt completely into magma that can erupt and create a new crust on the surface. The location of the mantle plume now lies underneath the Bárðarbunga central volcano within the property, which thus represents the "fire heart" of Iceland.

As the plate boundary or rift zone continues drifting westwards relative to the mantle plume and the plume's influence diminishes, a so-called rift jump may eventually occur, with activity on a new rift zone east of the old one taking over. Thus, the highly active East Volcanic Zone is a rift in the making, through the process of rift jumping (Fig 2.3, p. 32).

The nominated property represents the active interaction of these Earth processes. It is not the only place on Earth where a mantle plume and a plate boundary have interacted. However, at this point in geological time, it is the only place on dry land where these processes are actively interacting at a location that is easily visible and accessible. For this, the property is uniquely representative.

Further, the nominated property contains a near complete record of some of the major climate and environmental changes known in Earth's history, namely the ice age.


Future?
Rift migrates off Iceland. Oceanic Islands form. Iceland becomes oceanic plateau
50
Anthropocene
Now
Cenozoic
Quaternary
Neogene
Paleogene
50
100
Mesozoic
Cretaceous
Jurassic
200
Triassic
Paleozoic
Permian
300
Carboniferous
Devonian
400
Silurian
Ordovician
500
Cambrian
Plume
Post Iceland
Present day warming
Ice-free 4000 to 2000 years ago
3.3 million years ago
- Iceland Glaciers
17 million years ago
- Iceland remains emergent
Loop between glacial and interglacials
Magma
Pre Iceland
Land bridges sink due to thermal relaxation as Atlantic widens
Plume
ca. 30 million years ago
(Atlantic Ocean opens, but land bridge remains above plume, and detrital sediments collect on margin)
Magma
Plume
60–55 million years ago
Pre Atlantic
Stable continent for many millions of years
Caledonian Orogeny leaves weak joint for future rifting
444–400 million years ago
(Subduction transports enriched mantle below the future Iceland)
Key Symbols
External Environment
Climate and weather, rain = warm; snow = cold
Submerged surface, below sea; no sea
Human industry, and anthropogenic presence
Mountains, emergent land and volcanoes
Continental margin sedimentation
Internal Environment
Stable continental margin
Rifting continental margin
Oceanic rift
Stable ocean plate
Oceanic plateau (old hot spot)
Stable continental plate
Continental collision
Ocean - continent subduction
Magma
Magma production and intrusion
Plume
Hot spot plume, mantle convection

Significant ongoing geological processes in the development of landforms

The aforementioned IUCN report suggets that relevant World Heritage sites exhibiting processes that are currently shaping the Earth's surface, or that have done so in the past, could include outstanding examples of glaciation, volcanism, mass movement (terrestrial and submarine) and fluvial (river) and deltaic processes.

As noted above, Iceland in its entirety is produced by deep Earth- and plate tectonic processes that are all ongoing. These are particularly active within Vatnajökull National Park where they furthermore combine with glacial processes to produce an unsurpassed laboratory for studying and appreciating the workings of the Earth system. In Iceland, geological processes operate at much faster rates than in most other places on the planet, so fast that one can easily comprehend how they mould the landscape. Hence, the nominated property may be regarded as one of the best places on Earth to experience ongoing processes in the development of landforms: volcanism regularly produces new crust and carpets the surface with finer lapilli and ash; outlet glaciers carve out troughs and overdeepenings; the interaction of fire and ice produces jökulhlaups and an assortment of glaciovolcanic landforms; rain, groundwater and meltwater gather into cold-springs, create sandur plains (outwash plains) and river canyons and; the wind forms dust clouds that corrode the landscape and fertilise distant pastures.

Consequently, the nominated property is renowned for its contributions to earth sciences. For example, the Holuhraun eruption in 2014–2015 offered a unique chance to investigate, in real time, a major volcano-tectonic rifting event and a caldera subsidence (Ágústsdóttir et al., 2016; Guðmundsson et al., 2016; Reynolds et al., 2017). The subglacial Gjálp eruption in 1996 provided the first opportunity on Earth to study the process of tindar formation and its post-eruption evolution. In addition, this eruption was a test case for scientific studies on e.g. glacier melting and the glacier response to that melting, and the dynamics of volcano-ice interactions (Guðmundsson et al., 2004; Jakobsson & Guðmundsson, 2008 and references therein). Post eruption research on the 1783–1784 Laki and the 2014–2015 Holuhraun eruptions has contributed greatly to improved understanding of large fissure eruptions and their environmental consequences (e.g. Thórðarson et al., 1996, 2003; Thórðarson & Self, 1993, 2003; Self et al., 2006; Pedersen et al., 2017; Ilynskaya et al., 2017). Subglacial experiments on Breiðamerkurjökull (Boulton et al., 1974; Boulton, 1979) led to the discovery of a third mode of glacier flow, subglacial bed deformation, and triggered a paradigm shift in glaciology as a science.

The recent rapid recession of the southern outlet glaciers of Vatnajökull has further initiated a process-form regime that will be played out in every glacial landscape around the world, and because of its accessibility the area continues to serve as the perfect real-time observatory of such processes (Evans, 2016).

Top:Baugur, the main crater of the 2014–2015 Holuhraun eruption. Middle: Craters of the Laki cone row and a lava channel from air, 22 September 2010. Bottom: Kambar (right) and Fögrufjöll (far left) tindar formations from air, 22 September 2010 © Snorri Baldursson.

Significant geomorphic or physiographic features

This part of Criterion (viii) focuses on the landscape products of active or past geomorphic processes, mainly important in terms of their scientific value, although their aesthetic value is also appreciated. Properties of Outstanding Universal Value in this regard may include glaciers and ice caps, volcanoes and volcanic systems, mountains, fluvial landforms and river valleys, glacial and periglacial landforms and landscapes (Dingwall et al., 2005).

Eight out of ten central volcanoes contained within the property are subglacial and among them are two of the four most active volcanoes in Iceland, Grímsvötn and Bárðarbunga. Thus, the property displays a wide variety of volcanic and glaciovolcanic features, many of which are not found elsewhere on Earth in the same combination and variety (Wood, 2009; Smellie & Edwards, 2016) and either not present or underrepresented on the World Heritage List. In fact, all the landscapes within the property are shaped either by process-form relationships involving volcano-air, glacier-volcano or glacier-climate interactions during the last 2.8 million years. Significant volcanic and glaciovolcanic features that are poorly if at all represented on the World Heritage List include: basaltic lava shields of the Icelandic type (e.g. Trölladyngja), volcanic fissures and crater rows (e.g. the world renowned Lakagígar and the lesser known Fjallsendagígar), the equivalent tuya (e.g. Mt. Herðubreið and Kistufell) and tindar formations (e.g. Kambar and Fögrufjöll) moulded under glacial ice sheets and vast recent flood lavas (e.g. Holuhraun and part of the Laki lava flow). The property also features active sandur plains (e.g. Dyngjusandur), clusters of rootless craters within the Laki lava flow (1783–1784) and several subaerial and subglacial geothermal fields (e.g. Vonarskarð, Kverkfjöll and the Skaftárkatlar cauldrons).

The surging northern- and rapidly retreating southern outlet glaciers of Vatnajökull have delivered and will keep on delivering a wide range of easily accessible glacial landforms (Evans, 2016).

3.1.c Statement of Integrity

Vatnajökull National Park is considered adequate to express all the aspects of the interaction between a divergent plate boundary, a mantle plume and an ice cap. The key elements to bear in mind in this regard are the inclusions of entire landscape- and geophysical units, minimal human use and intervention, and intense international interest in the property as a scientific subject.

The nominated property covers approximately 25–30% of the central highlands of Iceland and extends to lowland areas to the north and south of the Vatnajökull ice cap to cover a total of 14% of the country. Most of it qualifies for IUCN Category II. The property contains the entire Vatnajökull ice cap, the largest by volume in Europe, with all its ice domes, ice flows and outlet glaciers. It encompasses the location of the Iceland mantle plume, under the Bárðarbunga central volcano, and spans some 200 km of an active oceanic rift on land. It includes ten active central volcanoes and the major part of the accompanying fissure swarms and subsidiary landforms of six of these. It also provides cross sections of extinct volcanoes that were active in the upper Miocene to lower Pliocene eras. It covers the complete catchment and impact area of major outflow glaciers, such as Breiðamerkurjökull and Iceland's most dynamic glacial lake, Lökulsárlón. It contains the active sandur plains of Dyngjusandur, and most of the riverbed of Iceland's longest glacial river, Jökulsá á Fjöllum. It embraces one of Earth's youngest and most actively eroding glacial river canyons, Jökulsárgljúfur.

Finally, it includes a complete range of volcanic, glaciovolcanic and glacial landforms and features.

The nominated property is only marginally affected by human use. Fewer than 15 historic farmsteads are found within its boundaries and none of these are actively farmed today. However, some 2000 ewes with lambs, a total of 5000–6000 animals, graze within the area for two months (July and August) especially in the commons of Fljótsdalshreppur, Hornafjörður and Skaftárhreppur municipalities. This is about 1% of the summer sheep population in Iceland and not considered a threat to the vegetation of the property. Three park employees and their families are the only permanent inhabitants on a year-round basis. Another 70–100 part-time employees (rangers, glacier guides, workers and visitor centre staff) live within the property for 2–12 months during the travel/tourist season.

Currently, the major concerns regarding the integrity of Vatnajökull National Park relate to wear and tear of nature and infrastructure by rapidly increasing numbers of visitors at certain popular spots within the park. Over the last five to six years the growth has been 20–30% annually. This rapid growth generates numerous management challenges, especially with regards to developing and implementing essential regulatory management systems and to upholding and maintaining adequate staff levels and infrastructures. However, the Outstanding Universal Value of the property, contingent as it is on the interplay of the powerful Earth processes occurring where a divergent plate boundary, mantle plume and vast ice cap coexist, is rather unaffected by local tourism and its potential impact.

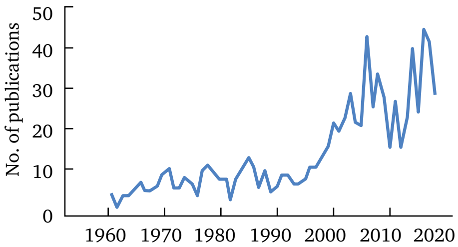


Figure 3.2.
Number of peer reviewed publications on various aspects of the nature of Vatnajökull National Park, published since 1960.

The intense, international scientific interest in the property is evidenced by some 775 scientific peer reviewed papers published over the last 50 years, 281 over the last ten years, on various aspects of plate tectonics, volcanism, glaciology, glacial geomorphology, colonisation of life and community development (Fig 3.2).

3.1.d Protection and Management Requirements

The entire nominated property enjoys strong legal protection. Vatnajökull National Park is protected as a national park (cf. Art. 51 of the Nature Conservation Act No. 44/1999 and IUCN Protection Category II) through special legislation from 2007, while the joined nature reserves of Herðubreiðarlindir and Lónsöræfi were declared protected areas in 1974 and 1977, respectively.

Overall, the property is very well managed, with a comprehensive management strategy and action plan in place since 2011 and 2013 (2nd ed.) and sufficient financial as well as human resources to secure its implementation. Key management issues include building and maintaining adequate infrastructure, including maintenance of the five visitor centres currently in use, and educating, managing and guiding increasing numbers of visitors.

A sophisticated long-term monitoring system has been set up, using space- and ground-based observations, for improved evaluation of seismo-tectonic movements and volcanic hazards as well as glacial flow and fluctuations. Key aspects of the property's flora and fauna are also monitored.

Oppostie: Tephra banks at Lakagígar with or without moss-cover, 12 August 2013 © Snorri Baldursson.

3.2 Comparative Analysis

At present, the only World Heritage Site representing a mantle plume interacting with an actively spreading oceanic ridge on land, is the cultural site of Þingvellir, Iceland. The nominated property, Vatnajökull National Park, adds a large ice cap and several highly active subglacial as well as subaerial volcanoes to this interaction, resulting in an array of equivalent landscape features that are either created under ice or air and are poorly if at all represented on the World Heritage List. The property, furthermore, contains a dynamic range of features created by expanding or retreating glaciers, making it a flagship educational and research site for the impacts of climate change on world glaciers.

The existence of Iceland may be attributed to the interplay between a divergent plate boundary and a mantle plume. Hence, the entire country is quite unique in terms of its geology and ongoing geophysical processes. The nominated property exhibits all the unique features of the geology of Iceland. There, this interplay has created an unprecedented diversity of volcanic landforms, enhanced by the ongoing interaction between erupting magma and glacial ice of varying extent.

However, the question posed here is if the property is outstanding and unique enough to merit a World Heritage status. To seek the answer for this question, the nominated property will be compared with other places on Earth where there are comparable processes ongoing. More specifically, this review will focus on places with similar tectonic, glaciovolcanic, volcanic or glaciological processes.

<u>Mid-ocean ridge on land</u>
The Mid-Atlantic Ridge is a mid-ocean ridge that runs along the entire floor of the Atlantic Ocean. Although it is almost entirely a submarine feature, a portion of it, namely Iceland, rises above sea level. The surface expressions of the ridge in Iceland are the neovolcanic zones, regions of active faulting and volcanism extending from the Reykjanes Peninsula in the southwest and zigzagging across Iceland before plunging back into the Atlantic Ocean in Öxarfjörður bay in the northeast (Fig 2.3, p. 32). This actively spreading plate boundary is Iceland's major geological show piece, being the only one of its kind exposed above sea level (Pálmason & Sæmundsson, 1974).

The need for a detailed review of the potential heritage value of the Mid-Atlantic Ridge was identified by the International Conference on UNESCO World Heritage, Earth Heritage, in 2004, with a possible serial trans-boundary nomination in mind. An expert workshop was convened in Reykjavík, Iceland in January 2007 to explore this idea, but the initiative seems to have faded out soon after that. The Reykjavík workshop identified Jan Mayen (Norway), Iceland, Azores (Portugal), St Paul's rock (Brazil), Ascension Island (UK), St. Helena (UK), Tristan da Cunha (UK), Gough Island (UK), Bouvet Island (Norway) as the visible parts of the Mid-Atlantic Ridge. Accordingly, there would be five World Heritage sites along the ridge: Þingvellir National Park and the island of Surtsey in Iceland, the vineyard culture of Pico Island and the town of Angara in the Azores, and Goch and Inaccessible Islands in the South Atlantic.

However, current thinking is that Iceland is the only island exemplifying the active part of the Mid-Atlantic Ridge (Páll Einarsson, 2017, pers. comm.). Presently, none of the other islands do, although they may have done so in the past. Not even the island of Surtsey can be considered an active part of the Mid-Atlantic Ridge's spreading zone. The active spreading in Iceland passes from the Reykjanes peninsula to Langjökull in the west as well as through the western and northern parts of Vatnajökull National Park in the east (Geirsson et al., 2006). Therefore, at present, only the cultural site of Þingvellir represents the active part of the Mid-Atlantic Ridge on the World Heritage List.

The island of Jan Mayen is located on a small continental fragment near the intersection of the Jan Mayen Fracture Zone (a transform fault) and the Mohns ridge. Although, the Beerenberg volcano (2277 m) is mostly covered by glacier, subaerial volcanism has been dominant in the Holocene and only a few tephra-forming eruptions have been recognised (Gjerløw et al., 2016).

The Azores islands are in a complex tectonic setting at the junction between three major lithospheric plates – the North American, African and Eurasian plates. The archipelago is the emerged part of the Azores Platform, transected by the axis of the Mid-Atlantic Ridge and thus long considered as a typical example of hot spot-ridge interaction (e.g. Métrich et al., 2014). However, no structures typical for a spreading seafloor are visible on the surface.

The British Overseas Territory of Saint Helena, Ascension Island and Tristan da Cunha are located quite far east of the Mid-Atlantic Ridge in the South Atlantic Ocean. All the islands are volcanic, but are formed by hot spots rather than being part of the ridge itself (Cresswell, 2016).

Glaciovolcanism

Glaciovolcanism, the interaction of magma and frozen water in all its forms is, outside of Iceland, especially prominent in Antarctica, Alaska and British Columbia (Smellie & Edwards, 2016), although found in other places (Fig 3.3). The term, as used here, embraces all volcanic eruptions where ice is involved. It does not include interactions of volcanic products with snow – as this happens all the time when volcanoes at high latitudes erupt – only those occurring under extensive ice caps or ice sheets, as well as subaerial eruptions whose products fall on or flow under ice (Edwards et al., 2015). The major difference between these two types of glaciovolcanism is the relative size of the volcano compared to the overlying and subsequently confining ice. In the former, the volcano is relatively small compared to the ice above, while in the latter, the volcano is large compared to the available amount of ice. Hence these two main types of glaciovolcanism can be called ice-dominant and volcano-dominant, respectively (Smellie & Edwards, 2016). Only ice-dominant glaciovolcanism produces major, lasting edifices on the surface of the Earth.

Volcano-dominant interactions are quite common in the world, including within the nominated property and at several World Heritage sites. They occur anywhere ice-capped stratovolcanoes erupt. However, there are two areas on Earth where ice-dominant interactions currently occur and magma reaches the Earth's surface under ice of extensive spatial cover and thickness. These are Iceland and Antarctica. Furthermore, only in Iceland, as exemplified by the landscapes of Vatnajökull National Park and the more widespread Móberg

Figure 3.3.
World map showing main areas with Quaternary glaciovolcanism (blue), including World Heritage Sites (red). It should be noted that glaciovolcanism has not been extensively studied in Central and South America (Smellie and Edwards, 2016).

(hyaloclastite) formation (Jakobsson & Guðmundsson, 2008), can glaciovolcanism be traced through time and associated with repeated loading and unloading of ice over the last 2.8 million years.

Glaciovolcanism in Antarctica is the most enduring and extensive on Earth, extending back to 28 Ma, as a minimum. Volcanic deposits are concentrated mainly within six volcanic fields that are scattered over an area stretching some 5000 km, from the sub-Antarctic South Sandwich Islands, via the Antarctic Peninsula and Alexander Island, through Ellsworth Land and Marie Byrd Land in West Antarctica, to Victoria Land in East Antarctica (Smellie & Edwards, 2016; Fig 3.2). South of the Antarctic Peninsula, the volcanic activity is focused along the West Antarctic Rift, a major active rift valley laying between East and West Antarctica. It has been suggested that the intense late Cenozoic volcanism in the area may be explained by an underlying mantle plume, although an alternative hypothesis is lower lithospheric extension (reviewed in Behrendt, 1999).

Glacial cover is extensive in all the volcanic fields of Antarctica. However, although glaciovolcanic deposits are varied and widely found, the degree of current subglacial activity is not easily quantified as many of the areas are remote with difficult accessibility. Also, when compared to Iceland, Holocene volcanic activity levels on Antarctica are low (Smellie & Edwards, 2016).

The abundance and variety of glaciovolcanic edifices, sequences and processes in Iceland is unmatched in any other volcanic province on Earth (Smellie, 2013). Prominent landforms and features include tuyas, tindar (móberg ridges), tephra mounds and tephra fields (Smellie & Edwards, 2016), móberg or pillow sheets (Jakobsson & Guðmundsson, 2008), jökulhlaups, canyons and sandur or glacial outwash plains (Baynes et al., 2015b; Arnalds, 2015). All these landforms and features are well developed within the nominated property and two of them, i.e. tindar and móberg sheets, are largely confined to Iceland, including the nominated property.

Tuyas are the most distinctive of all glaciovolcanic landforms (Box p. 41). They are especially common and prominent in Antarctica, British Columbia and Iceland (Edwards et al., 2015), including within the nominated property. An excellent example of a mafic tuya is Mt. Herðubreið, the "Queen of the mountains", as it is fondly referred to in Iceland, erupted under the Weichselian ice sheet. No subglacial eruption resulting in the formation of a tuya has been monitored in real time on Earth.

Tindar, elongated ridges of pillow lava and hyaloclastite, are a prominent landform produced by subglacial fissure eruptions. Tindar are common in Iceland, including dozens within the nominated property, but very rare elsewhere and then less well developed. In fact, tindar appear to be only documented at two other places on Earth, Antarctica and the Azas Plateau, Siberia. The formation of the tindar landform was observed and monitored for the first time during the 1996 Gjálp eruption in Vatnajökull (Guðmundsson et al., 1997). Exceptional examples of tindar ridges, tens of kilometres long, are found in the western part of the nominated property (Fig 2.10).

Sandur plains are prominent features in Iceland where volcanic and geothermal activity accelerate the melting of ice sheets and glaciers. Sandur plains derive their name from Skeiðarársandur, the outwash plain in front of Skeiðarárjökull and several lesser outlet glaciers to the south of Vatnajökull. Most of Skeiðarársandur lies outside the nominated property. However, the large and dynamic Dyngjusandur to the north and Breiðamerkursandur to the southeast are fully contained within it. Large sandur plains are rare or non-existent outside of Iceland.

Clusters of rootless cones may be formed when hot lava flows over wetlands or a frozen ground. These features are common in Iceland and observed on the Martian flow fields but are rare and then not as well preserved elsewhere on Earth (Box p. 46–47). A cluster of large, beautifully preserved rootless cones, is found inside the nominated property within the 1783–1784 Laki lava flow northeast of Mt. Laki.

Móberg sheets have only been described from Iceland. They are large, flat formations of pillow lava and hyaloclastite, believed to have formed where broad-fronted lavas flowed considerable distances under a thick Quaternary ice sheet in high-discharge fissure eruptions (Walker & Blake, 1966; Jakobsson & Guðmundsson, 2008). One such formation within the nominated property is Bjáfjöll, close to the western margin of Vatnajökull. This formation is 10 km long, 3 km wide and 0.2–0.3 km thick, made mostly of pillow lava (Vilmundardóttir et al., 2000).

Canyons may be created because of glaciovolcanism. Jökulsárgljúfur canyon in the northern part of the nominated property represents a striking example. The canyon was carved out during the mid to late Holocene in mostly three short-lived but extreme jökulhlaups where flow depth and discharge rate exceeded the threshold for erosion through plucking of large boulders rather than abrasion (e.g. Baynes et al., 2015a; Box p. 90).

The magnitude of the largest jökulhlaups that contributed to the formation of the Jökulsárgljúfur canyon, 900,000 m^3s^{-1}, is small compared to the largest floods estimated to have ever occurred on Earth, associated with the deglaciation of the large ice sheets in North America (5,000,000 m^3s^{-1}; Baker 1973) and Siberia (28,000,000 m^3s^{-1}; Baker et al., 1993). However, in these locations, the potential for such extreme floods was removed when the ice melted and the glacial lakes drained, leaving behind flood-carved landforms such as canyons, preserved in now 'fossilised' landscapes. Significantly, the potential for forthcoming floods remains in place for the Jökulsárgljúfur canyon due to the continued volcanic activity beneath the Vatnajökull ice cap.

When the diversity of volcanic and glaciovolcanic landforms of the nominated property is compared to other regions of the world, World Heritage sites or not, Vatnajökull National Park stands out as by far the most diverse. In fact, nowhere on Earth can as many and diverse landforms related to volcanism and geovolcanism be found and explored in one place (Table 3.1).

Sites with volcanism but no ice

In a thematic study commissioned by IUCN, Wood (2009) reviewed the present diversity, status and prospects of filling gaps regarding volcanic World Heritage. He examined the 878 properties listed up to and including 2008, as well as the 1468 sites proposed for nomination in the Tentative Lists of State Parties. The study concluded that 27 World Heritage properties display active volcanism and that these properties may contain as many as 101 active volcanoes, or >6% of all the world's Holocene subaerial volcanoes. Since Wood's review, three volcanic properties have been added to the World Heritage List, i.e. the Pitons, cirques and ramparts of Reunion Island (2010), Mt. Etna (2013) and the Gran Desierto de Altar Biosphere Reserve (2013).

Importantly for the current nomination, Wood (2009) identified several gaps in volcanic representation of the World Heritage List. First, he found that although large shield volcanoes and stratovolcanoes are well represented on the list, Icelandic-type "shield volcanoes" or monogenetic basaltic lava shields are missing. Second, while craters and calderas of different types are adequately represented, there are no linear vent systems, i.e. rows of cones and craters as e.g. the 27-km long Lakagígar cone row from 1783–1784.

Table 3.1.
Prominent sites around the world displaying volcano-air, volcano-glacier and/or volcano-climate interactions and the resulting diversity of landforms and features.

World Heritage Site	Country	Strato-volcano	Shield Volcano	Lava Shield	Flood lava	Tuya	Tindar	Móberg sheet	San-dur	Ice sheet	Glacier	Glacio-volc.**	Jökul-hlaup
Volcanoes of Kamchatka	Russia	X		X							X		
Heard and McDonald Islands	Australia	X									X		
Hawaii Volcanoes	USA		X	X	X								
Kluane/Wrangel-St.Elias/ Glacier Bay/Tachenst	Canada/USA	X	X							X	X		
Sangay National Park	Equador	X									X		
Kilimanjaro National Park	Tanzania	X									X		
Other parts of the World													
Vatnajökull National Park	Iceland	X	X	X	X	X	X	X	X	X	X	X	X
Antarctica	Antarctica	X	X			X	X			X	X	X	X
Alaska – Aleutian	USA	X									X		X
British Columbia	Canada	X	X	X		X					X		
Cascades	USA	X									X		
Trans Mexican Volcanic Belt	Mexico	X	X	X									
Azas Plateu	Russia					X	X						
Jan Mayen	Norway	X									X		X

*Flood lavas are >1 km^3, but <100 km^3. **Here we refer to active ice dominant glaciovolcanism cf. Smellie & Edwards (2016).

Third, while the partly submerged Surtsey World Heritage site represents a shallow-water phreatomagmatic eruption constructing a tuya-like edifice, fissure and central volcano eruptions under ice, forming tindar and tuya landforms, respectively, are poorly if at all represented on the list. Fourth, recent expansive lava flows and tephra fields such as those found in the nominated property are poorly represented on the World Heritage List. Finally, Wood (2009) noted the absence from the list of several world-renowned volcanoes, including Lakagígar.

All these gaps can be filled with the current nomination of Vatnajökull National Park. Representatives of these gap-filling landforms include e.g. the well-formed lava shield Trölladyngja north of the Vatnajökull ice cap, the spectacular cone rows of Eldgjá and Lakagígar to the southwest of the ice cap, the beautiful tuya Mt. Herðubreið in the north and the superb tindar formations Kambar, Fögrufjöll and Grænifjallgarður in the southwest.

Ice caps and glaciers

Most of the world's glacial ice is confined within Antarctica and Greenland, but ice caps and glaciers are found on all continents. There are at least five properties on the World Heritage List that have been nominated specifically or in large part due to their spectacular glaciers. These are: The Ice Field Ranges of Alaska and Yukon, the Illulisat Icefjord in Greenland, the glaciers of Jungfrau-Aletch Bietchhorn in Switzerland, the glaciers of the Great Himalaya National Park in India and Los Glacieres National Park in Argentina (Fig 3.3). So, what makes Vatnajökull unique or even special?

Vatnajökull is the largest ice cap in Europe by volume (Björnsson, 2017) and among the fifteen largest by area in the world. It is complex and dynamic due inter alia to repeated subglacial eruptions and jökulhlaups and surging events (Þórarinsson, 1950; Björnsson et al., 2010; Montanaro et al., 2016; Björnsson, 2017).

Few ice caps worldwide have better accessibility for conducting research than Vatnajökull and this is reflected in e.g. over 1190 publications dealing with the ice cap or neighbouring areas. The earliest written documents on Vatnajökull date from the 17th century (Björnsson, 2017). In fact, there is little doubt that Vatnajökull is among the best monitored and researched ice caps worldwide. Most other ice caps are in remote areas and direct observations are scarce. Additionally, harsh conditions in the field, for example in the high Arctic or on high mountain ranges, are a limiting factor for field research. In contrast, Vatnajökull is accessible all year round. There is only a 3–4 hours' drive from Reykjavík to the margin of Tungnaárjökull outlet glacier, from which most expeditions enter the ice cap. The use of motorised vehicles, including specially equipped jeeps, snowmobiles, and snow cats, has facilitated glaciological field campaigns immeasurably.

Vatnajökull is an important analogue for warm-based Pleistocene ice sheets (of the glacial periods). It provides a natural laboratory for a variety of glaciological research and has substantial international potential for forecasting and comprehending the conditions of ice caps and glaciers elsewhere. The ice cap responds very quickly to a warming climate because of the location of Iceland at atmospheric and oceanic boundaries in the North Atlantic Ocean (Björnsson et

Next page: Hoffelsjökull proglacial lake, 17 July 2017 © Þorvarður Árnason.

Figure 3.4.
World map showing the location of main ice caps of the world, outside of mainland Antarctica and Greenland (blue dots) and the location of World Heritage Sites where glaciological features are a significant part of the site's Outstanding Universal Value (red dots).

al., 2013; Flowers et al., 2005; Aðalgeirsdóttir et al., 2005). For the period of 1995–2010, the cumulative mass loss averaged over the entire glacier area was among the highest recorded for any glacier in the world during this time (Björnsson et al., 2013).

Because of the accessibility of Vatnajökull's outlet glaciers, they have served and will continue to serve, as a real-time observatory of glacier processes and changes. For example, Breiðamerkurjökull outlet glacier in the south is central to modern understanding of glacier bed processes and one of the best-known glaciers amongst glacial researchers globally (Evans, 2016). The northern outlet glacier Brúarjökull has offered an exceptional opportunity to study processes, sediments and landforms related to surging glaciers. Furthermore, the scale and unconfined ice-flow conditions at which surges take place at Brúarjökull makes it attractive to study as analogues for fast flowing glaciers in palaeo-glaciated regions, e.g. Scandinavia and North America. The land system model for surge-type glaciers (Evans et al., 1999, 2007) is fundamentally based on observations from Brúarjökull and other Icelandic surge-type glaciers.

3.3. Proposed Statement of Outstanding Universal Value

Brief synthesis

The nominated property, a total of 14,482 km², comprises the whole of Vatnajökull National Park, plus two contiguous protected areas. At its heart lies the 7800 km² Vatnajökull ice cap in southeast Iceland.

Iceland is the only part of the actively spreading Mid-Atlantic Ridge exposed above sea level, with the tectonic plates on either side moving apart by some 19 mm each year. This movement is accommodated in rift zones, two of which, the Eastern and Northern Volcanic Zones, pass through the nominated property. Underneath their intersection is a mantle plume providing a generous source of magma. The property contains ten central volcanoes, eight of which are subglacial. Two of the latter are among the four most active in Iceland. Most of the property's bedrock is basaltic, the oldest being erupted some 10 million years ago and the most recent in 2015. Outside of the ice cap, the terrain varies from extensive, flat lava flows to mountains, including tuyas and tindar (ridges) of brown hyaloclastites, erupted in fissure eruptions beneath ice age glaciers. The latter occur nowhere else in the world in such numbers.

The nominated property comprises an entire Earth system where magma and the lithosphere are incessantly interacting with the cryosphere, hydrosphere and atmosphere to create extremely dynamic and diverse geological processes and landforms that are currently underrepresented or not found on the World Heritage List. It was here that the phrase "Fire and Ice" was coined.

The Vatnajökull ice cap reached its greatest extent by the end of the 18th century and has on average been retreating since then. Recently, its retreat has accelerated in response to global warming, making the property a prime locality for exploring the impacts of climate change on world glaciers and the landforms left behind when they retreat.

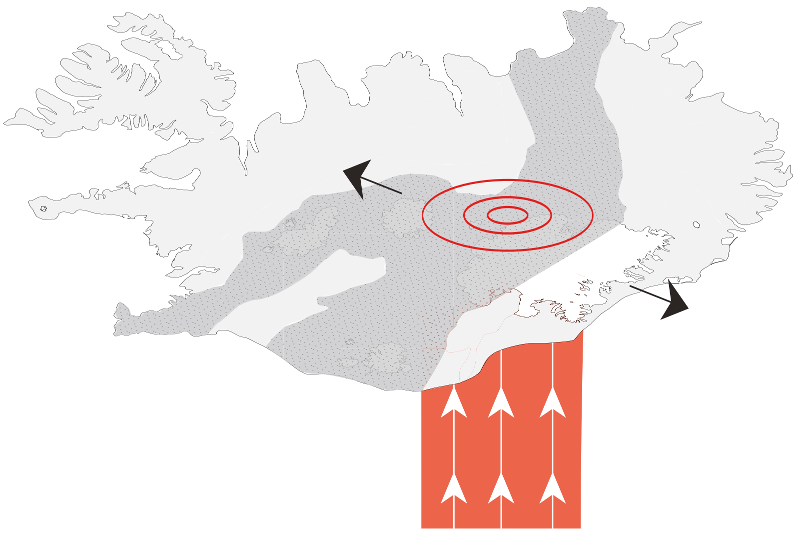
The volcanic zones of the property hold endemic groundwater fauna that has survived the ice age and single-celled organisms prosper in the inhospitable environment of subglacial lakes that may replicate conditions on early Earth and the icy satellites of Jupiter and Saturn.

Justification for criteria

Crietrion (viii). The coexistence and ongoing interaction of an active oceanic rift on land, a mantle plume, the atmosphere and an ice cap, which has varied in size and extent over the past 2.8 million years, make the nominated property unique in a global context.

Earth system interactions are constantly building and reshaping the property, creating remarkably diverse landscapes and a wide variety of tectonic, volcanic and glaciovolcanic features, many of which are not yet represented on the World Heritage List (Wood, 2009). Especially interesting and unique in this regard are the basaltic lava shields (Iceland shields), volcanic fissures and cone rows, vast flood lavas, and features of ice dominant glaciovolcanism, such as tuyas and tindar. Interestingly, the well exposed volcanic features

Figure 3.5.
Schematic illustration of the interplay of a divergent plate boundary, a mantle plume and an ice cap, demonstrating the Outstanding Universal Value of Vatnajökull National Park.



of the property have been used as analogues for similar features on the planet Mars. Geothermal heat and subglacial eruptions produce meltwater and jökulhlaups that maintain globally unique sandur plains, to the north and south of the Vatnajökull ice cap, as well as rapidly evolving canyons.

In addition, the property contains a dynamic array of glacial- and geomorphological features, created by expanding or retreating glaciers responding to changes in climate. These features can be easily accessed and explored at the snouts of Vatnajökull's many outlet glaciers and their forelands, especially in the southern lowlands, making the property a flagship glacial research location.

Statement of integrity

The nominated property covers approximately 25–30% of the central highlands of Iceland and extends onto lowland areas to the north and south to cover a total of 14% of the country. Most of the property qualifies for IUCN Category II. Its integrity is reflected in the inclusion of entire and intact landscape- and geophysical units, minimal human use and intervention and interest in the property as a scientific subject. The site contains the entire Vatnajökull ice cap, with all its subsidiary glaciers as they stood in 1998. It spans some 200 km of divergent plate boundary and encompasses ten central volcanoes and large parts of the accompanying fissure swarms and subsidiary landforms. The area is intact to a large extent and remote from habituated areas. In fact, some 85% of the property is classified as wilderness. An intense international scientific interest in the property is evidenced by at least 281 scientific peer reviewed papers, published over the last decade, on various aspects of plate tectonics, volcanism, glaciovolcanism, glaciology, glacial geomorphology and ecology. There has been no destructive human development within the property's boundaries. A few historic farms exist, but today only a few park employees live there on a year-round basis.

Requirements for protection and management

The great majority (98%) of the nominated property is protected as a national park, and the rest as nature reserves by law. Most of the land adjacent to the property is subject to the law on public land, where any invasive use requires approval by the Prime Minister's Office. The property is successfully managed by the government agency, Vatnajökull National Park, which is supported at all levels by the Icelandic government, local municipalities and businesses. A comprehensive management strategy and action plan are in place and there are sufficient financial as well as human resources for its implementation. A long-term monitoring system has been set up, using space- and ground-based observations, for improved evaluation of seismo-tectonic movements and volcanic hazards as well as for glacial flow and fluctuations and key aspects of the property's biota.

Risk management is a major issue in this highly dynamic setting where natural hazards are common. Other management issues include preventing wear and tear of nature at popular visitor destinations within the property, and maintaining adequate infrastructure for educating, managing and guiding the ever-increasing numbers of visitors which were approaching one million in 2017.

The Gjálp crater in Vatnajökull on 5 November 1996 © Ragnar Th. Sigurðsson.

Top: Gyrfalcon, *Falco rusticolus* © Daníel Bergmann. Middle: Heinabergsjökull, 2 February 2002 © Þorvarður Árnason. Bottom: The northeastern-most crater on the Eldgjá fissure © Walter Huber.

4. State of Conservation and Factors Affecting the Property

Natural conditions, the barrenness and remoteness of the area, together with a robust legal and management framework ensure the very good, and improving, state of conservation of the nominated property. Unabated climate warming will in the long-term effectively remove the Vatnajökull ice cap, a significant part of the property's Outstanding Universal Value, but likewise create a fascinating ecological laboratory. Ongoing risks from natural hazards and pressures from rapidly increasing tourism are monitored and managed in a responsible way.

4. State of Conservation and Factors Affecting the Property

4.a Present State of Conservation

Some 51% of the nominated property is glacial ice and another 37% comprise desert-like wilderness areas, covered to a large extent by Holocene lava fields, sandur and tephra plains and gravelly flats that have not been altered by direct or indirect human use. Large parts of the central highland's neovolcanic zones are naturally devoid of soils and vegetation due to their elevation, active volcanism and past climate. However, some of the denuded areas closest to the highland rim in the north were formerly vegetated. Intense erosion, caused by a combination of volcanism and sheep grazing, especially in the late 19th and early 20th centuries (Þórhallsdóttir et al., 2013), has now left these lands devoid of vegetation. The state of the remaining soils within the park boundaries varies. It is good in lowland areas and highland areas in the east and southeast. However, in the southwest (Laki, Langisjór area) and northern highlands (southeast of Jökulsárgljúfur canyon) there are still areas with active soil erosion.

Top: Sprengisandur close to Nýidalur. Bottom: View from Svarthöfði by Vonarskarð to the south and the Kaldakvísl river © Snorri Baldursson.

Traditional use of land is permitted in parts of the nominated property. Sheep grazing is allowed in highland pastures in the north, west and east – although most of the highlands within the property are far too remote and barren for sheep to ever go there – as well as limited areas south of the ice cap. A quality management system, developed by the Soil Conservation Service in cooperation with farmers, is in place to ensure that grazing on public land is sustainable. As per the agreement, sheep that roam into areas deemed by the Soil Conservation Service to be unqualified for grazing are marked and slaughtered in the fall.

It is impossible to provide an accurate number of sheep that graze within the nominated property; they tend to roam in and out of it during the summer months of July and August. The Soil Conservation Service estimates (Gústaf M. Ásbjörnsson, written communication, 2017) that during the summer months some 20,000 ewes roam the highland pastures of the eight municipalities surrounding the nominated property. A fair guess is that 10% of these stay within the property for a significant part of the summer. This makes some 2,000 ewes, each with 1.8 lambs on average, altogether some 5,600 sheep.

All grazing has an impact, and past sheep grazing has undoubtedly had detrimental effects on the vegetation within the nominated property, as elsewhere in the neovolcanic zones of Iceland. However, it is often difficult to differentiate the impact of grazing from that of natural hazards such as volcanic ash fall, dust clouds, jökulhlaups, and other natural erosion processes. Although grazing impacts may still be discernible locally within the property, they are hardly relevant in assessing its proposed Outstanding Universal Value. Further, with warming climate, the vegetation is in general expected to become more robust and better able to withstand any incidental grazing by sheep. Similarly, the overall state of the property's terrestrial and freshwater biological communities is expected to improve with warming climates, all else being equal.

Direct human use of the nominated property is restricted to tourism and hunting. There is limited wildfowling (pink footed goose, graylag goose and ptarmigan) in some parts of the property, most of it taking place in the highlands around Mt. Snæfell in the east. Goose hunting is allowed from 20 August each year in most areas where geese can be found. Ptarmigan hunting is allowed during four weekends, starting the last weekend of October each year, with a current 40,000-bird quota for the entire country. Reindeer are culled, from 20 August, in the eastern highlands around Mt. Snæfell and within the Heinaberg/Hoffell and Lónsöræfi areas in the southeast. However, a total ban on hunting applies to Mt. Snæfell itself and to the Eyjabakkar wetland areas southeast of the mountain (Fig 4.1).

A total ban on all hunting, except the feral mink, also applies to the former national parks of Skaftafell in the south and Jökulsárgljúfur canyon in the north.

Localised deterioration of land and vegetation is evident on and around foot paths and viewpoints at some of the more popular visitor destinations within the nominated property. Conservation efforts in these areas are primarily aimed at reinforcing hiking routes and viewing points, but also at repairing damaged areas and meeting the challenge of the ever-increasing number of visitors (section 4. b. (vii)). A novel method of repairing "wild" trails and trampled areas in the fringe-moss heaths, e.g. around Lakagígar, is to replace them with pieces of moss mats that are taken at more remote locations

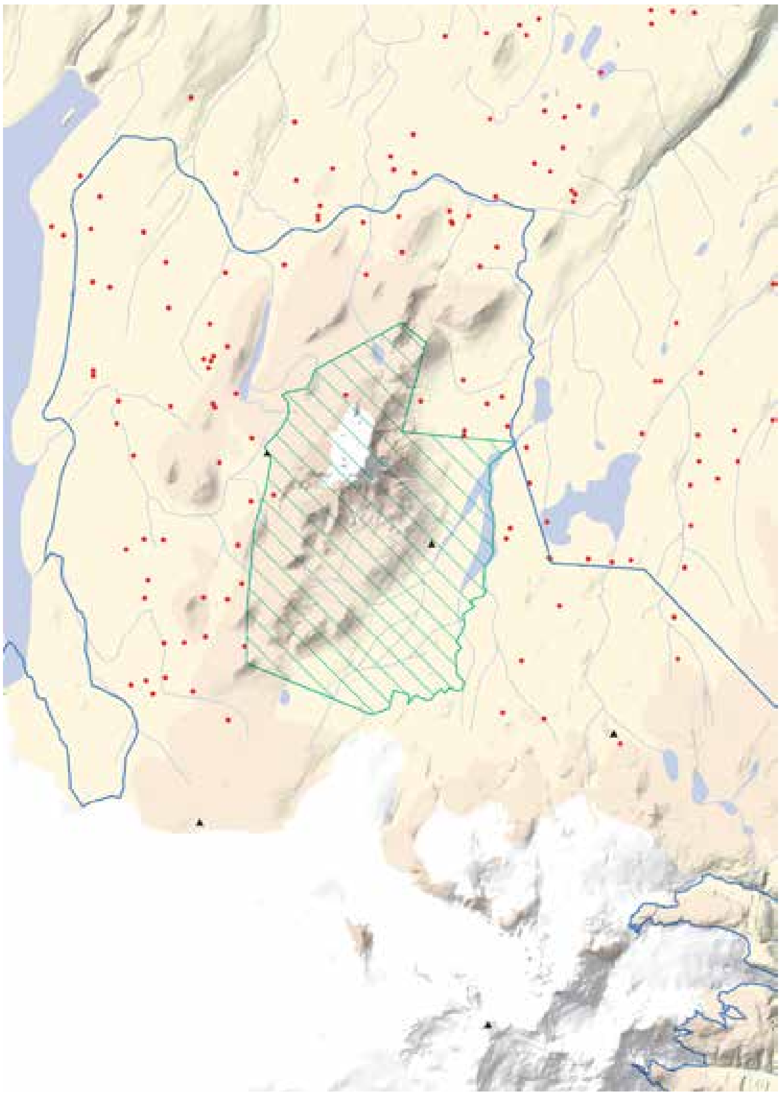


Figure 4.1.
The wildlife sanctuary of Mt. Snæfell and the Eyjabakkar wetlands in the northeast of the nominated property (green hatched area). The red dots represent shot reindeer in 2016.

within the property. The moss mats will eventually regenerate at the source location, but by closing visible wild trails at frequently visited sites, traffic along them is discouraged.

4.b Factors Affecting the Property

The nominated property comprises 14,482 km² of land, most of which, as noted above, is either glacial ice or barren land. Less than 6% of the property is lowland (below 400 m). At present, there are no imminent outside threats to the proposed Outstanding Universal Value of the property; natural hazards such as tectonic movements, volcanic eruptions and jökulhlaups are an integral part of this value.

4.b (i) Development Pressures

The park legislation (section 5.b) effectively prevents any quarrying or large-scale development, such as erecting hydroelectric or geothermal power plants, asphalted highways, farms or hotels, within the nominated property. Thus, most development activities occurring there are low-key and aimed at facilitating visitor access, education and recreation, with minimal compromise to its natural values.

In a five-year period from 2011 to 2016, the number of tourists visiting Iceland has more than tripled, from some 565,000 in 2011 to 1,792,000 in 2016. This corresponds to a national average of a 25% increase in tourism per year. The increasing popularity of Iceland as a tourist destination is mirrored by a parallel increase at the most popular tourist attractions within the nominated property (see section 4.b (iv)). However, visitation at the less accessible highland regions of the property has grown much less, and at some renowned destinations, such as Lakagígar, remained the same for the last six years (Fig 4.5).

Obviously, more than 25% annual increase in the number of visitors has put a heavy strain on the nature and infrastructure at the most popular sites. Park authorities have so far been reluctant to limit access to specific destinations through direct interventions, but rather focused on engineering solutions aimed at strengthening tourist facilities, e.g. expanding parking zones, building new toilet facilities and food and rest areas, rebuilding or resurfacing hiking trails and erecting viewing platforms. Increasingly, however, the park administration has appreciated that the recent boost in tourism seems to be a permanent rather than a passing phenomenon. Hence, the focus has progressively turned toward regulatory measures that restrict access or spread the tourism flow more efficiently in time and space. For instance, an automatic parking fee system was set up at Skaftafell in the autumn of 2017, opening possibilities of collecting different fees depending on the time of year and day.

Top: A trampled view point being repaired by moss transplants © Snorri Baldursson. Bottom: Moss transplants prepared for transport © Vatnajökull National Park.

4.b (ii) Environmental Pressures

There are no heavy industries, or industries that handle or produce environmentally hazardous materials, within or close to the nominated property. In fact, the property is very well placed with respect to local pollution. Hence, the only environmental pressures of any significance are those operating on a larger regional or global scale, such as climate change, desertification and invasive alien species.

Climate change

Continued climate warming will in the long-term significantly affect a major aspect of the Outstanding Universal Value of the nominated property, the Vatnajökull ice cap.

Glaciers recede all over the world because of climate warming and Vatnajökull is no exception to this general trend. Since the beginning of the 20th century, the ice cap has shrunk by about 300 km³ (approx. 10%) and the snouts of the outlet glaciers have retreated by about 2–5 km, most notably the ones descending onto the southern lowlands (see section 2.a (iii)). Individual termini have been receding by up to 100 m per year and dipping in elevation by as much as eight metres (Björnsson, 2017). Computerised models of the response of Vatnajökull to changes in mass balance, assuming 2–3°C warming during the 21st century, indicate that within the next 50 years Vatnajökull might lose a quarter of its current volume. After 200 years, there will only be glaciers on Öræfajökull in the south and in the highlands between Grímsvötn, Bárðarbunga and the Kverkfjöll mountains in the north (Aðalgeirsdóttir et al., 2006; Fig 2.64).

There will be a parallel increase in the total water drainage from the glacier, and it will be maintained at a high level well into the 22nd century before rapidly abating. Proglacial lakes will form in

The forefield and snout of Fláajökull from air on 13 July 2016 © Þorvarður Árnason.

front of most outlet glaciers descending onto the southern lowlands, and these will turn into clear mountain lakes as time passes. Once the ice has melted, the land is expected to rise by some 100 m at the centre of the ice cap and half as much at its margins. This pressure relief may cause an upsurge in volcanic activity within the subglacial volcanic systems of Vatnajökull, with an increased risk of tephra falls and jökulhlaups (see pp. 169–171).

Hence, climate warming, should it continue unchecked for centuries, will effectively remove one key aspect, glacial ice, from the property's Outstanding Universal Value. However, during this melting of the ice cap, the property will demonstrate a fascinating universal value as an outdoor laboratory and classroom in glacier and glaciovolcanic dynamics in relation to climate change, and in ecosystem development on lifeless, formerly glaciated temperate lands.

Rauðhóll (Red hill) in the Tungnaáröræfi wilderness, 25 July 2011 © Snorri Baldursson.

Desertification

Desert areas dominate the land north and west of Vatnajökull, dark coloured volcanic basalt sands that are quite unique on a global scale (section 2.a (v)). These are in part natural sandy deserts in the sense that they are formed by natural processes. Most of the sand was originally deposited by jökulhlaups, or the regular braided flow of glacial rivers, and as volcanic ash during eruptions. Desert conditions are maintained by the instability of the surface, which prevents natural succession, aided by lack of seed sources and the fact that young seedlings are often uprooted by frost heaving and needle-ice formation. The sand lacks an ability to retain water, which makes these surfaces vulnerable to periodic draughts. A few of the areas, however, especially to the north of the Askja volcano, were formerly vegetated. Their desertification is attributed to volcanic ash deposition (mainly Veiðivötn 1477) and lowering of ecosystem resilience by sheep grazing, especially in the late 19th century.

Alien invasive species

Alien species within the nominated property are mostly confined to the lowland sites at Skaftafell in the south and Ásbyrgi (within Jökulsárgljúfur canyon) in the north. Exotic tree and scrub species were planted at these sites between 1950 and 1970, before they became national parks in 1967 and 1973, respectively. At Skaftafell, a small stand of Sitka spruce, *Picea sitchensis*, and black cottonwood, *Populus trichocarpa*, was planted. At Ásbyrgi the plantations were more extensive, with white spruce, *Picea glauca*, blue spruce, *P. engelmannii*, Scots pine, *Pinus silvestris* and contorta pine, *P. contorta*, planted in addition to the species mentioned above. At the campsites in both places, the exotic *Salix borealis* has been used for shelterbelts.

After Jökulsárgljúfur canyon and Skaftafell national parks merged with Vatnajökull National Park in 2008, a decision was taken not to remove these plantations but to attend to them through thinning, removing stray trees and preventing them from spreading naturally. At Skaftafell, only a few trees of sitka spruce now remain; all the black cottonwood trees have been removed to prevent seeding.

Nootka lupin, *Lupinus nootkatensis*, invading the Skaftáreldahraun lava flow field, 20 August 2013 © Snorri Baldursson.

The only invasive alien species of any concern within the nominated property is the herbaceous Nootka lupine, L*upinus*

nootkatensis, which is spreading wildly at Skaftafell. The species has been known in Iceland since the late 19th century. However, it first became naturalised after 1945 when seeds were imported from Alaska and sown at several afforestation sites throughout the country. At Skaftafell it was brought to Morsárdalur valley in the mid-1950s where it grew for two decades in one patch, mainly. After a large mud avalanche fell through the lupine patch onto the river plains below carrying thousands of viable seeds, the species became invasive and has been expanding its range ever since. Nootka lupine now covers some 100 ha in Morsárdalur valley. It also covers several hectares of the foreland of the Skaftafellsjökull outlet glacier, initially dispersed there from plantations at a neighbouring farm.

Much effort has been made to control the Nootka lupine at Skaftafell. Since 1994, volunteers, first commissioned by the British Trust for Conservation Volunteers (BTCV) and later Iceland Conservation Volunteers (ICV), have been cutting lupine at strategic points to control it and prevent further spread. Between 2005 and 2010, an experiment was made to use grazing sheep to control the lupine within a 20-ha fenced area. Both methods, although somewhat successful in reducing the speed of invasion, have proven futile in terms of controlling the spread of lupine within the park.

4.b (iii) Natural Disasters and Risk Preparedness

Natural Disasters

Natural hazards and disasters are obviously a persistent threat within the nominated property. These can relate to volcanic events, earthquakes, extreme weather events or jökulhlaups.

The Icelandic Meteorological Office (IMO) monitors natural hazards in Iceland, including within the nominated property, and is also responsible for issuing warnings and forecasts about such hazards when relevant. The IMO runs an extensive monitoring net of e.g. seismometers, GPS stations and water gauges to monitor any natural changes or development that could lead to volcanic or seismic hazards (Fig 4.2).

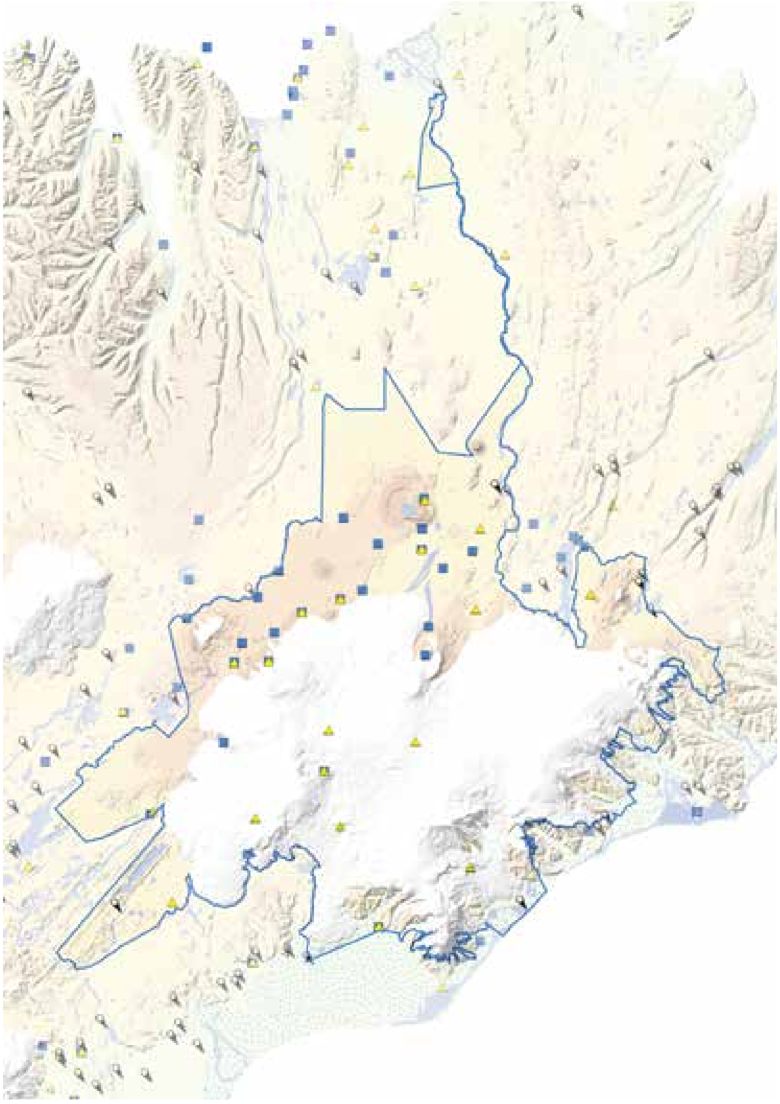
Top: Accidents happen in Vatnajökull National Park as elsewhere, but fortunately no one got hurt, 9 August 2010 © Snorri Baldursson. Bottom: Approaching and entering an ice cave requires utmost care, 27 October 2015 © Þorvarður Árnason.

Risk Preparedness

Civil protection in Iceland is under the aegis of the Ministry of Justice and administered by the National Commissioner of the Icelandic Police through the Department of Civil Protection and Emergency Management. This department is responsible for the preparedness, coordination and running of the National Crisis Coordination Centre.

Civil protection committees are responsible for risk assessment, preparedness and the making of contingency plans at municipality level. The committees are chosen by the municipality councils, led by the commissioner of the local police. In case of a natural hazard within Vatnajökull National Park, park managers or other staff take active part in the work of the civil protection committees. Although local authorities hold the primary responsibility of making contingency plans, they are made in close cooperation with all stakeholders, including the Vatnajökull National Park staff. For example, in the case of the Holuhraun eruption in 2014–2015, the knowledge of park staff about e.g. local natural conditions, passability of mountain roads, escape routes and tourist behaviour within the

Figure 4.2.
The network of measuring devises maintained by the Icelandic Meteorological Office to monitor natural hazards within and outside the nominated property.



Vatnajökull National Park Boarder
Discharge gauging stations
Seismograph stations
GPS stations

park proved indispensable for the making of realistic contingency plans. When contingency plans are activated, or an event occurs that calls for an operation, the relevant police commissioner coordinates the response on a local level. If the event is large and requires help from nearby municipalities or governmental institutes, the Emergency Centre is activated and coordinated by the National Commissioner.

Contingency plans

Contingency plans are available for all police districts within Vatnajökull National Park. These plans aim at shortening response time from the precursor or start of an event until action is taken. These plans are scenario-based, e.g. a possible explosive subglacial eruption in the Vatnajökull ice cap, with concurrent ash fall, poisonous volcanic gas release and major outburst floods.

Most of the operators within the park, including park rangers, police, scientists, staff of the National Commissioner, and tour operators are using either VHF or TETRA radios and can communicate quickly if needed. Mobile phone coverage is extensive, although not complete, and the system is used to issue warnings by sending out messages to all cell phones within a given danger zone. Visitors are encouraged to keep their phone on during visits.

Role of Park authorities in risk preparedness and staff training

In addition to local contingency plans, Vatnajökull National Park has prepared its own Safety Strategy, which covers the safety of guests and staff in the face of hazards, natural or otherwise. The strategy delineates the responsibility of the park, versus that of local and national authorities, in terms of emergency preparedness and response, and provides objectives and actions related to that responsibility.

Contingency plans are prepared for each administrative region within the park. The plans contain telephone numbers of relevant emergency personnel and the placement of safety gear, and define first responses that should be taken by staff in case of natural hazards, disasters or accidents involving guests or staff. Park contingency plans are meant to cover the period from an event happening until the relevant local or national authorities can take control of the situation.

Risk assessments are made for specific places, hiking paths or fords that are considered potentially risky or dangerous. If the risk is assessed to be unacceptable, improvements are made, including closing the place/trail or putting in place extra safety measures such as handrails or viewing platforms.

All national park employees are educated about relevant contingency plans and risk assessments. They are trained in first aid and the use of relevant communication equipment, how to be aware, how to respond in case of accidents or hazards and how to document near-accidents.

Finally, general emergency practices are held where a natural hazard (e.g. an eruption) or major accident (e.g. a bus falling into a ravine) is simulated and the staff tested for their preparedness.

Hazard maps

The Association for Search and Rescue has published a crevasse map of Vatnajökull to help travel operators on the ice cap avoid danger zones (Fig 4.3). A crevasse map needs to be updated regularly, especially in times of rapid glacial changes.

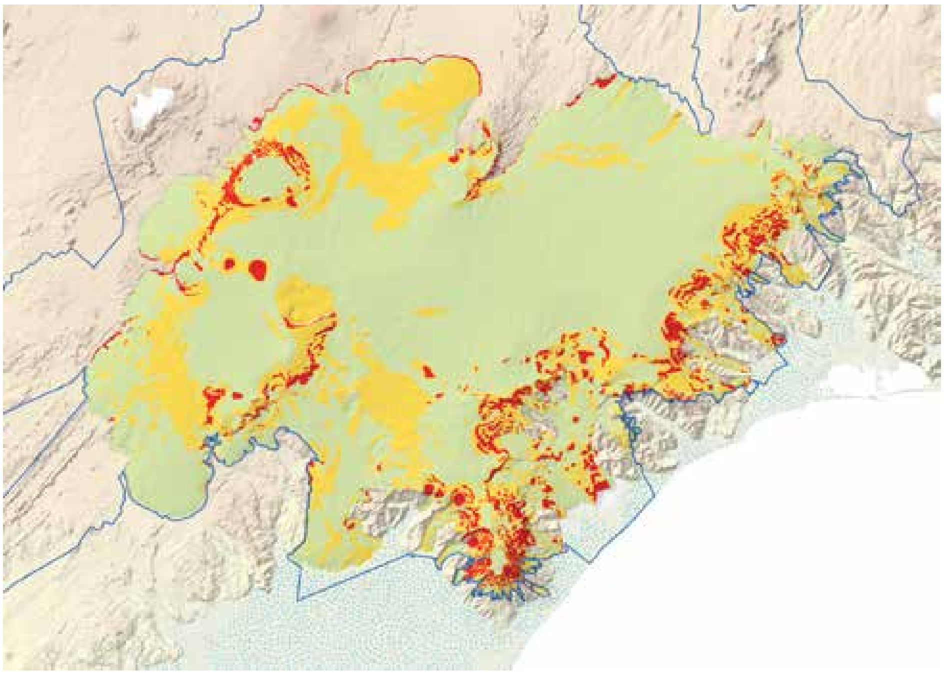


Fig 4.3.
A crevasse map of Vatnajökull 2015. Green areas: little or no crevasses, passable year-round; Yellow areas: crevasses of variable size, passability depends on time of year and snow depth and extreme caution is needed if navigation is attempted.
Red areas: heavily crevassed, impassable and life threatening year-round. Cartography by Snævarr Guðmundsson, based on several sources of aerial photographs, satellite image data and oblique aerial images, from 2003–2014.

4.b (iv) Responsible Visitation at World Heritage Sites

Current levels and trends in visitation

The huge size of the nominated property, relatively low density of guests in large areas, 25 entrance roads and more if all minor trails are counted, and no entrance fees, make it impossible to provide the exact number of guests that visit the property each year. Instead, indirect measures have been used to estimate these numbers. Automated traffic counters for cars, calibrated for mean number of passengers per car, provide a good estimate of visitors passing a given spot on a road. Also, automated visitor counters placed at the beginning of a hiking trail or the entrance to a visitor centre, provide accurate estimates of visitors at these sites.

An expanding network of automated counters over the past five years has now produced a reasonably good overall picture of numbers and distribution of guests within the park. Although visitors can be encountered in all parts of the park, tourism is concentrated to a few popular destinations. By far the most visitors are encountered at Skaftafell and Jökulsárlón lagoon south of the Vatnajökull ice cap, 620,000 and 640,000 respectively in 2016. Dettifoss waterfall in Jökulsárgljúfur canyon comes third with 197,000, three times less than the most popular sites. Other sites within the property lag far behind in visitor numbers (Fig 4.4).

The massive increase in tourism in Iceland since 2011 is fully reflected at sites which are accessible on a year-round basis, i.e. Skaftafell and Jökulsárlón lagoon, in the southeast lowlands and Dettifoss in the northern highlands (after road improvements in 2014). These sites show a 14–30% annual increase over the last few years (Fig 4.4). In contrast, visitation at renowned highland sites has remained rather stable over the last five years, except for Askja volcano where visitation jumped 17% between 2015 and 2016. Regarding this, it should be noted that the spring and early summer of 2015 was exceptionally cold with many highland roads opening 3–4 weeks later than on average.

According to Isavia's (Iceland Civil Aviation Administration) passenger forecast, passenger movement through Keflavík Airport will increase in 2017 by some 30% compared to 2016. Íslandsbanki's economic forecast for 2016–2018 predicts a 35% increase in the number

Figure 4.4.
Visitation at some of the best-known destinations within Vatnajökull National Park in 2016. Over 70% of visitors only stop at Skaftafell or Jökulsárlón, or both. Source: Þórhallsdóttir et al. (2017).

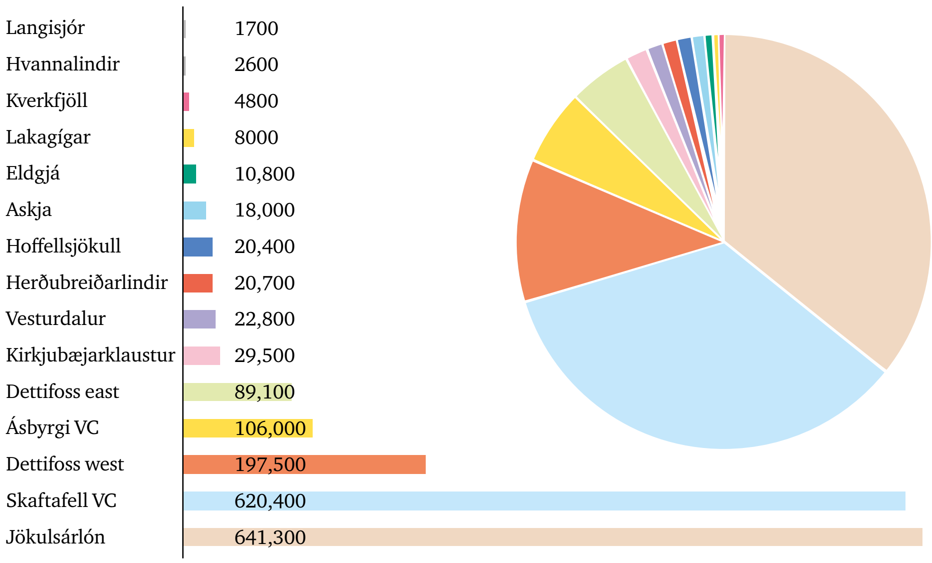
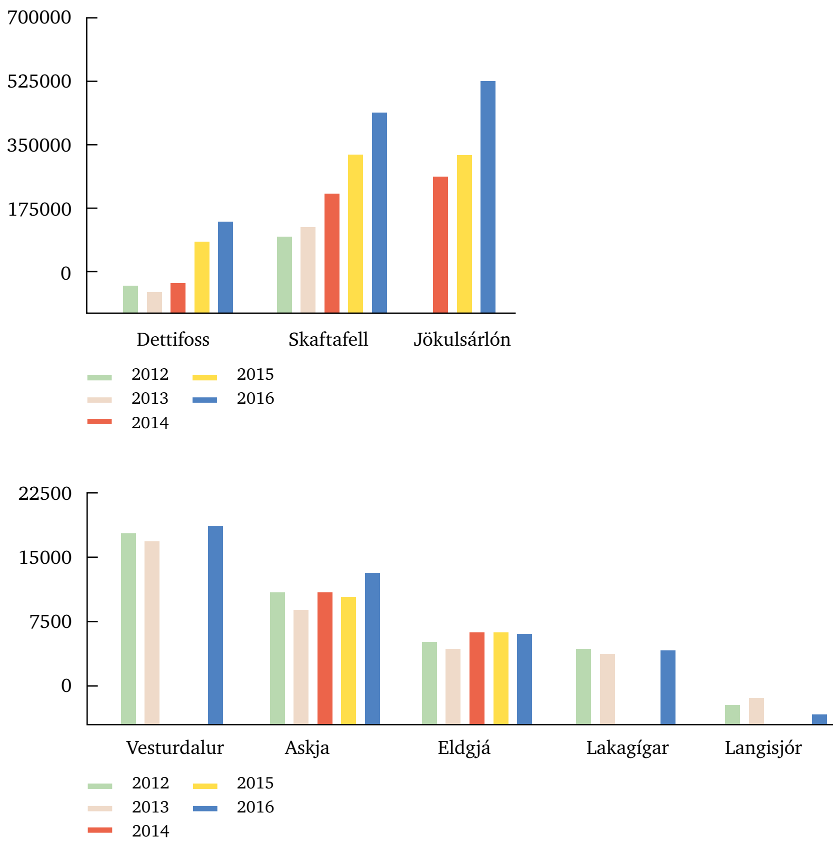


Figure 4.5.
Top: Visitation at three sites accessible on a year-round basis. Bottom: Visitation at five highland sites that are only accessible for two to four months each year. Missing columns are due to default traffic counters. Source: Þórhallsdóttir et al. (2017).



of foreign visitors to Iceland in 2017, i.e. an increase from 1.8 million in 2016 to 2.4 million. If these predictions come true, visitation at Skaftafell and Jökulsárlón will almost certainly increase by at least 25%. Thus, some 750,000 and 800,000 visitors may be expected at these sites in 2017, respectively.

Top: Hikers on Svínafellsjökull, 29 May 2015 © Þorvarður Árnason. Bottom: Chunks of ice at the beach of Breiðamerkursandur are popular among photographers, 20 February 2014 © Snorri Baldursson.

Will inscription facilitate visitation at Vatnajökull National Park?
Recent studies have shown mixed results regarding if and to what extent a World Heritage listing will increase tourism to a site (reviewed in e.g. Ribaudo & Figini, 2017). Su & Lin (2014), using pooled data from 66 countries for the period 2006–2009, concluded that increasing the number of World Heritage sites will significantly increase international tourist arrivals, and more so at natural sites. However, others find this an unfounded generalisation (e.g. Poria et al., 2011; Ribaudo & Figini, 2017). Ribaudo and Figini (2017), analysing 16 Italian World Heritage Sites, found that growth rates of tourism five years before and after listing remained on average the same over all the 16 sites, although there was much internal variation, increase at some sites, decrease at others. They concluded that diversity is the norm and "for a mature destination like Italy, there is no statistical evidence that World Heritage listing is associated with accelerating market growth rates".

Considering the current popularity of Iceland as a tourist destination, inscription of Vatnajökull National Park on the World Heritage List is not expected to markedly affect total visitor arrivals to the country. However, it is to be expected that World Heritage status will increase awareness and interest in Vatnajökull National Park as a destination within Iceland. Given the experience from e.g. Italy, it is probably safe to predict a 5–10% increase in visitation due to the World Heritage listing alone. We also predict that the composition of the visitors will change toward, in general, more nature-conscious tourists. In a survey at the Þingvellir World Heritage Site in 2015, 30% of the guests surveyed indicated that inscription had significantly affected their choice of destination (Sæþórsdóttir et al., 2016). The survey, however, did not ask if the Þingvellir World Heritage Site was an important reason for their visit to Iceland.

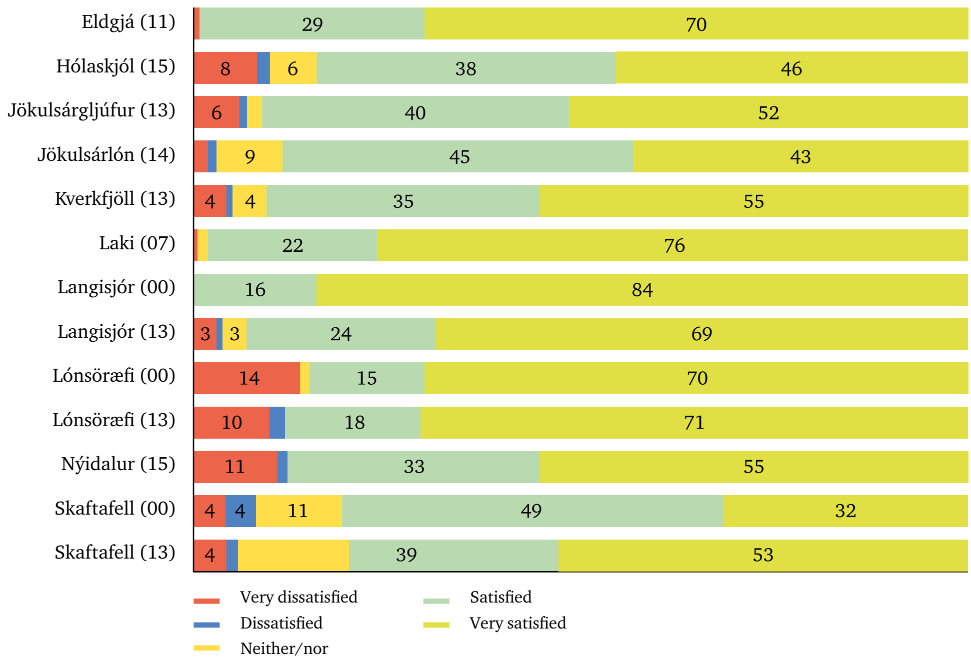
Visitor satisfaction

Since the year 2000, a total of 10,088 questionnaires relating to visitor satisfaction, overcrowding and environmental damage have been collected from tourists within Vatnajökull National Park for different research projects (Sæþórsdóttir, 2017, unpublished; Sæþórsdóttir et al., 2016). Only a few of these have been commissioned by park authorities.

Over 80% of respondents in these surveys have expressed satisfaction with their visits and overall less than 10% have expressed dissatisfaction. However, 10–14% claimed to be very dissatisfied in Lónsöræfi in surveys conducted in 2000 and 2013 and 11% in Nýidalur in a survey conducted in 2015. At Eldgjá, Lakagígar and Langisjór in 2000, over 98% of tourists were satisfied or very satisfied with their trips (Fig 4.6). At the three sites, Langisjór, Lónsöræfi and Skaftafell, where data are available from 2000 and 2013, visitor satisfaction either increases or decreases between the surveys, with no clear trends established.

Most visitors, irrespective of sites, consider the number of tourists to be suitable. However, at two sites, Skaftafell in 2000 and Jökulsárlón in 2014, almost 30% of respondents felt that tourists were rather or too many at the time. It is interesting that fewer respondents complained of crowding at Skaftafell in 2013 than in 2000, despite an increase of over 500% in tourist numbers. Overall, between 70 and 85% of visitors surveyed notice little or no erosion of foot paths within Vatnajökull National Park (Fig 4.7). The highest proportion of tourists noticing foot path erosion was recorded at Kverkfjöll in 2013 (16%) and the lowest in Jökulsárgljúfur in 2001 (1%). Few tourists surveyed noticed damage to

Figure 4.6.
Satisfaction of visitors within Vatnajökull National Park at different sites and times. Soure: Sæþórsdóttir et al. (2016).



vegetation within the park. The areas with the highest proportion of respondents noticing trampling impacts were Kverkfjöll in 2013 (10%) and Lakagígar in 2007 (9%). Damaged vegetation was least noticed in Lónsöræfi 2013 and Jökulsárgljúfur 2001 (Fig 4.7). Still fewer visitors noticed damage to geological formations within the property. The highest proportion recorded was at Langisjór in 2013 and Jökulsárlón in 2014 when 4% of respondents noticed damage of that sort. It is further very uncommon for tourists to notice garbage on their trips within the property. The site with the highest proportion of respondents noticing garbage in nature was 7% in Kverkfjöll 2013.

Based on the research by Sæþórsdóttir and co-workers it can be concluded that a great majority of visitors to Vatnajökull National Park are satisfied with the visit and the condition of the park's nature.

Responsible visitation

Nature tourism is a rapidly growing branch of tourism with an increaser of some 20% per year and a 10–30% share of global tourism (see e.g. Buckley, 2009; Hallet al., 2009; Lovelock & Lovelock, 2013). Nature tourism celebrates diverse experiences and is in general more dependent on the quality of nature than other types of tourism (Fredman & Tyrväinen, 2010). With increasing numbers of tourists there is a real danger that nature destinations lose their original allure (Sæþórsdóttir, 2010, 2013; Butler, 1980).

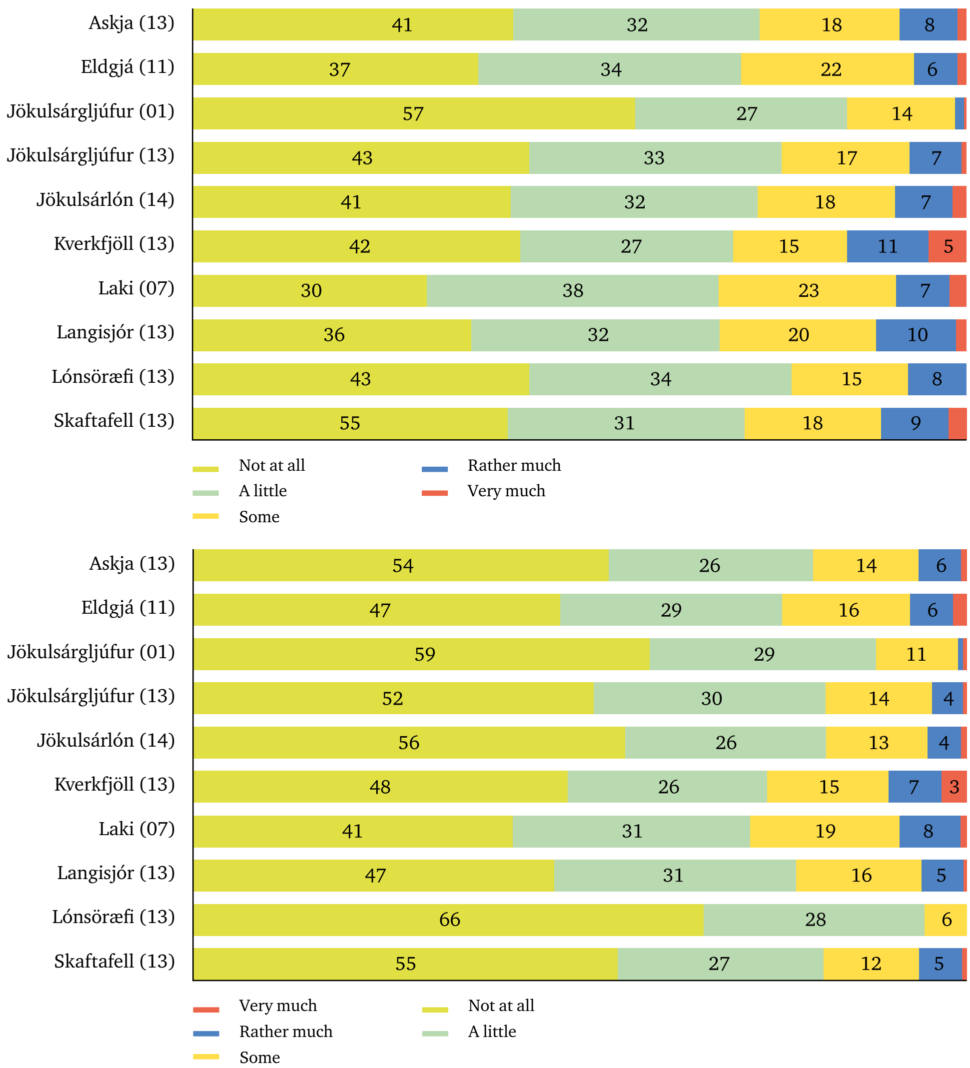


Figure 4.7.
Erosion of foot paths (top) and damaged vegetation (bottom) noticed by visitors at different times and sites within Vatnajökull National Park.

Top: Kayakers on Heinabergslón proglacial lake, 19 July 2016 © Þorvarður Árnason. Middle: Exploring an ice cave, 27 October 2014 © Þorvarður Árnason. Bottom: Relaxing at the Botnstjörn lake in Ásbyrgi, 30 June 2009 © Vatnajökull National Park.

Determining tourism carrying capacity, both ecological and social, is therefore a key management tool. Tourism carrying capacity is the number of visitors that an area can accommodate before the crowds negatively impact the nature of the site, the experience of the tourists, or the social acceptance level of the hosts (Martin & Uysal, 1990).

There are of course many types of tourists and hosts with different views and tolerance levels. Therefore, national park and wilderness area authorities in e.g. the USA and Scandinavia are increasingly applying strategic tools, such as purist scale and recreation opportunity spectrum, in their planning for responsible tourism (e.g. Stankey, 1973; Fredman & Emmelin, 2001; Vistad, 1995; Wallsten, 1988; Sæþórsdóttir, 2010). The area in question is studied and different recreational opportunities are assigned to specific subareas depending on their physical attributes and the type of tourism that they naturally support. Thus, a single national park can have zones ranging from relatively highly developed ones to wilderness areas with no infrastructure at all.

So far, these planning tools have not been used strategically within the nominated property. However, given the rapid increase in visitation, the park authorities are now considering ways to improve the daily flow of visitors through and within the property. The current Vatnajökull National Park Management Plan attempts to roughly classify land into use categories such as “service areas”, “areas with special conservation measures” and “park wilderness areas”. This rough land-use classification scheme is now being revised with the aim to establish a strict, geo-referenced zoning system within the property, based on natural features and ease of access. This system is expected to be implemented in 2019 or 2020. The park authorities are also considering measures to manage the flow of tourists to and within the property. These measures include automated parking fees that vary with location within the park, season and time of day. A pilot system was put in place in Skaftafell in late summer 2017, as noted above.

To date (2018), authorities of Vatnajökull National Park have been hesitant to launch direct access control measures. Access limitation is a sensitive subject in Iceland due to a strong tradition for public freedom to roam both publicly and privately-owned land for recreation (allmannaréttur: everyman’s right).

Vakinn quality certification

In 2013, the five visitor centres of Vatnajökull National Park were certified by Vakinn, the official quality and environmental system for Icelandic tourism. Vakinn is run by the Icelandic Tourist Board and based on Qualmark – New Zealand’s tourism official mark of quality, although adapted to Icelandic conditions.

Independent quality assurance is becoming increasingly important for international visitors. Survey results show that travellers prefer companies with a credible and independent quality certification. The aim of Vakinn is to meet this demand by increasing quality, safety and environmental awareness within Icelandic tourism and at the same time strengthening a sense of social responsibility among actors in the field.

The quality accreditation system consists of a star grading system for accommodation and quality certification for tourism services

Left: Tourists bathe in the Víti crater lake, 18 August 2016 © Snorri Baldursson. Next page: Aurora borealis over Öræfajökull on 2 Mars 2014 © Þorvarður Árnason.

other than accommodation. The classification for the latter is based on a total of 30 sets of general and specific criteria depending on the type of services provided. To qualify, companies must fulfil 70% of the general quality criteria and 100% of the specific quality criteria. Certified members can apply for environmental grading, which like Vakinn is based on Qualmark in New Zealand. Member companies and agencies are audited once a year.

4.b (v) Number of Inhabitants within the Property and Buffer Zone

Only three employees of Vatnajökull National Park and their families live within the property on a permanent, year-round basis. The park manager of the southern region lives at Hæðir, one of the three old farmsteads in Skaftafell. The assistant park manager of the southern region also lives in Skaftafell. The park manager of the northern region lives at the old farmstead Ás, within the Jökulsárgljúfur canyon. Thus, at present, altogether, five souls live within the property on a continuous basis. Most temporary employees, i.e. rangers, workers and service staff, live within the property during their time of employment, which can range from less than two months in the highlands to 12 months at the busiest lowland sites, such as Skaftafell.

5. Protection and Management of the Property

The nominated property enjoys full legal protection and its management is ensured through a comprehensive management plan. Although, almost entirely owned and financed by the State, a sophisticated and decentralised governing structure guarantees strong influence of local communities regarding long-term operation of the property. Staff is well trained and there are policies and programs in place to educate visitors and promote the property. The property's infrastructure, partly based on overnight-huts and service areas owned by travel associations and local communities, is expanding, with all new infrastructure being state-owned.

5. Protection and Management of the Property

5.a Ownership

There are two basic categories of land ownership within the nominated property: public ownership and private ownership. The latter may be state-owned or privately owned.

Most of the land within the nominated property is public land, known as þjóðlenda (Fig 5.1). Public lands are defined as uninhabited territories which until 1998 were not subject to private ownership. These are mostly areas in the highlands of Iceland, which were either not utilised at all (e.g. lava fields and glaciers) or used by farmers for grazing. In 1998 the Act on Public Land no. 58/1998 was passed, initiating a process whereby the boundaries between private and public lands were defined. Although the process is still ongoing, over 50% of Iceland has been declared public land. Significant parts of this public land have already been turned into a national park, namely Vatnajökull National Park, or other types of protected areas. Public lands are managed jointly by the Prime Minister's Office and authorities of the local municipalities to which they belong. Farmers keep their traditional right to grazing on most public lands. Public land cannot be sold under current legislation.

The lands belonging to the former national parks of Skaftafell and Jökulsárgljúfur, are owned by the State. Two farmsteads, Hoffell and Skálafell, in the southeastern part of the property are privately owned, but partly included in Vatnajökull National Park and subject to its rules and management strategy, by an agreement between the Ministry for the Environment and Natural Resources and the landowners signed in 2007. These agreements will come up for revision in 2027.

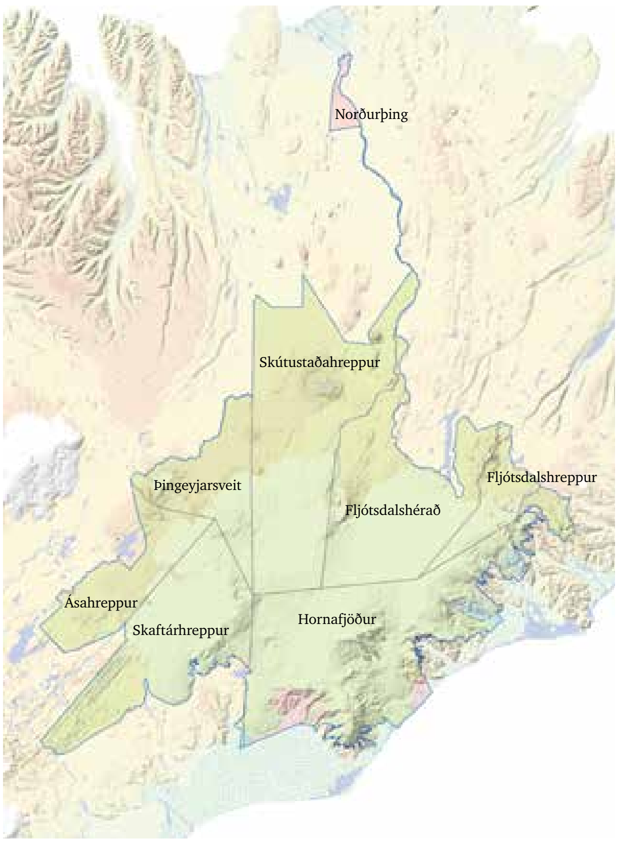


Figure 5.1.
Types of ownership of the nominated property; public land (green), state-owned land (pink) and private land (blue). The grey lines denote the eight municipalities that extend into the property.

The evolution of Vatnajökull National Park

Preparations for the foundation of Vatnajökull National Park occupied a period of nine years beginning in the spring of 1999, when the Alþingi passed a resolution directing the Minister for the Environment to examine the possibility of creating a national park with Vatnajökull ice cap at its centre. Following this, several committees and working parties were set up to explore the idea. A parliamentary committee submitted its recommendations in May of 2004, proposing a national park that would include the whole ice cap together with a large adjacent area to the north of it. In early 2005, the Icelandic government agreed to proceed with these recommendations. A working committee was appointed consisting of representatives of the Ministry, of communities adjoining the proposed park and of independent organisations. The committee submitted its report in November 2006, containing proposals on the size of the park, its administrative structure and service network. In spring 2007 the Icelandic Parliament passed the Vatnajökull National Park Act, no. 60/2007, and on 7 June 2008 the national park was formally established by Regulations no. 608/2008.

Since its establishment, Vatnajökull National Park has been constantly growing as disputes over land ownership are settled. At its establishment on 8 June 2008, the Park spanned some 10,800 km². The year after, 2009, it was extended by almost 2,000 km² with the addition of Mt. Askja, Dyngjufjöll, Trölladyngja and Ódáðahraun north of the Vatnajökull ice cap. Later in 2009, a further 50 km² were added when the mountainous area adjacent to Hoffellsjökull glacier in the southeast became part of it. In July 2011, Langisjór and part of the Eldgjá fissure to the southwest of Vatnajökull were added to the park, altogether some 420 km²; and in 2013, the 678 km² Krepputunga area northeast of the ice cap was incorporated into the park. Finally, in 2017, the Jökulsárlón lagoon with Breiðamerkursandur and surrounding areas (Figure 5.2) were added to the park. Part of this latest addition was privately owned until bought by the State. Hence, at the time of writing, Vatnajökull National Park proper covers 14,141 km².

A block of ice basking in the surf at Breiðamerkursandur © Walter Huber.

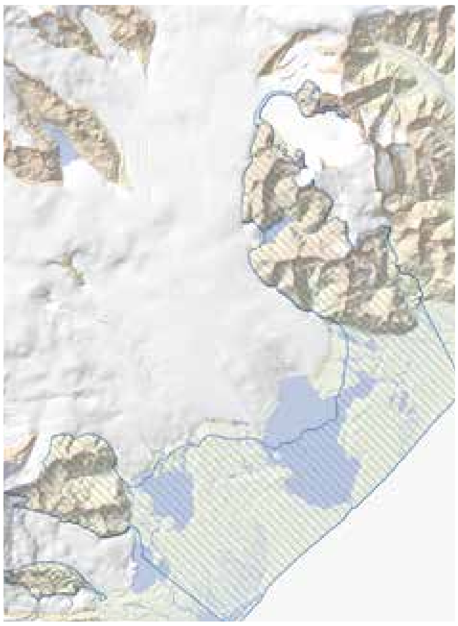


Figure 5.2.
Jökulsárlón, Fjallsárlón and surrounding areas (denoted by a blue line) were added to Vatnajökull National Park in July 2017. This represents the latest addition to the park at the time of writing.

5.b Protective Designation

Park legislation

The great majority of the nominated property, or 14,141 km² (97%), is protected by the Act on Vatnajökull National Park No. 60/2007 and Regulations No. 608/2008, with subsequent amendments, (Appendix 3). Article 2 of the Act lists the primary objectives of the park, which are to:

- Protect the area's landscapes, biosphere, geological formations and cultural relics.
- Provide access and opportunities for the public to become acquainted with and enjoy the area's nature and history.
- Facilitate research into and educate about the area to increase public awareness of its qualities and values.
- Seek to support and empower neighbouring rural areas through encouraging sustainable use and job opportunities based on the values of the Park.

Figure 5.3.
Different protection categories within Vatnajökull National Park, cf. IUCN categories of protected areas. Green, Category II: National park; Pink, Category Ib: Wilderness area; Orange, Category VI: Protected area with sustainable use of natural resources.

The protective designation, "national park", is based on the Act on Nature Conservation No. 60/2013, Section VIII, Article 47, which states that national parks are large natural areas that are relatively untouched by human influence and contain outstanding or representative biological or geological heritage or landscapes. This definition matches IUCN's protected area category II definition. The national park designation shall secure access to the public for recreation and education; public right to access can only be restricted provisionally for protecting plants, wildlife, cultural or geological heritage. All development or human action that might permanently damage the nature of a national park is forbidden according to the Act. In general, the land within national parks shall be owned by the State or be a public land. However, the Ministry for the Environment and Natural Resources may enter into an agreement with private landowners for inclusion of their land within a national park.

In the legal sense, the entire Vatnajökull National Park is a national park. However, for management purposes, two areas within its boundary have additional status as protected area categories Ib and VI, sensu IUCN (Fig 5.3):

- The Esjufjöll mountains and surrounding area in the Vatnajökull ice cap are classified as an uninhabited wilderness, IUCN category Ib.
- The Hoffell, Heinaberg, Hjallanes and Hafrafell areas in the southern region and Skælingar area in the western region are classified as protected areas with sustainable use of natural resources, IUCN category VI, emphasising cultural values and traditional land use; here the emphasis is on sustainable sheep grazing and tourism.

Parts of the nominated property, i.e. Herðubreiðarfriðland Nature Reserve and surrounding public lands in the central highlands to the north of the ice cap and the Lónsáröræfi wilderness area east of it, are independent protected areas, established respectively in 1974 and 1977 as nature reserves according to the Nature Conservation Act No. 47/1991 in force at the time (cf. Article 49 of the Nature Conservation Act no. 60/2013). Both areas were conserved primarily because of their spectacular landscapes and recreational value, although their size was not sufficient to merit independent national park status.

Other important legislations for the protection and management of the property are e.g. the Cultural Heritage Act No. 80/2012, the Planning Act No. 123/2010, discussed in section 5.c, the Act on Public Land No. 58/1998 and Act No. 48/2011 on the Plan for Nature Protection and Energy Utilisation, discussed below.

Is there a need for a buffer zone?
There is no buffer zone defined around the nominated property for the following reasons:

• First, the protection applied to the neighbouring land areas of the nominated property is deemed adequate. All land is subject to Article 3 of the Act on Nature Conservation No. 60/2013, which inter alia aims to protect areas of special geological or landscape value, including areas that encompass geological processes that signify the geological history of Iceland, protect geological features of national or universal value, protect landscapes of exceptional natural beauty or aesthetic importance and protect uninhabited wilderness areas of the country. In addition to the general protection provided by the nature conservation act, all land adjacent to the nominated property in the southwest, west, north and northeast highlands is subject to the Act on Public Land no. 58/1998 (see section 5.a, Fig 5.1), specifying that a government permit is required for any extractive or other destructive uses such as mining, quarrying or harnessing of hydro or geothermal power, and that a permit from the local municipality is needed for less consumptive uses.

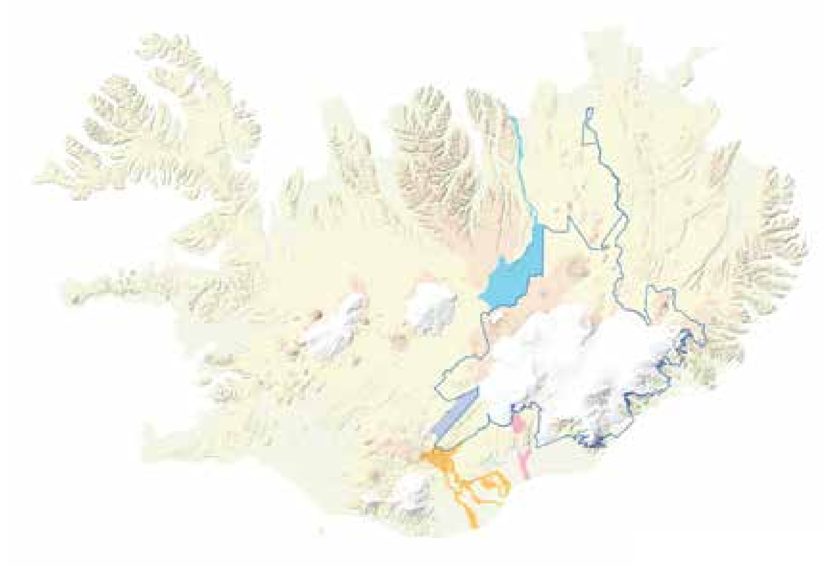
Some highland areas adjacent to the nominated property are further protected from destructive use by Act No. 48/2011 on the Plan for Nature Protection and Energy Utilisation (Master Plan). The Master Plan was designed to bridge opposing views and interests regarding land use in areas that are rich in energy resources, be they hydrological or geothermal. More specifically, the process classifies areas with potential energy harnessing options into three categories: protected category, waiting further assessment category and to be exploited category. The law specifies that areas classified in the protection category shall be protected by law from energy harnessing. Three glacial river catchment areas adjacent to the nominated property have been proposed for the protection category, Skjálfandafljót catchment in the north, Tungnaá catchment in the west and Djúpá catchment in the south. One geothermal area, Gjástykki, to the north of the nominated property, has been placed in the protection category (Fig 5.4).

• Second, the sheer size of the property, 1.48 million ha, which is enough to include examples of entire geophysical landscape- and ecosystem units, does not call for a dedicated buffer zone.

• Third, the Outstanding Universal Value of the property – the interplay between volcanism and a temperate glacier – is not particularly sensitive to land use or human development.

• Fourth, in the south, the retreat of the ice cap and glaciers since 1998 has provided a 500–1500 m natural buffer zone. In addition, a large percentage of ice-free areas within the Hornafjörður

Figure 5.4.
River catchment- and geothermal areas proposed for the protected category through the Master Plan process 1999–2016.



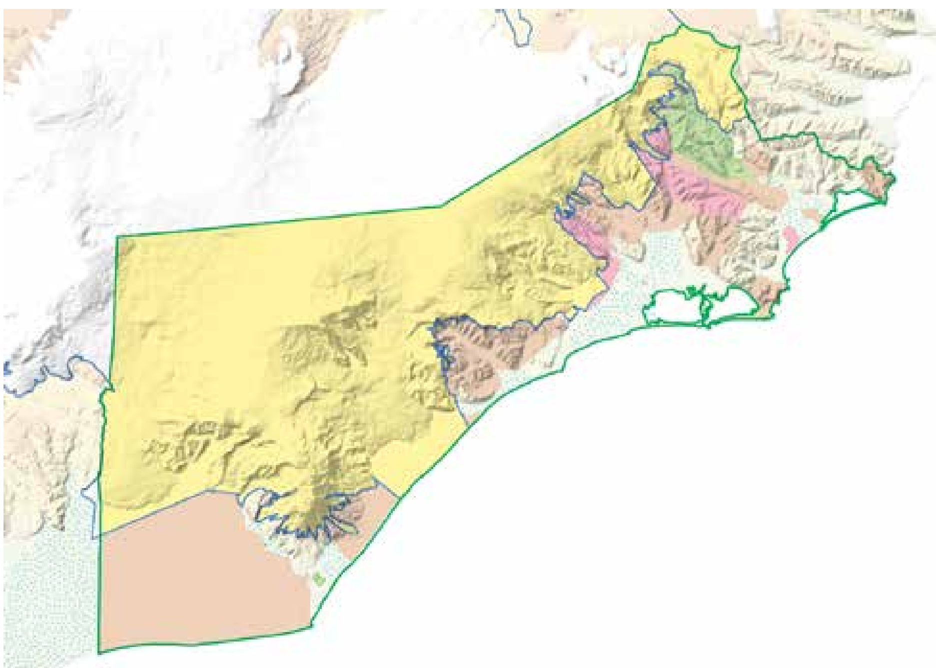
Vatnajökull National Park boundary
Skjálfandafljót watershed
Djúpá watershed
Tungnaá watershed
Skaftá watershed

municipality, where most of the lowland areas of the property is located, are either formally designated protected areas included in class A of the Nature Conservation Registry, areas given local protection (hverfisvernd) or areas listed within classes B and C of the Nature Conservation Registry (Fig 5.5). Areas listed in class B of the Nature Conservation Registry are priority areas to be formally protected within five years from listing, and areas listed in class C are areas, species or habitat types, that need future protection. These may not be disturbed or developed, except in critical need and only if no other options are available.

5.c Means of Implementing Protective Measure

The government agency Vatnajökull National Park (Vatnajökulsþjóðgarður) is the primary state agency responsible for implementing the park legislation. The agency Vatnajökull National Park operates under the aegis of the Ministry for the Environment and Natural Resources. Protective measures are implemented primarily

Figure 5.5.
Areas within the municipality of Hornafjörður, southeast of Vatnajökull, with special protection status.



Hornafjörður municipality
Vatnajökull National Park boundary
National park
Proposed protected areas
Municipality protection
Nature reserve

through the Vatnajökull National Park Management Plan (Appendix 4, attached as a separate volume), approved by the Minister.

Because of its huge size and logistical challenges, Vatnajökull National Park is divided into four administrative regions (Fig 5.6), named after the cardinal compass points: north, south, east and west. In each region, there are one or two park managers and a regional advisory committee. The minister appoints a governing board for the park which comprises seven voting members: the four chairs of the regional committees, one member nominated by environmental conservation associations, and a chair and deputy chair who are appointed directly by the minister. Representatives of outdoor- and travel associations have observer status on the board of directors.

The board is responsible for the overall operation and management of Vatnajökull National Park and allocates funding. It appoints a managing director who runs the park on a daily basis, implements the financial plan and administers the park's finances. The managing director supervises human resources, appoints managers for administrative regions, based on proposals from the regional committees, and ensures coordination among the regions.

The minister appoints an advisory committee for each administrative region. The committees comprise six members each; three

Figure 5.6.
The four administrative regions of Vatnajökull National Park and location of its main infrastructures.

are nominated by local authorities, one by the tourism sector in the area, one by outdoor activity associations, and one by local environmental associations. The chair of each regional committee sits on the park's governing board. The regional advisory committees advise the park manager in his/her function and serve in a coordination role between the park management, local authorities, landowners and other stakeholders in the area. Thus, they ensure vital input from local people in the management of the park.

Park managers oversee day to day management of their respective regions. There are five park managers, one for each region, except the northern one where there are two managers, one for the lowland part and another for the highland part. The park managers work closely with the managing director and the regional advisory committees. They hire park personnel, oversee reception and education of guests and monitor compliance with laws, regulations and provisions of the management plan in their respective regions. They work with the police and other monitoring bodies when necessary and are authorised to temporarily close areas, e.g. in the case of visitor overload or if vegetation or wildlife is threatened, and can expel from the park anyone who violates its rules.

Basalt columns at Hljóðaklettar, Jökulsárgljúfur canyon © Snorri Baldursson.

Vatnajökull National Park (the agency) also manages the protected nature reserves of Herðubreiðarlindir and Lónsöræfi, based on a contract with the Environmental Agency of Iceland, which is the state agency responsible for implementing the Act on Nature Conservation No. 60/2013 and for managing most protected areas in Iceland.

The park's cultural heritage is protected in collaboration with the Cultural Heritage Agency (Minjastofnun), which retains the legal power of decisions over all archaeological relics in compliance with the Cultural Heritage Act no. 80/2012. This power is irrespective of who owns the land. The agency is responsible for decision-making and protective measures regarding archaeological sites. It issues permits for archaeological research and supervises them, and acts in an advisory capacity on the preservation and presentation of relics of cultural interest that relate to its field of work. Within the Vatnajökull National Park, the Cultural Heritage Agency specifies which cultural and archaeological relics need special protection measures. These measures are then implemented in collaboration with the park authorities.

5.d Existing Plans Related to the Municipality and Region in which the Proposed Property is Located

According to the Planning Act No. 123/2010, spatial planning in Iceland occurs at three governance levels. On a state level, there is the National Planning Strategy, on a regional level, regional plans and on a local municipality level, municipal plans. The National Planning Strategy and municipal plans are mandatory while regional plans are optional, except for the capital region.

National Planning Strategy

A National Planning Strategy was approved for the first time by the Parliament in 2016. It is a new tool for coordinating all planning work in Iceland. It proposes a policy which is intended to ensure coordination of spatial planning at regional and local levels. One section of the National Planning Strategy deals with the central highlands of Iceland. Its overall goal is to safeguard the conservation and recreational values of the highland's nature and landscapes. The strategy further stipulates that development within the central highlands must be kept to a bare minimum and that any infrastructure should respect the uniqueness of the area and its wilderness qualities.

Regional plans

A regional plan has been approved for the three municipalities to the north of the Vatnajökull ice cap, focusing on the sustainable use of geothermal resources in the area. The plan, however, only applies to areas north of the line delineating the central highlands and the National Park boundary.

Municipal plans

Iceland is divided into 74 municipalities and 21 of them reach well into the central highlands. The nominated property belongs to eight of these. All have approved municipal plans that are valid for between 12 and 20 years (Table 5.1). Municipal plans, according to the Planning Act No. 123/2010 and the Planning Regulations No. 400/1998, are statutory framework plans for land use in a particular municipality.

Table 5.1.
Validity of municipal plans relevant to the nominated property.

Municipality	Validity of municipal plan
Þingeyjarsveit	2010–2022
Skútustaðahreppur	2011–2023
Norðurþing	2010–2030
Fljótsdalshérað	2008–2028
Fljótsdalshreppur	2014–2030
Sveitarfélagið Hornafjörður	2012–2030
Skaftárhreppur	2010–2022
Ásahreppur	2010–2022

Although municipal planning obligations extend into the nominated property, the Vatnajökull National Park Act no. 60/2007 stipulates that local authorities are bound by the terms of the park's Management Plan (MP) when making planning decisions relating to areas within the park. The MP is, therefore, decisive in local authority planning. It should, nevertheless, be stressed that the MP itself has been created in collaboration with the relevant local authorities and numerous other stakeholders within and outside their municipalities, ensuring local input. To avoid repetition, it is assumed that planning-related issues that have been accepted as elements of the park's MP will be incorporated into the relevant municipal and/or detail plans and elaborated further in these. Standard planning procedures will then come into play, including a democratic consultation with the public and the relevant stakeholders.

The present Planning Act no. 123/2010 and its predecessors stress the obligation to ensure democratic participation by the public and local authorities in the formulation of spatial and strategic plans.

Next page: From Krepputunga north of Vatnajökull, Mt. Herðubreið in the clouds, 17 August 2016 © Snorri Baldursson.

Mt. Snæfell from air on 18 April 2008 © Skarphéðinn Þórisson.

Planning process and permits

Under the Planning Act No. 123/2010, local authorities are responsible for the promulgation, consultation, advertising and approval of municipal plans and detail plans for specific areas or projects. All construction and development projects within Vatnajökull National Park shall follow a municipal plan authorised based on the policy laid out in the park's MP. Granting of development and building permits shall follow a detail plan which has been approved by the local and park authorities. The latter handle the preparation of detail plans within the park and submit them to the relevant local authority for proper handling before approval.

Local Building Officers grant construction permits within the park, as applicable, following consideration by a building committee and/or municipal council. The same officers monitor the implementation of construction projects which are subject to permits as provided in the Man-made Structures Act No. 160/2010.

While a building or development project is in progress, the relevant park manager monitors compliance with park laws and regulations, including stipulations of the park's MP. During any such project, care shall be taken not to disturb the nature of the area beyond what is permitted by the terms of the development permit and specifications.

Most of the land within Vatnajökull National Park is now public land under the Act on Public Lands No. 58/1998 (see p. 226). Under this act various categories of use of public lands, such as the construction of buildings, disturbing the ground, long-term utilisation of peripheral resources, or utilisation of water or geothermal rights, are subject to licence from the Prime Minister or local authorities. With a new amendment to the Vatnajökull National Park Act in 2017, the park's MP takes precedence over provisions in the Public Lands Act in this regard.

5.e Property Management Plan

There is one management plan (MP) for the entire nominated property, Vatnajökull National Park and the protected areas of Herðubreiðarlindir and Lónsöræfi (Appendix 4). The plan defines general policy for the areas and contains stipulations on a variety of procedural details to ensure that their development conforms to the principles and government policy laid down in the relevant laws and regulations, in the case of Vatnajökull National Park, and the declarations on the establishment of the individual protected areas.

The drawing of the Vatnajökull National Park MP is a highly structured process. It is supervised be the regional advisory committees and the park's governing board with a high degree of inclusion of residents, interest organisations, relevant institutions and other stakeholders, as appropriate. The plan is approved by the Minister for the Environment and Natural Resources before entering into force. The first MP was approved in 2011. It was revised and re-approved in 2013.

The Vatnajökull MP plays an important role in decision-making. Under the Vatnajökull National Park Act, local authorities are bound by its content in their planning for areas within the park. In other words, the management plan takes precedence over local authority plans, and permits can only be granted within its parameters.

A main part of the plan describes the policy of Vatnajökull National Park. Its vision is set out in three parts: to protect, maintain and develop; to experience; and to create. Objectives are set out and classed in the same way as the vision. Under each objective is a series of operational targets which frame the individual tasks of the management and operational areas.

Top: Scientists on Vatnajökull © Hrafnhildur Hannesdóttir.
Bottom: Board members and staff of Vatnajökull National Park on an excursion in the highlands north of Askja, 11 August 2015 © Snorri Baldursson.

A section on land use stipulates conservation and utilisation in specific areas. For each area, a brief account is given of the premises, after which objectives are stated, and finally conditions framing the conservation, or utilisation of the location. Special Protection Areas are defined, i.e. areas deemed to have special conservation value, which must be protected from excessive traffic or by other means. Special Features that exist at multiple locations, for example rootless craters, are defined with the additional protection provisions provided. This is followed by a definition of Wilderness Areas within the Park and an enumeration of these. The definition is the same as the one provided for in the Act on Conservation of Nature No. 60/2013 (see section 2.a (v)).

The MP enumerates all the roads and trails within Vatnajökull National Park and their grade in terms of navigation and safety. The principal walking routes are defined, along with footbridges, bridle paths, picnic areas and cycle paths. The different service units of the Park are listed and defined to clarify their nature (see Table 5.3). Areas where traditional land use such as grazing, fishing and collection of birds' eggs is permitted is specified in the MP in accordance with the park's regulations.

The principal fields of research and monitoring of the park's state of conservation are laid out. These are divided into three categories: basic research, long-term research (monitoring), and economic/social research. The final chapters of the MP are concerned with the implementation and impact of the plan and procedure for its amendments.

Operations and outgoings	2008	2009	2010	2011	2012	2013	2014	2015	2016
Salary expenses	96	108	146	174	205	230	240	264	313
Other expenses	86	130	143	174	197	217	235	232	241
Total operating expenses	182	240	294	351	404	454	482	500	559
Gross income	46	118	127	141	171	187	209	220	241
Net income	137	121	167	210	235	267	273	280	317
Investments	148	201	433	128	144	174	124	138	82
Treasury allocations									
– for operations	73	106	170	198	233	275	272	280	318
– for investm./constructions	161	201	215	150	170	190	125	148	84
Total Treasury allocations	234	307	385	348	403	465	397	428	402
Suppl. Budget allocations	18				90			17	
Profit (loss) on operations	-31	30	-215	-5	-54	-30	-2	3	-48
Balance at beginning of year	55	21	51	-164	-169	-54	-31	-46	-82
Pricipal at year-end	21	51	-164	-169	-54	-31	-46	-82	-68

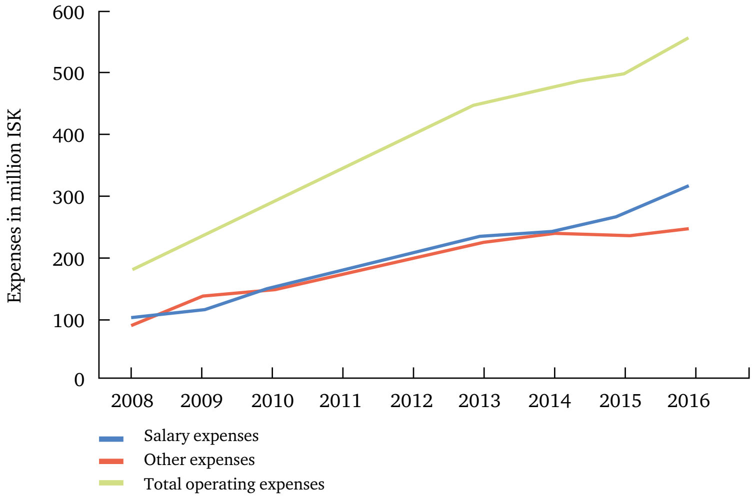
Table 5.2.
Break down of Vatnajökull National Park's finances 2008–2016 (in millions of ISK).

5.f Sources and Levels of Finance

Vatnajökull National Park is funded through two main sources. Approximately 70% of its yearly budget comes from the central government's financial bill and another 30% through its own income from camping/parking fees and sales of various foods and merchandise in the park's visitor centres (Table 5.2; Fig 5.7). The government funding is divided into two different functional parts, which are not to be mixed: a) for day to day operation and b) construction of various infrastructures (investments).

A significant but fluctuating contribution toward specific projects has also come from the government controlled Tourist Site Protection Fund – which supported projects aimed at developing, maintaining and protecting nature and man-made structures at tourist attractions (public and private) – and the non-profit organisation Friends of Vatnajökull that supports research, promotional and educational projects relevant for the park based on competitive grants. Especially important have been grants for designing and constructing hiking and educational trails and viewing platforms, and preparing educational material and exhibitions at the various visitor centres of the property. In 2017, the laws on the Tourist Site Protection Fund were changed so that it now only supports investments of municipalities and private landowners, while all funds for investments at government controlled sites are channelled through the financial bill. The financing is deemed sufficient for conserving the Outstanding Universal Value of the nominated property.

Figure 5.7.
From its establishment in 2008, the total budget of Vatnajökull National Park has almost tripled. Since 2014, growth in investments has stagnated while salaries continue to increase.



5.g Sources of Expertise and Training in Conservation and Management Techniques

All the permanent employees of Vatnajökull National Park have a university degree in different fields of natural or social sciences; in biology, geology, geography, tourism, forestry or education as well as in business management and book keeping. All permanent staff members working in the field are required to take courses in first aid and rescue, and some of them have training as Wilderness First Responders.

The Park benefits from the luxury of being able to select part-time rangers from a large surplus of applicants each year. Most of these have completed or are about to complete a university degree in natural or social sciences. They are all required to obtain a Rangers Diploma by taking a two-month course, run by the Environment Agency of Iceland. Through this course they are trained in nature conservation, laws and regulations, nature interpretation and communication. Those who have a Search and Rescue (ICE-SAR) licence and experience as members of one of the 100 nationwide SAR teams are preferred, all else being equal. Lower educational requirements are demanded of other part-time staff, such as restaurant staff and general workers.

All in all, it is concluded that the combined expertise of the staff in management, communication and conservation of the natural and cultural heritage of the nominated property is adequate, although the number of permanent employees is considered insufficient in the long run.

5.h Visitor Facilities and Infrastructure

Visitor facilities are places where guests can use services or access information in some way. These facilities or service areas can be divided into eight categories depending on the type and variety of services provided (Table 5.3; Fig 5.6). Most of these are run by Vatnajökull National Park, but the park's management board can enter an agreement with a private individual or entity to run some of these services. In many cases two or more of these facilities are in the same service area and the distinction between them may be blurred.

The following general stipulations apply to visitor facilities and other service units within the nominated property:

- The number of service areas shall be kept to a minimum and be located where they impact least on the region's natural and cultural values and its unique landscapes,

- building design and planning shall use the best available techniques to predict the appearance of the building in the area before commencing construction,

- buildings shall be low-rise, harmonise with the landscape and have an appearance that reflects the character of the local area,

- quality workmanship shall be ensured for buildings and their facilities,

- the drainage system shall not cause pollution, and all drains and septic tanks shall meet the highest standard requirements and be approved by the health and safety inspector,

- refuse from the service units must not cause pollution; sorting and disposal of refuse should comply with the park's environmental policy.

Before a new service unit is made, several factors are to be addressed and evaluated such as the necessity of the project, possibilities and advantages of the location regarding natural and cultural features, roads, footpaths, and cycle paths, risks to natural or cultural values arising from the project, development of operations, traffic and visitor numbers in the area, operational basis for the project, type and scale of service, and running cost. Service areas with buildings must also be specified in local development plans and detail plans are required for all infrastructures. The eight types of service units are described in Table 5.3, their number and locations within or outside the nominated property.

Overnight stays by park visitors must in general be at dedicated campsites. However, hikers and cyclists may pitch conventional tents for one night at a distance of at least four km from the nearest designated campsite. Park visitors travelling by car on roads marked F3 – F stands for mountain road and F3 is considered only fit for modified 4x4s – are also allowed to pitch conventional tents for one night by the roadside. However, camping outside marked campsites is prohibited in the following areas: in Jökulsárgljúfur canyon, in areas with special protection status such as Mt. Askja and Esjufjöll, in the lowland areas at Hoffell and Heinaberg, on Skaftafellsheiði, in Bæjarstaðarskógur woods and the Morsárdalur valley in Skaftafell.

Table 5.3 (opposite).
Visitor facilities and service areas within Vatnajökulsþjóðgarður National Park.

Type of service unit	No.	Location (region)
Visitor Centres Visitor centres are located at or close to the main access routes to the four administrative regions. They are open year-round, or as funding allows, and should as a minimum provide a manned information desk, instructions and information in the form of exhibits, events and/or walks, toilets, refuse disposal, restaurants and/or picnic areas.	5	Ásbyrgi (N), Skriðuklaustur (E)*, Höfn (S)*, Skaftafell (S), Kirkjubæjarklaustur (W)*
Information centres/visitor stations Information centres or visitor stations are sited on popular routes into, but not necessarily inside the park. They offer toilets, an information desk and small displays with necessary minimum information and shall be open at least during the summer months. Information centres may be run by private parties.	7	Möðrudalur (E)*, Hoffell (S), Skálafell (S)*, Laki (W), Eldgjá (W), Hrauneyjar (W), Nýidalur (W)
Ranger stations Ranger stations are generally located close to major traffic routes within the park. Their main function is to provide accommodation for rangers, but in some cases, they also serve as manned information centres. Ranger stations can be operated in cooperation with, or leased from, private parties. It is considered an advantage to use pre-existing buildings and services.	11	Ásbyrgi (N), Vesturdalur (N), Drekagil/Askja (N), Hvannalindir (E), Kverkfjöll (E), Snæfell (E), Skaftafell (S), Blágil (W)*, Hólaskjól (W)*, Hald (W)*, Nýidalur (W)
Visitor shelters Visitor shelters are unmanned/irregularly manned facilities with toilets and running water, with self-service information and instructions in the form of interpretive boards and announcements. Visitor shelters are open in seasons when other services are available in the area.	2	Tjarnargígur (W), Langisjór (W)
Picnic areas for day visitors Picnic areas are generally located at sites that attract fairly large numbers of people and where there is a reason to provide services such as car park, toilet (W.C. or latrine), picnic tables, refuse collection (lowland sites), information and interpretive boards.	17	Ásbyrgi (N), Vesturdalur (N), Dettifoss (N), Drekagil (N), Skriðuklaustur (E)*, Hvannalindir (E), Kverkfjöll (E), Snæfell (E), Hoffell (S), Heinaberg (S), Skaftafell (S), Kirkjubæjarklaustur (W)*, Laki (W), Tjarnargígur (W), Eldgjá (W), Langisjór (W), Jökulheimar (W), Hrauneyjar (W)*, Nýidalur (W)
Campsites Most campsites within the park are run by Vatnajökull National Park, but a few are run by travel associations.There are three categories of campsites: Class one: constructed campsites with extensive services. Class two: campsites with basic services (toilet, cooking facilities), mostly in their natural state and unobtrusive in the landscape. Class three: hikers' campsites, with no or very limited services.	21	**Class one**: Ásbyrgi (N), Skaftafell (S) **Class two**: Vesturdalur (N), Dettifoss (N), Herðubreiðarlindir (N), Drekagil (N), Geldingafell (E), Snæfell (E), Kverkfjöll (E), Blágil (W)*, Skælingar (W), Langisjór (W), Sveinstindur (W), Nýidalur (W). **Class three**: Dyngjufell (N), Bræðrafell (N), Kistufell (N), Gæsavötn (N), Gjallandi (N), Langisjór-SE (W), Vonarskarð (W)
Huts Huts within or affiliated with Vatnajökull National Park fall into four general categories: Overnight huts. Accessible by motor vehicles and generally with campsites. Most were built long before the establishment of the park and may be owned and/or operated by external parties. Research huts. Built for the use of scientists – mostly of the Glaciological Society. Round-up huts. Specifically built by residents or municipalities for use by shepherds involved in the autumn round-up of sheep, but available to the public at other times of the year. Restricted-use huts. Private or for special needs such as shelters for telecommunication installations, geodetic surveys, road or power line construction etc. Some huts may fall into more than one category.	31	**Overnight huts:** Herðubreiðarlindir (N), Suðurárbotnar (N), Dyngjufell (N), Bræðrafell (N), Drekagil (N), Kistufell (N), Kverkfjöll (E), Snæfell (E), Geldingafell (E), Blágil (W)*, Hrossatungur (W)*, Hólaskjól (W)*, Skælingar (W), Sveinstindur (W), Nýidalur (W). **Research huts (Glaciological Society)**: Dyngja (N), Hveradalir (E), Grímsfjall (W), Jökulheimar (W), Esjufjöll (S). **Round-up huts:** Sauðárkofi (E), Blágil (W)*, Hrossatungur (W)*, Hólaskjól (W)*, Skælingar (W), Sveinstindur (W). **Restricted-use huts:** Gæsavötn (N), Goðahnjúkar (E), Sylgjufell (W)
Information and interpretive boards Information and interpretive boards are placed at all roads leading into the park as well as at most sites of interest. More extensive signage may be placed at the entrances to the park where it is considered essential to inform visitors. Smaller signs, including warning signs, information and interpretive posts, are placed by popular footpaths and picnic areas on less-used highland routes.	>90	**North:** Askja/Vikraborgir (2), Gjallandi (1), Ásbyrgi (5), Svínadalur (3), Dettifossvegur (4), Dettifoss W (1), Dettifoss E (3), Hólmatungur (1) **East:** Snæfellsöræfi (6), Hvannalindir (3), Kverkfjöll (2) Kreppubrú (2) Hengifoss (1), Egilsstaðir (1) **South:** Hjallanes (5), Heinaberg (8), Hoffell (7), Lónsöræfi (4) **West:** Kirkjubæjarklaustur (2), Lakagígar (5), Fjallabak (2), Eldgjá, Langisjór (5), Blautulón (2), Sprengisandsleið – F26 (3), Nýidalur, Vonarskarð (6), Tungnaáröræfi (3)

* Located outside the nominated property

Examples of infrastructure within Vatnajökull National Park. Top: The overnight hut at Snæfell © Skarphéðinn Þórisson. Middle: The research hut of the Glaciological Society at Grímsfjall on Vatnajökull ice cap © Snorri Baldursson. Bottom: Gamlabúð visitor centre at Höfn in Hornafjörður © Helga Davids.

Examples of infrastructure within Vatnajökull National Park, cont. Top: A ranger guides children through the exhibition at Snæfellsstofa visitor centre in Skriðdalur © Rhombie Sandoval. Middle: The rangers' station at Hvannalindir © Snorri Baldursson. Bottom: The visitor centre at Langisjór © Snorri Baldursson.

5.i Policies and Programmes Related to the Presentation and Promotion of the Property

Top: Volunteers building a wooden trail at Ástjörn lake, Ásbyrgi, 24 August 2017 © Guðmundur Ögmundsson.
Bottom: Rangers marking a jeep trail at Breiðbakur on 7 July 2010 © Snorri Baldursson.

Internal programmes

Many of the day to day activities within Vatnajökull National Park revolve around dissemination of information, presentation and promotion of the park and its values. Since its inception, these outreach and educational activities have mostly been on an ad hoc basis, depending to a large degree on the capacities and priorities of each administrative unit. However, in late 2017, an Education and Outreach Plan was approved for the park and the protected areas overseen by it. This plan defines the status of activities related to education and dissemination of information and provides a vision and objectives for future programmes and activities, as well as defining desired visitor experience.

Education and outreach activities of the nominated property fall into the following categories:

Visitor centres: The five visitor centres are the main education and outreach hubs of Vatnajökull National Park. They all provide an exhibition on different aspects of the park values and deliver first-rate visitor services and facilities. A new designated visitor centre is under construction at Kirkjubæjarklaustur (W) to replace the current centre that has been temporarily housed in the village's administrative building.

Summer programme: Each spring, in each of the ten areas where rangers are located, a programme of summer activities is published, outlining interpretive walks, "children's hours", longer hikes accompanied by rangers and special events such as guest lectures or gatherings.

Lectures and group receptions: Many interest-groups ask to be given a lecture by a park manager or ranger on various aspects of the nominated property. Such lectures are generally held at the visitor centres, but the park managers also give lectures on an ad hoc basis to interest groups outside of the park's premises.

Local schools: The park managers or other permanent staff visit local schools in adjacent municipalities at least once a year to educate about Vatnajökull National Park and nature conservation, and to discuss the park's role in the community. Also, school classes are invited to visit specific areas of the park and/or its visitor centres on a regular basis. However, most highland areas are closed because of winter conditions during most of the school season.

Roadside discourse: Due to the vast size of the property and the limited numbers of visitors present at any given time at the more remote highland sites, rangers have been deployed at strategic access roads to these sites. The rangers stop all vehicles passing, bid the passengers welcome, give out maps and information material and invite questions and discussions. This has turned out to be a very gratifying service for all concerned.

Visitor/information trails: These are short, self-service nature interpretation trails each focusing on a specific theme. Along the trail there are 8–12 marked information spots where the visitors can obtain specific bits of information, through either an

Left: The Icelandic Coast Guard transports building materials for a viewing platform at Ófærufoss, Eldgjá, 22 June 2013 © Snorri Baldursson.

information board, leaflet provided free of charge or an electronic device, such as a smartphone. Seven interpretative trails have been laid out within the park, dealing with themes such as volcanism, general geology, glaciers and glacial landscapes, wild flowers and traditional land use.

Information boards: Information boards with maps and short text are provided at parking places, viewing points and the beginning of most hiking routes.

Website: Vatnajökull National Park maintains an official website (www.vjp.is) with all basic visitor information and more substantive accounts of various natural values, features or topics related to the park. The website was totally revamped and relaunched in the summer of 2017.

Social media: Vatnajökull National Park maintains a Facebook page, providing snapshots of day to day activities within the park.

"Children's hour" with a ranger at Skaftafell (above) and interpretative walk, Vesturdalur (below) © Guðmundur Ögmundsson.

Publications: Vatnajökull National Park publishes strategic documents such as the Management Plan, Education and Outreach Plan, Business Policy, information brochures and maps, annual reports, and research treatises. These are all available from the park's website. The park has further commissioned short documentaries on the different regions of the park that are available to guests at the visitor centres.

Melting glaciers is a cooperative project of Vatnajökull National Park, the Icelandic Meteorological Office and the Ministry for the Environment and Natural Resources. It was launched in 2017 with the publication of an educational booklet about the impacts of climate warming on the park's glaciers. Other parts of the project to be finalised in 2018, include a special website on climate change and glaciers, three short educational trails in front of Skaftafellsjökull, Breiðamerkurjökull and Heinabergsjökull outlet glaciers, a yearly newsletter and an online educational program for guides.

External programmes

In 2013, the five visitor centres of Vatnajökull National Park got certified as quality tourist destinations by Vakinn, the official quality and environmental system for Icelandic tourism (see section 4.b (iv)). Joining Vakinn meant a thorough inspection and improvement of all the park's social-, safety- and service measures relating both to staff and visitors. Agencies and companies of Vakinn are audited every year.

The Friends of Vatnajökull association is a non-profit organisation that was founded in 2009 as a funding body for Vatnajökull National Park. The role of the association is to raise funds to support research, promotion and education to ensure that as many people as possible can enjoy the natural phenomena and the unique natural history that the park offers.

In the period 2010–2016, the Friends of Vatnajökull gave out 120 grants based on competition, valued in total at over 300 million ISK. These grants have gone to private individuals and research institutions, as well as directly to the park, and have supported a wide variety of research, outreach and educational projects within or relevant to the park.

5.j Staffing Levels

Vatnajökull National Park has at present 16 permanent employees dealing directly with the management and administration of the property. The 16 employees are based at eight locations in Reykjavík, Mývatn, Ásbyrgi, Egilsstaðir, Skriðuklaustur, Höfn, Skaftafell and Kirkjubæjarklaustur. In addition, specialists are hired on a short-term basis to work on specific issues, including the nomination of Vatnajökull National Park for inclusion in the World Heritage List. Legal and planning advice, as well as design work of various kinds, is mostly contracted from outside sources.

Each year, the park hires between 60 and 70 part-time staff to work as rangers, service staff at the property's visitor centres or as general workers. These may be hired for as short as two months for the highland stations and up to a year for some of the lowland sites.

Although, considered passable, additional permanent and part-time staff is needed to operate the nominated property in an optimal way.

Aurora borealis over Öræfajökull on 2 November 2014 © Þorvarður Árnason.

Sea thrift, *Armeria maritima* (right), and moss campion, *Silene acaulis* (bottom), growing on a tephra field by Lakagígar © Snorri Baldursson.

6. Monitoring

The physical and biological state of the nominated property, its natural hazards and ecological and social carrying capacity are regularly surveyed and monitored by a host of research institutions.

6. Monitoring

6.a Key Indicators for Measuring State of Conservation

Geology

The Outstanding Universal Value of the nominated property is expressed by the processes and features of volcanism and glaciology, more precisely, the interactions of a divergent plate boundary within the Earth's lithosphere, a mantle plume deep within the Earth and a large ice cap on the Earth's surface. These processes are not affected by any local pressures that the managers of the property can control, but they will be monitored so that their effects are known. However, anthropogenic climate warming is affecting mass loss and retreat of the Vatnajökull ice cap and its outlet glaciers. Monitoring the mass balance of the ice cap and the retreat of its multiple outlet glaciers provides key indicators of the ice cap's response to global climate change. The Institute of Earth Science, University of Iceland (IES) and the Iceland Glaciological Society (IGS) are the main bodies monitoring volcanism and glacier changes in Iceland, including within the nominated property.

Biota

Climate change and various regional and local processes, such as unsustainable use, habitat fragmentation and invasive alien species may affect the long- and short-term conservation status of the property's flora and fauna. The Icelandic Institute of Natural History (IINH), in collaboration with three local nature research centres, the Northeast-, East- and Southeast Nature Research Centre, is responsible for monitoring status and change in native habitats, species and populations, as well as alien species invasions within the nominated property. Recent major surveys and groundwork by the IINH provide good baselines for such monitoring, namely, the complete classification and mapping of Icelandic habitat types (Ottósson et al., 2016) and the definition of internationally important bird areas (IBAs) and new population estimates for 81 species of birds that occur regularly in Iceland (Skarphéðinsson et al., 2016). The Soil Conservation Service of Iceland (SCSI) in collaboration with farmers is responsible for assessing and monitoring the state of public sheep grazing areas (commons).

Geological hazards

Iceland is a high volcanic-risk area because of its frequent and powerful eruptions. Many volcanoes are located under ice caps, leading to phreatomagmatic eruptions, often generating plumes exceeding 10–12 km in height and causing ash fall in distant places. Seismic hazards are also common. The Icelandic Meteorological Office (IMO), in collaboration with many Icelandic and international research groups, including the IES leads long-term monitoring of geohazards in Iceland and is responsible for maintaining instrument networks for this purpose. These instrument networks include seismometers, GPS, strainmeters (Sacks-Evertson borehole dilatometers), river flow and conduction meters, radars, infrasound networks, and scanning DOAS spectrometers (see section 4.b (iii)).

Top: Hairy fringe-moss mat, *Racomitrium lanuginosum*, at Lakagígar © Snorri Baldursson. Middle: Young reindeer bulls in Kringilsárrani © Skarphéðinn Þórisson. Bottom: Jökulhlaup in Skaftá 2 October 2015 © Snorri Baldursson.

Table 6.1 (opposite).
Key values and indicators for monitoring the state of conservation of the nominated property and the agencies holding the relevant data. Abbreviations: UI-IES, University of Iceland, Institute of Earth Sciences; UI-SENS, University of Iceland, School of Engineering and Natural Sciences; IMO, Icelandic Meteorological Office; IINH, Icelandic Institute of Natural History; SCSI, Soil Conservation Service of Iceland; IGS, Iceland Glaciological Society; NNRC, North Iceland Nature Research Centre; EINRC, East Iceland Nature Research Centre; SINRC, Southeast Iceland Nature Research Centre.

Responsible tourism and tourist satisfaction
Steady progress has been made toward accurately estimating visitor numbers within the nominated property, through strategic emplacement of traffic counters (cars and people) on park roads, hiking routes and entrances to visitor centres. This network of counters is deployed and maintained by researchers at the University of Iceland in collaboration with Vatnajökull National Park (Þórhallsdóttir et al., 2017). The park also relies heavily on researchers at the University of Iceland for investigating trends in tourism, tourist satisfaction and tourism impact on Icelandic nature, including the nominated property (e.g. Sæþórsdóttir, 2012; Ólafsdóttir & Runnström, 2013).

6.b Administrative Arrangements for Monitoring Property

General requirements for monitoring and research of the nominated property are established in the Vatnajökull National Park Management Plan (Appendix 4). Although these have not yet been fully actualised, current arrangements for monitoring the state of conservation of the property are considered acceptable.

Vatnajökull National Park (the agency) is primarily responsible for implementing the Management Plan and thus defining indicators pertaining to the state of conservation and sustainable use of the park. However, nine external agencies collect data to populate these indicators (see Table 6.1). The contact information for these agencies is as follows:

University of Iceland
Institute of Earth Sciences
Dunhagi 3
107 Reykjavík
http://earthice.hi.is

University of Iceland
Faculty of Life and Environmental Sciences
Askja, Sturlugata 7
101 Reykjavík
http://english.hi.is

Icelandic Meteorological Office
Bústaðavegur 7–9
108 Reykjavík
http://imo.is

Icelandic Institute of Natural History
Urriðaholtsstræti 6–8
210 Garðabæ
http://ni.is

Iceland Glaciological Society
P.O. Box 5128
108 Reykjavík
http://jorfi.is

Soil Conservation Service of Iceland
Gunnarsholt
851 Hella
http://land.is

Northeast Iceland Nature Research Centre
Hafnarstétt 3
640 Húsavík
http://nna.is

East Iceland Nature Research Centre
Mýrargötu 10
740 Neskaupsstaður
http://na.is

Southeast Iceland Nature Research Centre
Litlubrú 2
780 Höfn í Hornafirði
http://nattsa.is

Value/feature	Indicator	Method	Evaluation	Frequency	Data holder
Geology					
Volcanism / Volcanic events	No. of eruptive events within the property	Observation, documentation	Assessment of frequency of events considering history	Periodically – at the time of event	UI-IES
Glaciology	Mass balance of the ice cap	Ice probe and stake measurements	Comparison of results with previous years to discover trends	Annually	UI-IES
Glaciology	Adv./retreat of termini of outlet glaciers in m	Direct measurements at fixed locations	Comparison of results with previous years to discover trends	Annually	IGS
Geological hazards					
Risk of eruption	Deformation of volcanoes (surface changes)	Network of GPS stations/gas sensors	Assessment of state of volcanoes	Continuously	IMO, UI-IES
Risk of earthquakes	Seismic activity	Network of seismometers – alert maps and shake maps	Location, frequency and magnitude – assessment of precursory signals to eruptions	Continuously	IMO
Risk of jökulhlaups	Water level and water chemistry	Network of river flow sensors in all major glacial rivers	Comparison with baseline flow and previous records	Continuously	IMO
Biota					
Vegetation	Vegetation cover and composition	Fixed plots in Skaftafell, Esjufjöll and Jökulsárgljúfur canyon	Changes in plant cover and composition over time	Every five to ten years	IINH
Grazing areas	State of grazing areas	Surveys, weight of lambs in fall	Changes in plant cover and lamb weight over time	Biennially	SCSI
Reindeer	Number of animals	Aerial counts of the Fljótsdalur herd	Population dynamics	Annually	EINRC
Falcon	Number of occupied territories	Direct counts within the nominated property	Population dynamics	Annually	IINH
Ptarmigan	No. of males in spring	Direct counts in Skaftafell (S)	Population dynamics	Annually	IINH
Pink footed goose	No. of moulting birds	Aerial counts of moulting flocks at Eyjabakkar Ramsar site (E)	Population dynamics and trends	Annually	EINRC
Great Arctic skua	Population trends	Counts of nests on Breiðamerkursandur IBA	Population dynamics and trends	Periodically	IINH
Barnacle goose	Population trends	Counts of nests on Skúmey, Jökulsárlón	Population dynamics and trends	Periodically, every three years	SENRC
Moths	No. of each species in traps	Light traps in Jökulsárgljúfur canyon (N)	Species composition and population dynamics	Annually	NNRC
Invasive alien species	Changes in distribution of Nootka lupine	Remote sensing, aerial photography	Assessment of spread and countermeasures	Every few years	IINH, VNP
Responsible tourism					
Visitor statistics and distribution	Number of visitors at key sites	Automated car- and visitor counters at key locations, surveys, camping fees	Assessment of visitor trends	Continuously	UI-SENS, VNP
Visitor experiences	Visitor assessment of sites, facilities and services	Surveys	Qualitative and quantitative assessment of visitor satisfaction	Every few years	UI-SENS, VNP
Wear and tear of nature	Wear and tear of trails and viewpoints, “wild” paths, waste in nature	Observations, photos and maps	Assessment of status and trends and the need for corrective measures	Continuously	VNP

6.c Reports of Previous Reporting Exercises

In preparation for the drafting of the first management plan of the park (2009–2010), the advisory bodies of each administrative region were tasked with compiling comprehensive reports for each region, highlighting inter alia the natural and cultural values of the respective areas, current conservation concerns, traditional and other land use, roads and infrastructures. These reports were then used as a basis for compiling the first and later versions of the Vatnajökull National Park MP (Appendix 4).

In 2011, a comprehensive guide to Vatnajökull National Park was published by the Friends of Vatnajökull association (Guttormsson, 2011) in four languages.

The aforementioned, are the only treatises covering the entire Vatnajökull National Park. However, several books have been published dealing with specific areas of the park, such as the Vatnajökull ice cap, Jökulsárgljúfur canyon, Skaftafell, the Laki eruption (Skaftá Fires) and environs and Jökulsárlón lagoon. These include The Mysteries of Vatnajökull (Guttormsson & Sigurðsson, 1997; in Icelandic); Glaciers of Iceland (Björnsson, 2009; in Icelandic); The Glaciers of Iceland: A Historical, Scientific and Cultural Overview (Björnsson, 2017); Jökulsá Canyon: An Icelandic Wonderland (Gunnlaugsson, 1975; in Icelandic); Jökulsárgljúfur Canyon: Dettifoss, Ásbyrgi and Everything in Between (Helgadóttir, 2008; guidebook in Icelandic); Skaftafell: History of a Farmstead (Tómasson, 1980), Skaftafell - National Park (Bergmann, 2005; photography with introduction); Skaftafell in Iceland: A Thousand Years of Change (Ives, 2007); Fires of the Earth: the Laki eruption 1783–1784 (Steingrímsson, 1788; English translation, 1988); Skaftá Fires 1783–1784: Essays and Anecdotes (Gunnlaugsson, 1984 (ed.), in Icelandic); The 1783–84 Laki eruption: Tephra production and course of events (Thórðarson, 1989); The Laki Craters and the Fire District (Baldursson, 2017; photography with introduction); Jökulsárlón lagoon: All Year Round (Árnason, 2010; photography with introduction).

FUTUREVOLC (2012–2016) was a collaborative project funded by the Environment programme of the FP7 programme of the European Commission, addressing the topic "Long-term monitoring experiment in geologically active regions of Europe prone to natural hazards: the Supersite concept".

The main objectives of the project were to establish an integrated volcanological monitoring system through European collaboration, develop new methods to evaluate volcanic crises, increase scientific understanding of magmatic processes and improve delivery of relevant information to civil protection and authorities. During the project the largest effusive lava eruption in Iceland since 1783 occurred at Holuhraun within the Bárðarbunga volcanic system (August 2014–February 2015). The results can be viewed at: www.futurevolc.hi.is.

Opposite: Tourists enjoying the icebergs at Jökulsárlón lagoon on 14 July 2017 © Þorvarður Árnason. Next page: Sphagnum moss, *Sphagnum* sp., in Jökulsárgljufur canyon © Snorri Baldursson.

7. Documentation

7. Documentation

7.a Photographs and Audiovisual Image Inventory and Authorisation Form

Appendix 2: Image inventory

7.b Texts Relating to Protective Designation

Appendix 1: Maps

Appendix 3: Vatnajökull National Park legislation (attached as a separate volume)

Appendix 4: Management Plan 2013 (attached as a separate volume)

7.c Form and Date of Most Recent Records or Inventory of Property

Vatnajökull National Park has attracted the interest of many scientists. Thus, detailed information exists on its natural history in numerous scientific publications, many of which are cited in this nomination or presented with it as supplementary material (section 7.e). Inventories of flora and fauna are attached in Appendix 3. This nomination report represents the most resent comprehensive overview of the property. Previous reports and books dealing with various parts or aspects of the property are listed in section 6.c.

Appendix 2: Inventory of property

Appendix 4: Management Plan 2013 – contains a summary of natural features and attributes (attached as a separate volume)

7.d Address where Inventory, Records and Archives are Held

Inventories of flora and fauna
Icelandic Institute of Natural History
Urriðaholtsstræti 6-8
210 Garðabær

Natural hazards
Icelandic Meteorological Office
Bústaðavegi 7-9
108 Reykjavík

Geology and Volcanology
Institute of Earth Sciences, University of Iceland
Dunhaga 5
107 Reykjavík

7.e Bibliography

This Bibliography contains 1194 papers and essays, thereof 775 peer reviewed, dealing with various natural and social aspects of the Vatnajökull National Park property. The oldest one dates from 1714 and the newest from 2018.

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Þórisson, SG, and R Þórarinsdóttir. 2017. Reindeer monitoring in East Iceland in 2016 and proposal of hunting quota and compensation areas in 2017.

Crustose lichens on a rock by Heinabergslón © Snorri Baldursson.

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8. Contact Information of Responsible Authorities

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8.b Official Local Institution/Agency

Vatnajökull National Park is a decentralised agency with administrative offices in Reykjavík and Egilsstaðir (East), and six regional offices where visitor centres and regional park managers are housed:

Administration:
Vatnajökull National Park
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8.c Other Local Institutions

Not relevant

8.d Official Web Address

http://www.vatnajokulsthjodgardur.is/http://www.vjp.is

Next page: Lake Langisjór,
26 September 2011 © Snorri
Baldursson.

The Gjálp eruption, first week of November 1996 © Ragnar Th. Sigurðsson.

9. Signature on Behalf of the State Party

Date

Lilja Alfreðsdóttir

Minister of Education, Science and Culture

Guðmundur Ingi Guðbrandsson

Minister for the Environment and Natural Resources

Citation by Section

Section 2

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Appendix 1: Maps

Appendix 1.1: Geological- and other maps from the nomination report (Fig numbers refer to numbers in the maind text)

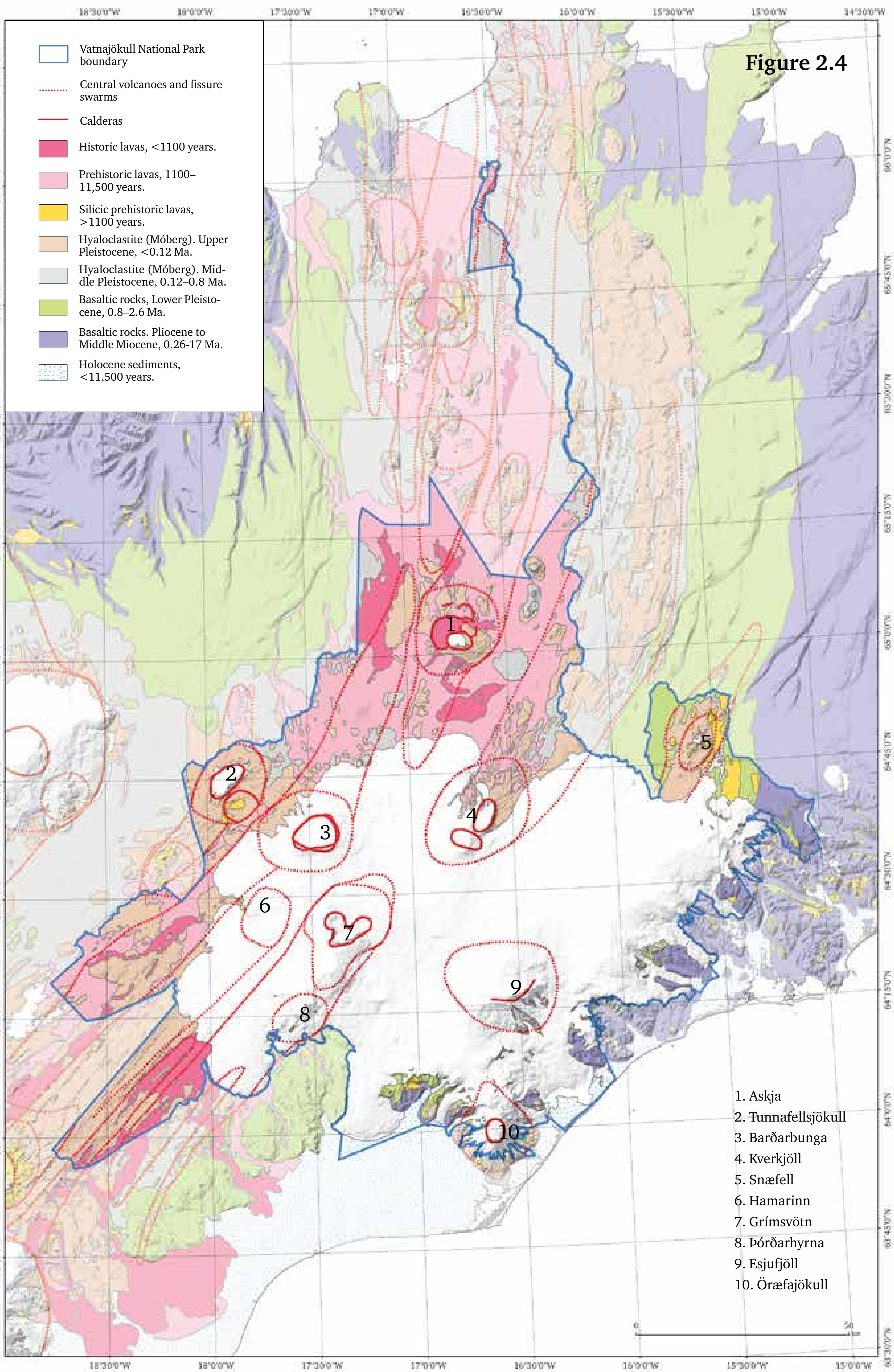


Figure 2.4
Vatnajökull National Park boundary
Central volcanoes and fissure swarms
Calderas
Historic lavas, <1100 years.
Prehistoric lavas, 1100–11,500 years.
Silicic prehistoric lavas, >1100 years.
Hyaloclastite (Móberg). Upper Pleistocene, <0.12 Ma.
Hyaloclastite (Móberg). Middle Pleistocene, 0.12–0.8 Ma.
Basaltic rocks, Lower Pleistocene, 0.8–2.6 Ma.
Basaltic rocks. Pliocene to Middle Miocene, 0.26-17 Ma.
Holocene sediments, <11,500 years.
1
2
3
4
5
6
7
8
9
10
1. Askja
2. Tunnafellsjökull
3. Barðarbunga
4. Kverkjöll
5. Snæfell
6. Hamarinn
7. Grímsvötn
8. Þórðarhyrna
9. Esjufjöll
10. Öræfajökull

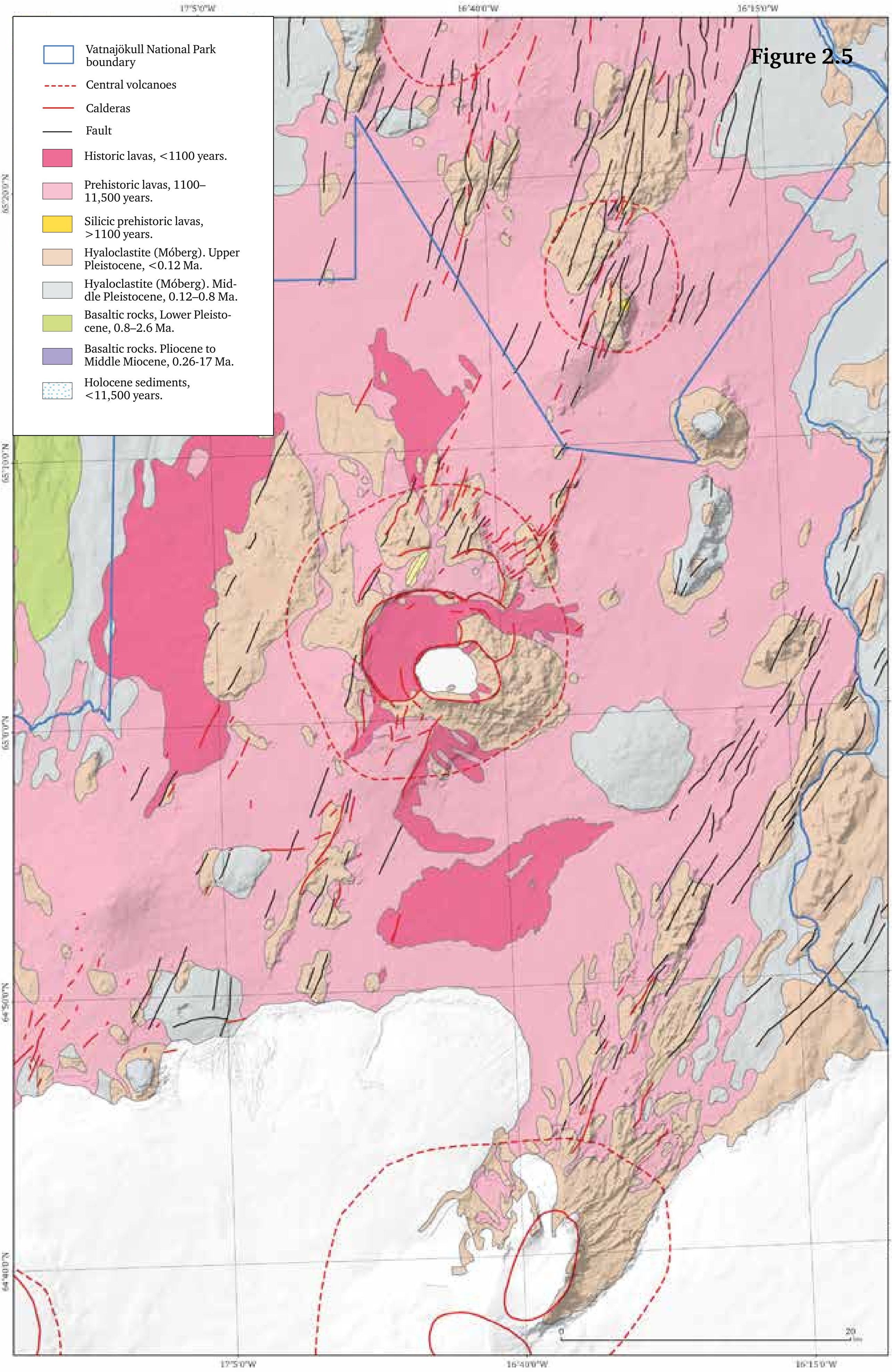

Vatnajökull National Park boundary
Central volcanoes
Calderas
Fault
Historic lavas, <1100 years.
Prehistoric lavas, 1100–11,500 years.
Silicic prehistoric lavas, >1100 years.
Hyaloclastite (Móberg). Upper Pleistocene, <0.12 Ma.
Hyaloclastite (Móberg). Middle Pleistocene, 0.12–0.8 Ma.
Basaltic rocks, Lower Pleistocene, 0.8–2.6 Ma.
Basaltic rocks. Pliocene to Middle Miocene, 0.26-17 Ma.
Holocene sediments, <11,500 years.
17°5'0"W
16°40'0"W
16°15'0"W
65°20'0"N
65°10'0"N
65°0'0"N
64°50'0"N
64°40'0"N
0
20

Figure 2.5

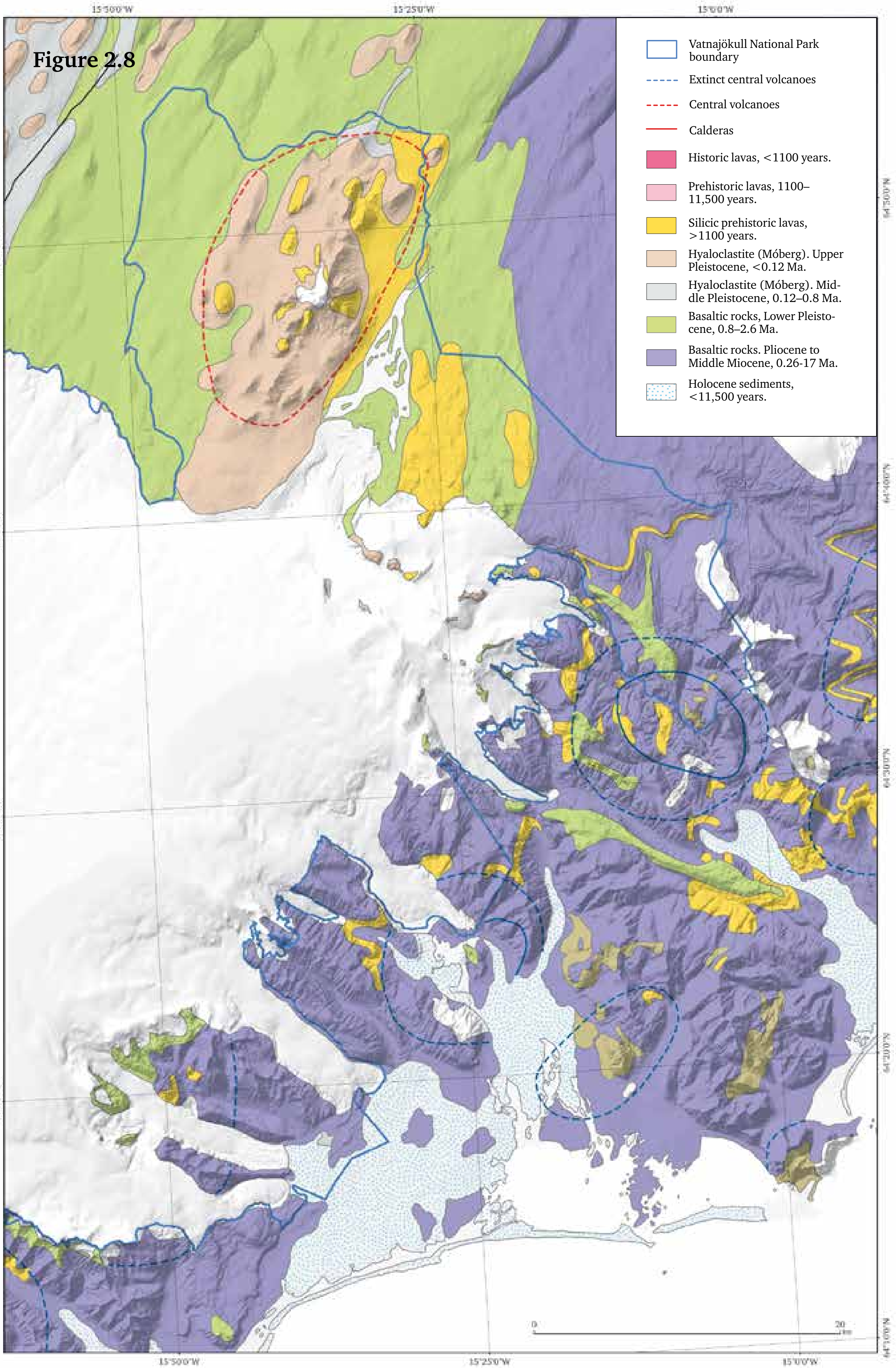


Figure 2.8
Vatnajökull National Park boundary
Extinct central volcanoes
Central volcanoes
Calderas
Historic lavas, <1100 years.
Prehistoric lavas, 1100–11,500 years.
Silicic prehistoric lavas, >1100 years.
Hyaloclastite (Móberg). Upper Pleistocene, <0.12 Ma.
Hyaloclastite (Móberg). Middle Pleistocene, 0.12–0.8 Ma.
Basaltic rocks, Lower Pleistocene, 0.8–2.6 Ma.
Basaltic rocks. Pliocene to Middle Miocene, 0.26-17 Ma.
Holocene sediments, <11,500 years.
15°50'0"W
15°25'0"W
15°0'0"W
0
20

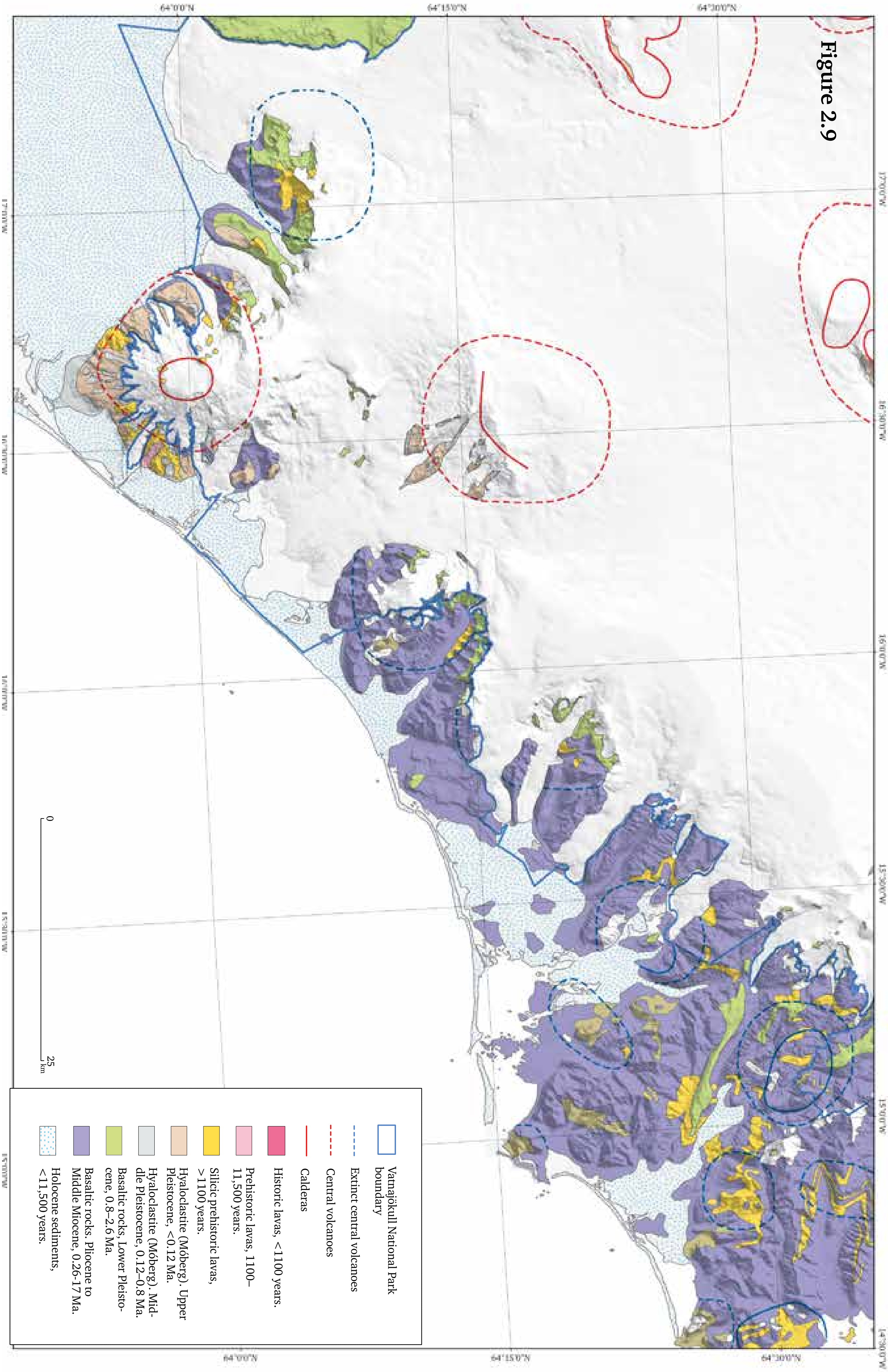

Vatnajökull National Park boundary
Extinct central volcanoes
Central volcanoes
Calderas
Historic lavas, <1100 years.
Prehistoric lavas, 1100–11,500 years.
Silicic prehistoric lavas, >1100 years.
Hyaloclastite (Móberg). Upper Pleistocene, <0.12 Ma.
Hyaloclastite (Móberg). Middle Pleistocene, 0.12–0.8 Ma.
Basaltic rocks, Lower Pleistocene, 0.8–2.6 Ma.
Basaltic rocks. Pliocene to Middle Miocene, 0.26-17 Ma.
Holocene sediments, <11,500 years.
0
25 km

Figure 2.9

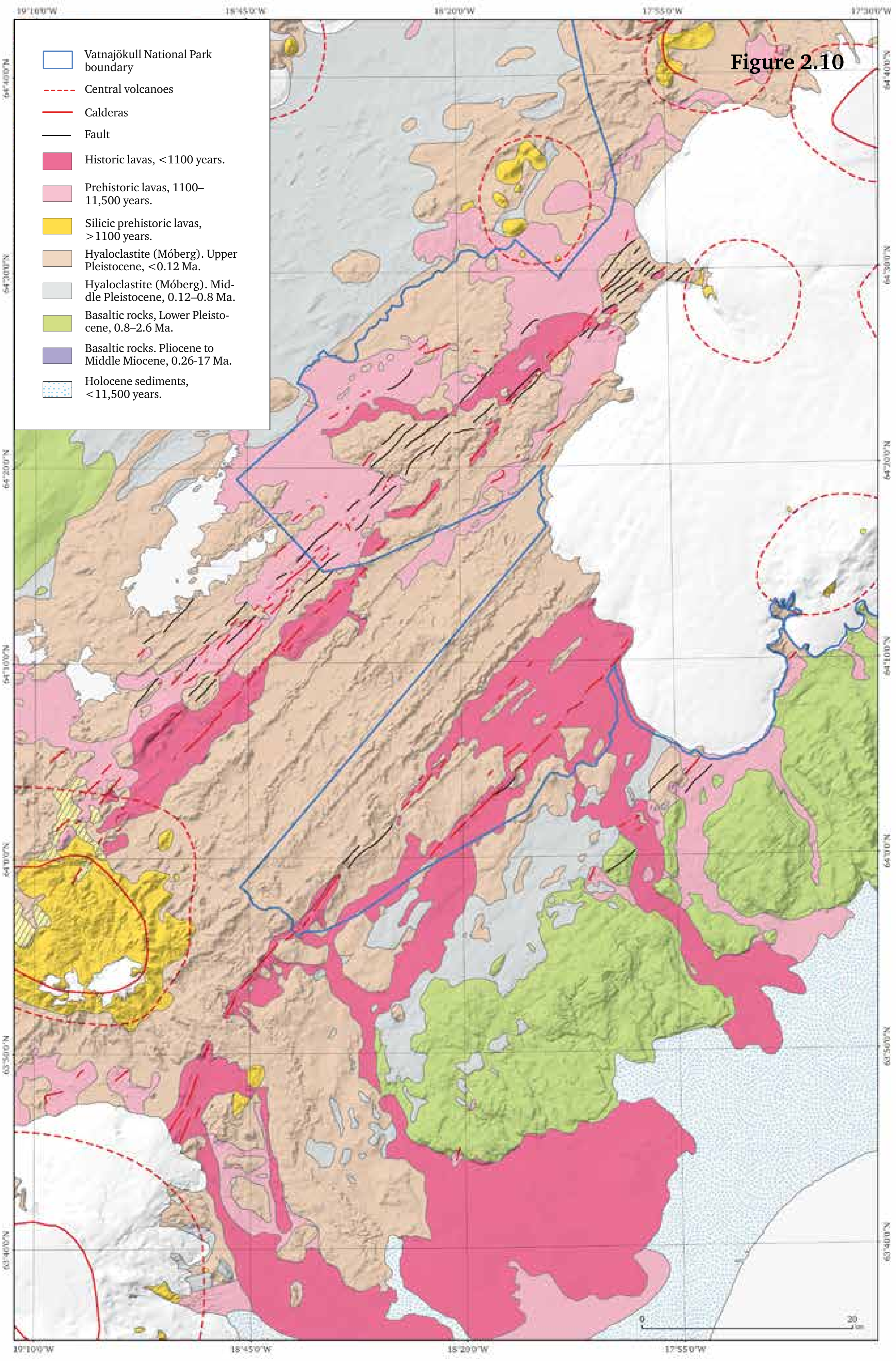

Vatnajökull National Park boundary
Central volcanoes
Calderas
Fault
Historic lavas, <1100 years.
Prehistoric lavas, 1100–11,500 years.
Silicic prehistoric lavas, >1100 years.
Hyaloclastite (Móberg). Upper Pleistocene, <0.12 Ma.
Hyaloclastite (Móberg). Middle Pleistocene, 0.12–0.8 Ma.
Basaltic rocks, Lower Pleistocene, 0.8–2.6 Ma.
Basaltic rocks. Pliocene to Middle Miocene, 0.26-17 Ma.
Holocene sediments, <11,500 years.
19°10'0"W
18°45'0"W
18°20'0"W
17°55'0"W
17°30'0"W
64°40'0"N
64°30'0"N
64°20'0"N
64°10'0"N
64°0'0"N
63°50'0"N
63°40'0"N
0
20

Figure 2.10

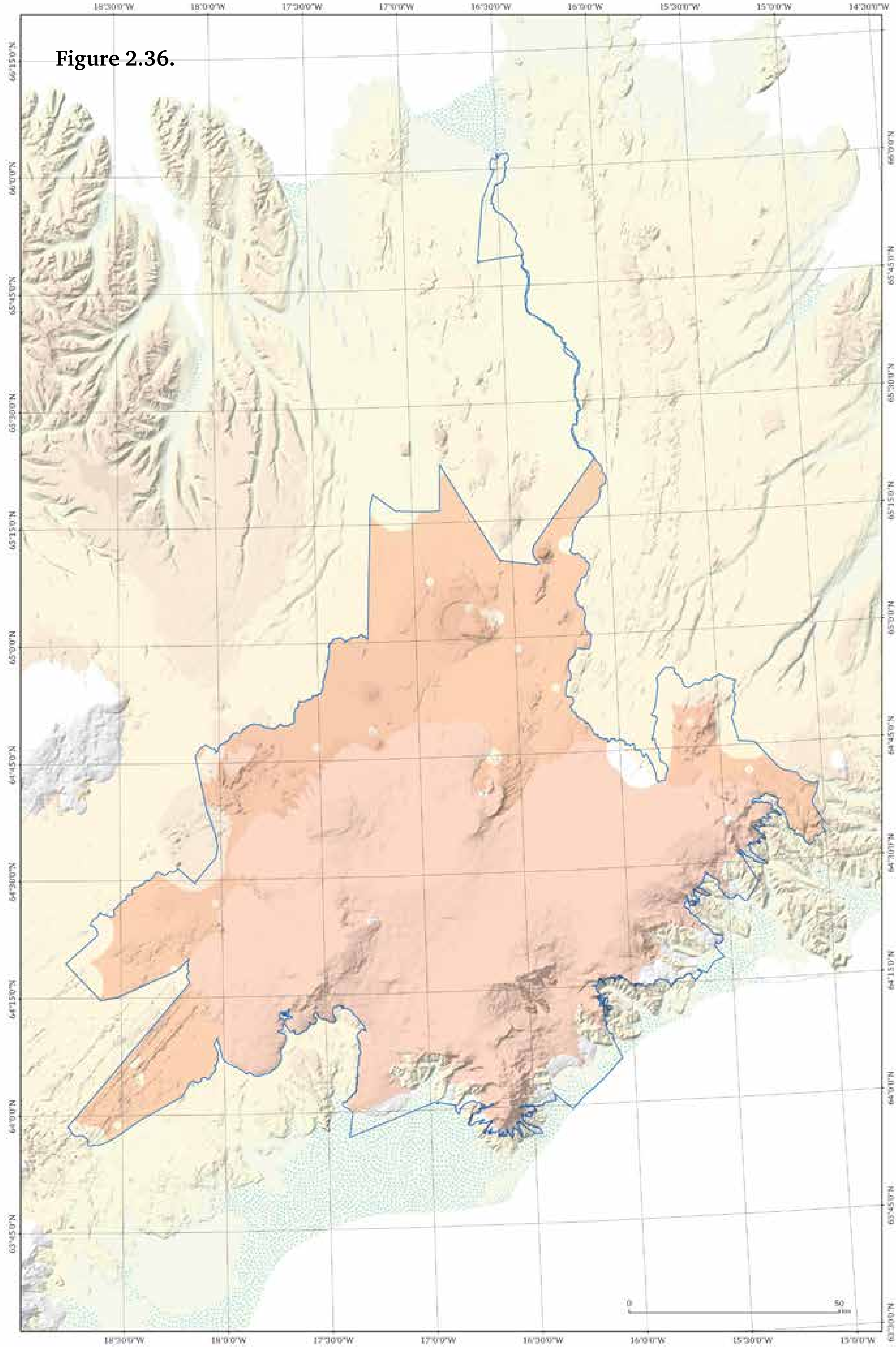

18°30'0"W
18°0'0"W
17°30'0"W
17°0'0"W
16°30'0"W
16°0'0"W
15°30'0"W
15°0'0"W
14°30'0"W
66°15'0"N
66°0'0"N
65°45'0"N
65°30'0"N
65°15'0"N
65°0'0"N
64°45'0"N
64°30'0"N
64°15'0"N
64°0'0"N
63°45'0"N
0
50

Figure 2.36.

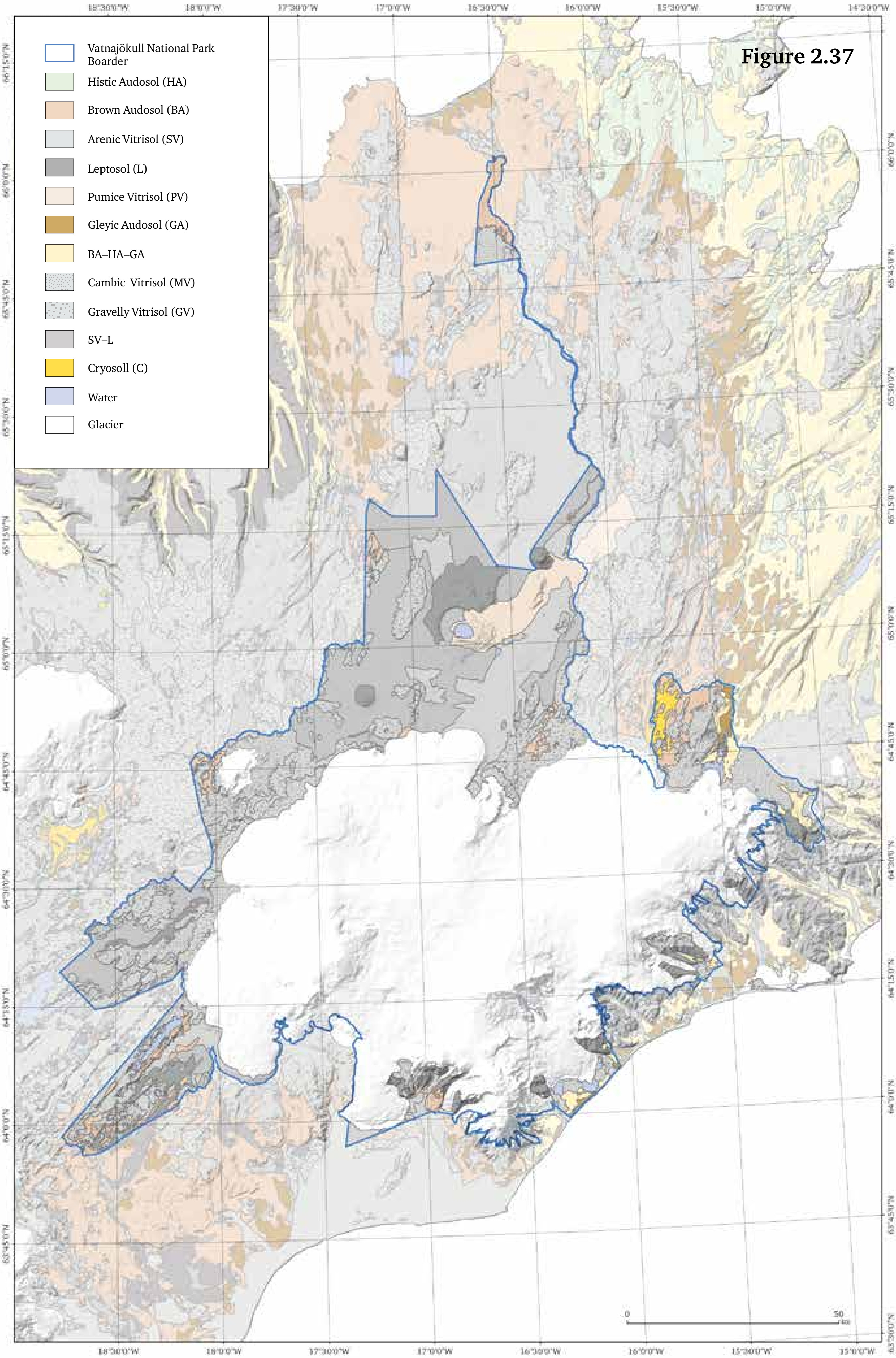

Vatnajökull National Park Boarder
Histic Audosol (HA)
Brown Audosol (BA)
Arenic Vitrisol (SV)
Leptosol (L)
Pumice Vitrisol (PV)
Gleyic Audosol (GA)
BA–HA–GA
Cambic Vitrisol (MV)
Gravelly Vitrisol (GV)
SV–L
Cryosoll (C)
Water
Glacier
0
50

Figure 2.37

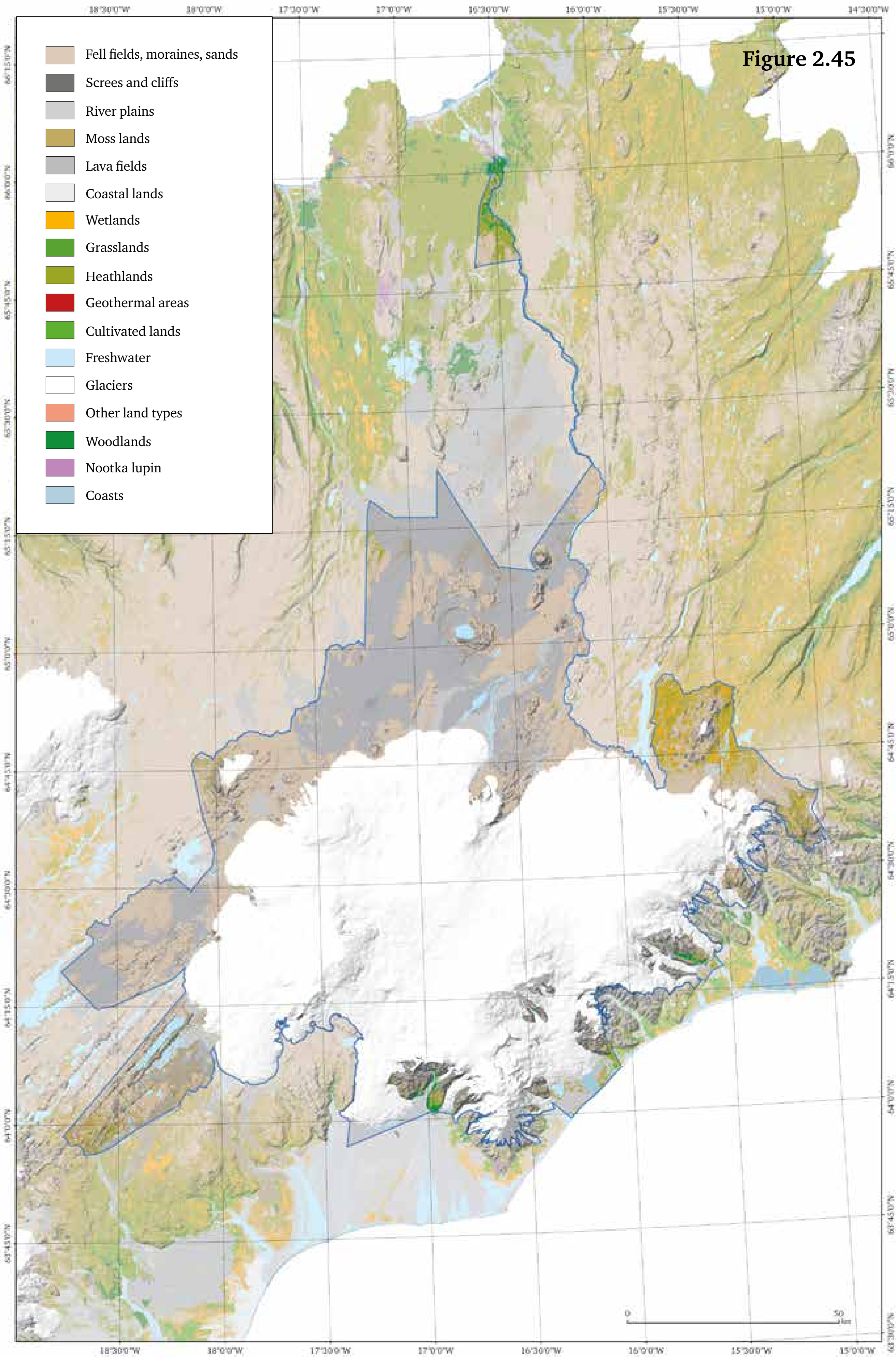
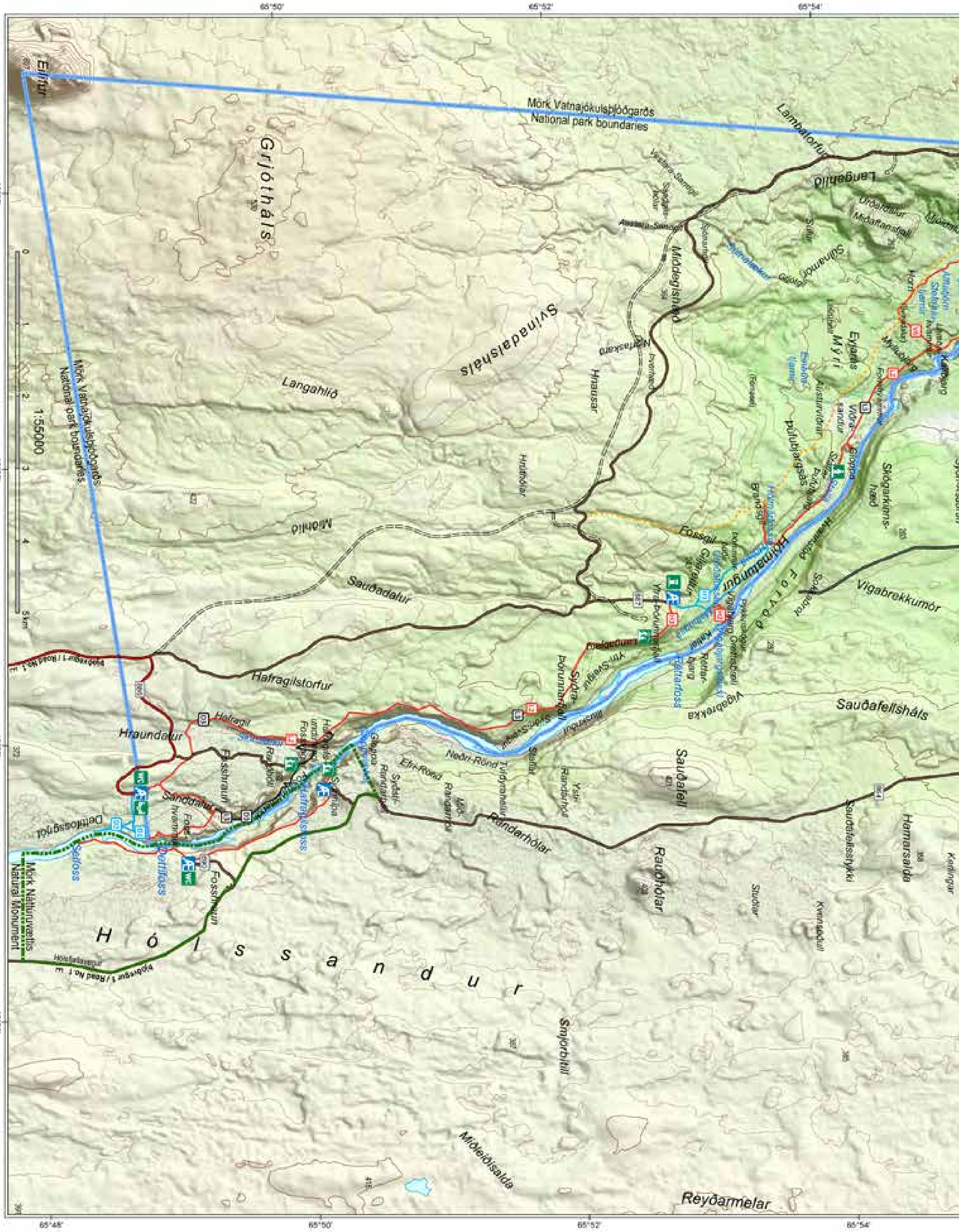
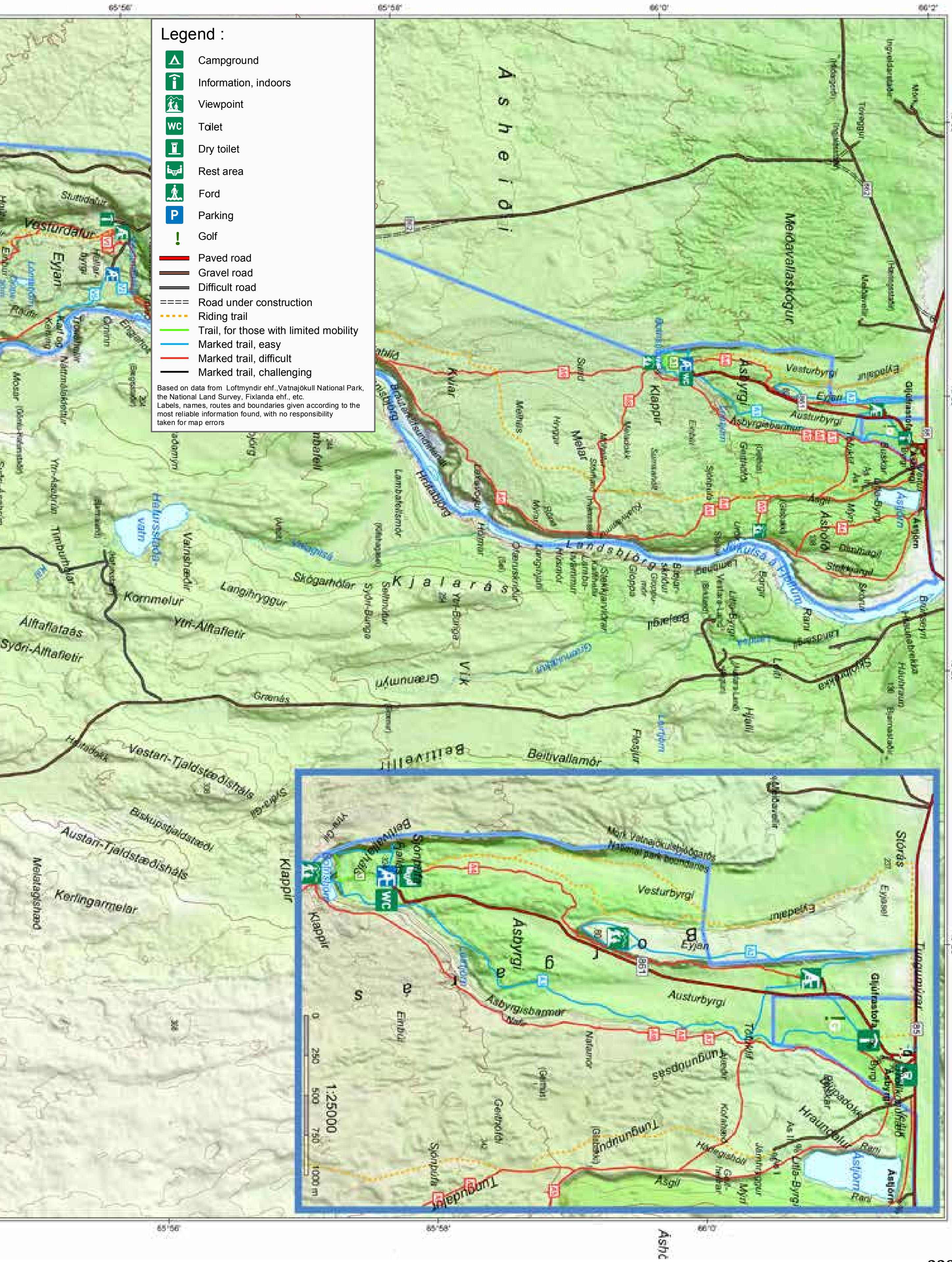

Fell fields, moraines, sands
Screes and cliffs
River plains
Moss lands
Lava fields
Coastal lands
Wetlands
Grasslands
Heathlands
Geothermal areas
Cultivated lands
Freshwater
Glaciers
Other land types
Woodlands
Nootka lupin
Coasts
0
50
km

Figure 2.45

Appendix 1.2: Hiking- and detail maps of the nominated property

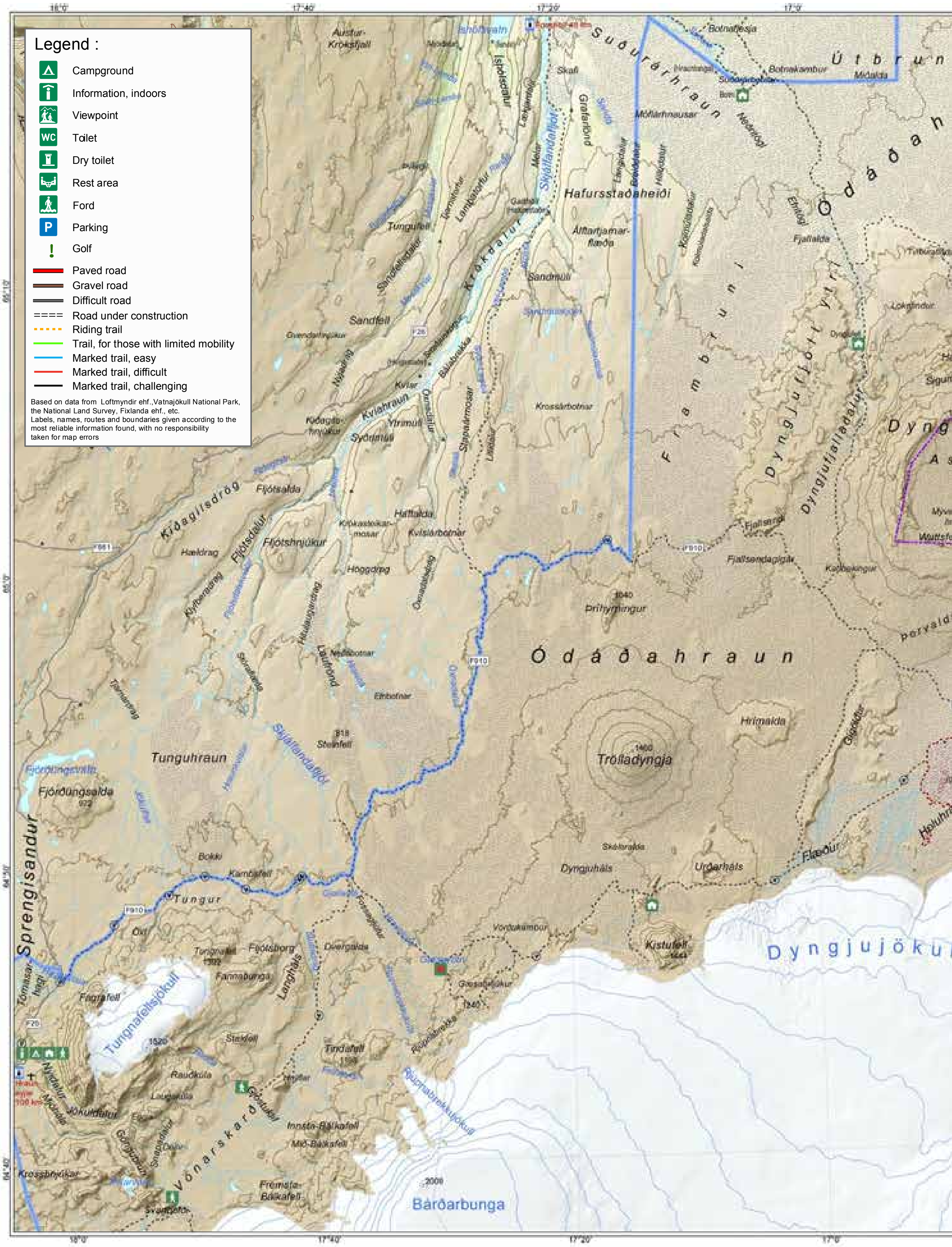
Jökulsárglúfur Canyon

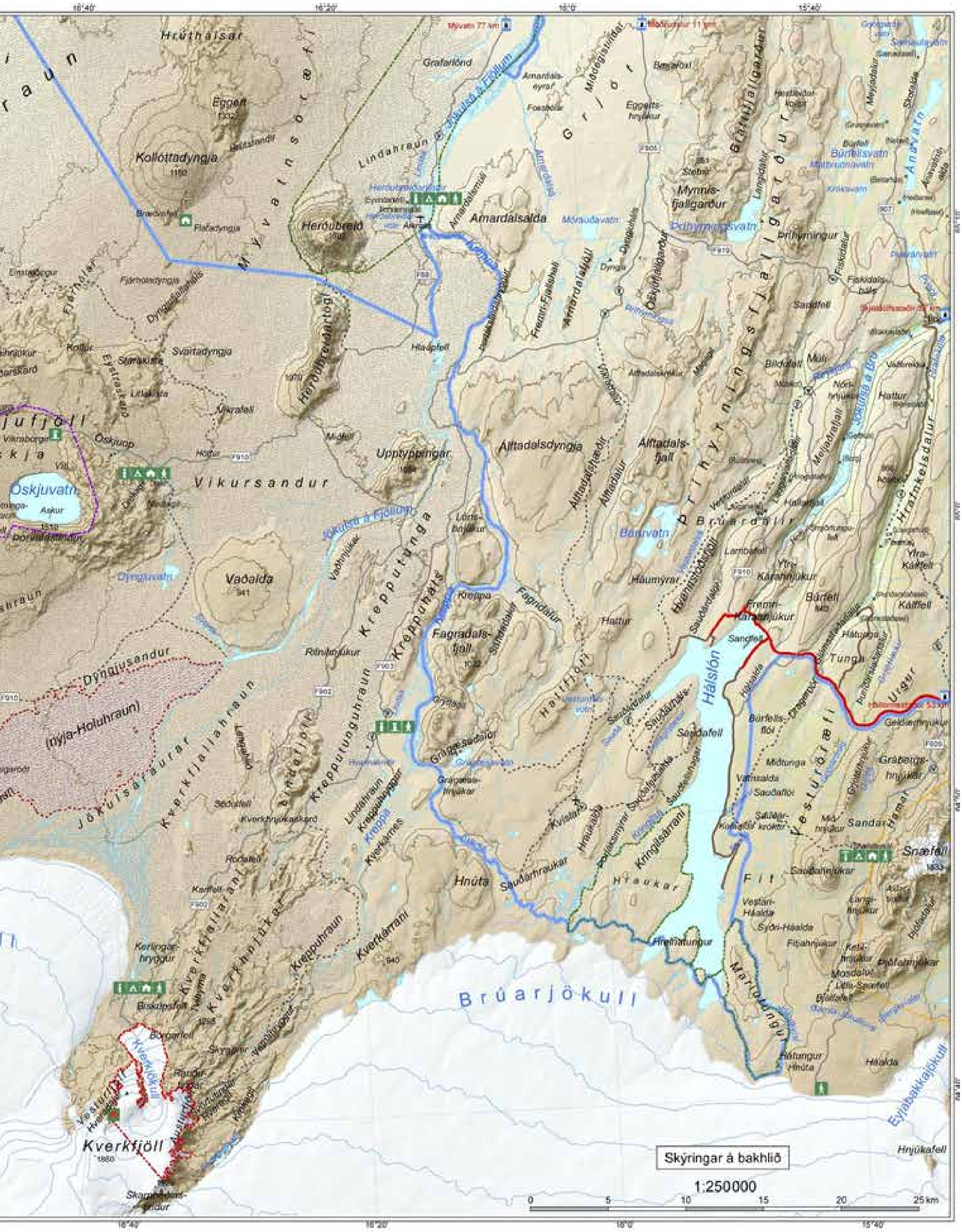




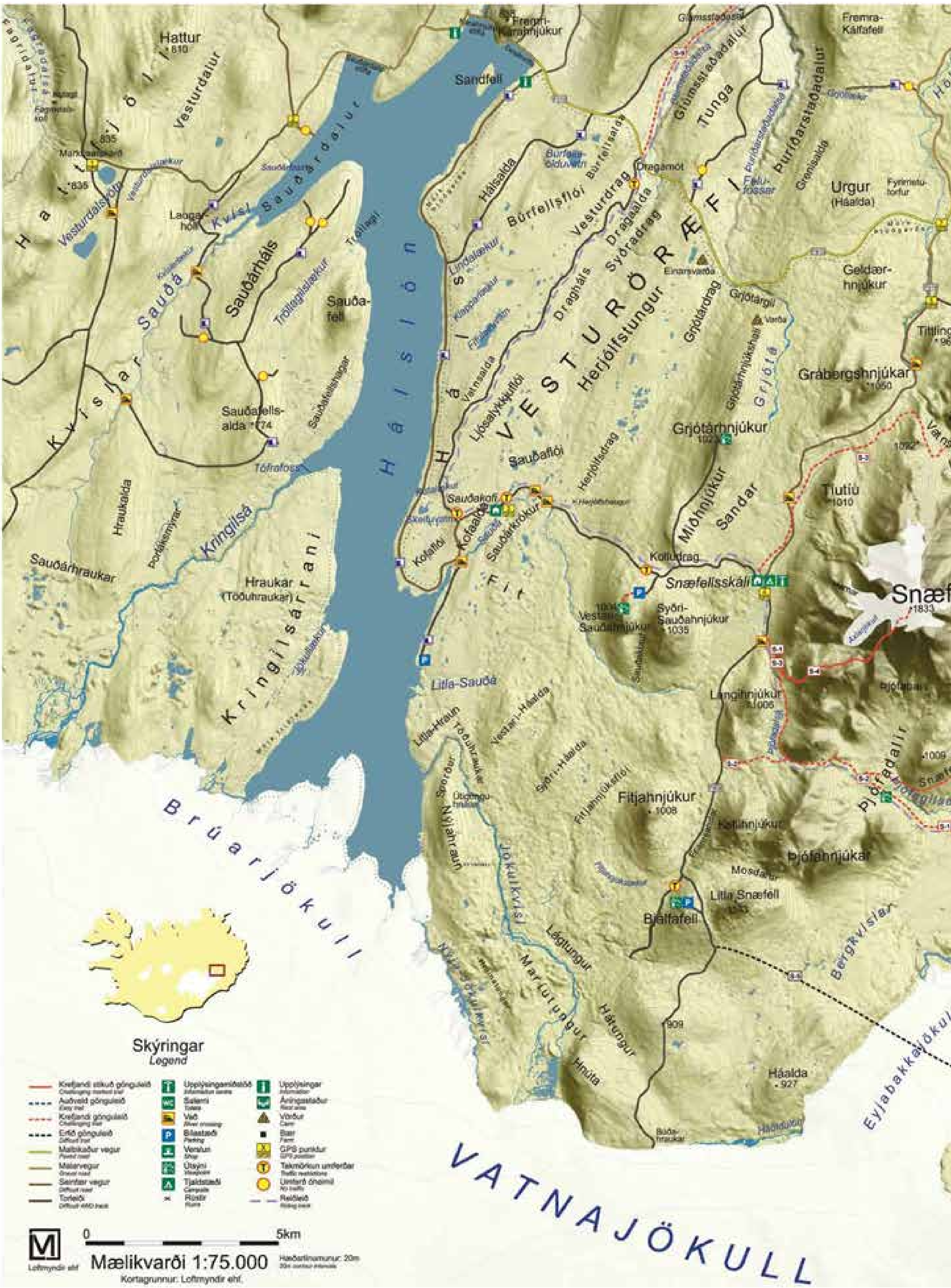
Legend :
Campground
Information, indoors
Viewpoint
Toilet
Dry toilet
Rest area
Ford
Parking
Golf
Paved road
Gravel road
Difficult road
Road under construction
Riding trail
Trail, for those with limited mobility
Marked trail, easy
Marked trail, difficult
Marked trail, challenging
Based on data from Loftmyndir ehf.,Vatnajökull National Park, the National Land Survey, Fixlanda ehf., etc.
Labels, names, routes and boundaries given according to the most reliable information found, with no responsibility taken for map errors
1:25000
0 250 500 750 1000 m

The Northern Highlands



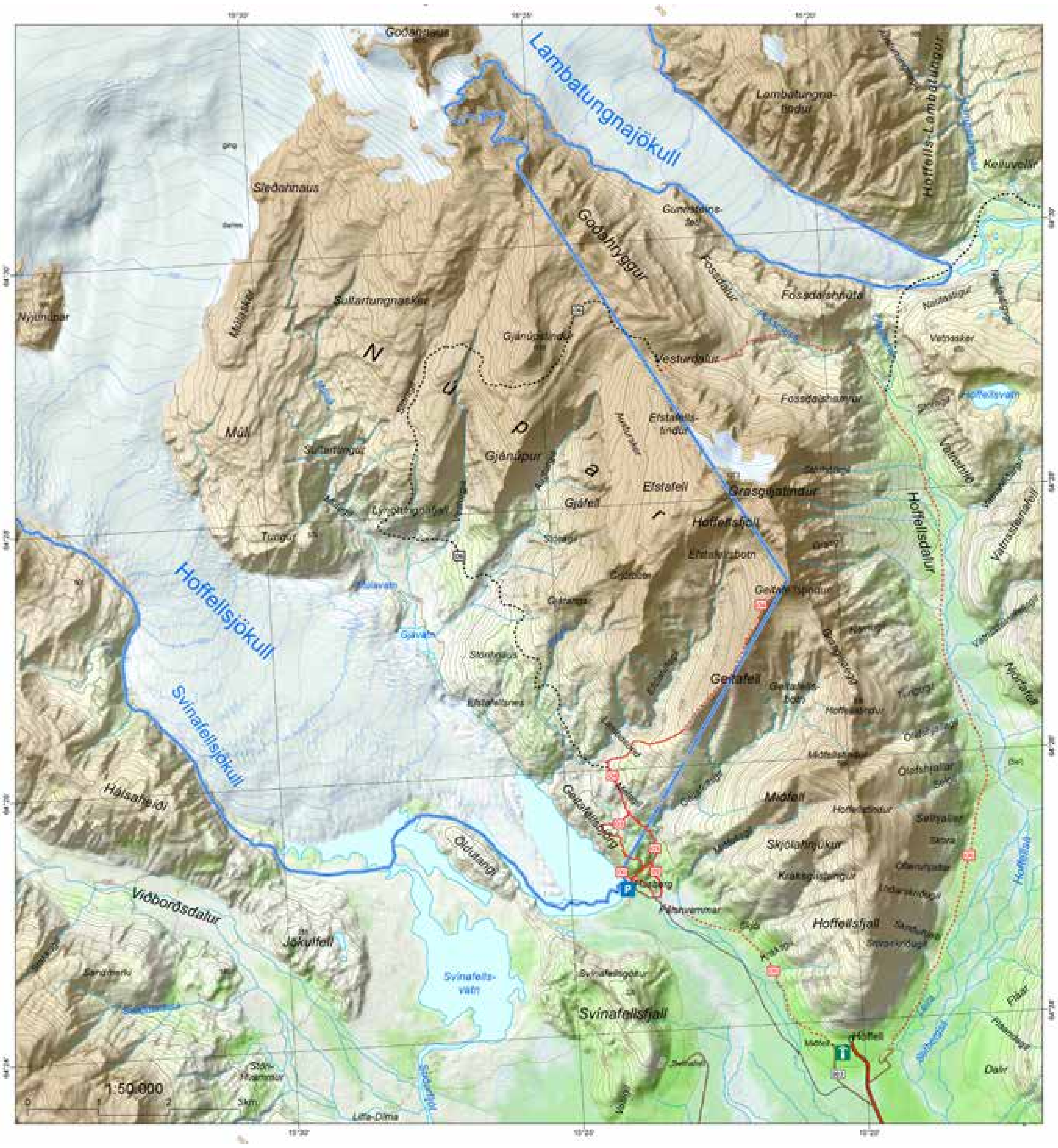

Hrúthálsar
Eggert
Kollóttadyngja
Herðubreið
Lindahraun
Grafarlönd
Arnardalsalda
Mynnis-
fjallgarður
Þríhyrningsvatn
Upptyppingar
Álftadalsdyngja
Álftadals-
fjall
Vikursandur
Öskjuvatn
Askur
Vaðalda
Dyngjusandur
(nýja-Holuhraun)
Kreppa
Fagradals-
fjall
Hálslón
Sandfell
Brúardalir
Búrfell
Fremri-
Kárahnjúkur
Snæfell
Hnúta
Kverkfjöll
Brúarjökull
Kringilsárrani
Hraukar
Vestur-Öræfi
Fit
Kverkárrani
Eyjabakkajökull
Hjúkafell
Skýringar á bakhlið
1:250000
0
5
10
15
20
25 km
16°40'
16°20'
16°0'
15°40'

The Eastern Region



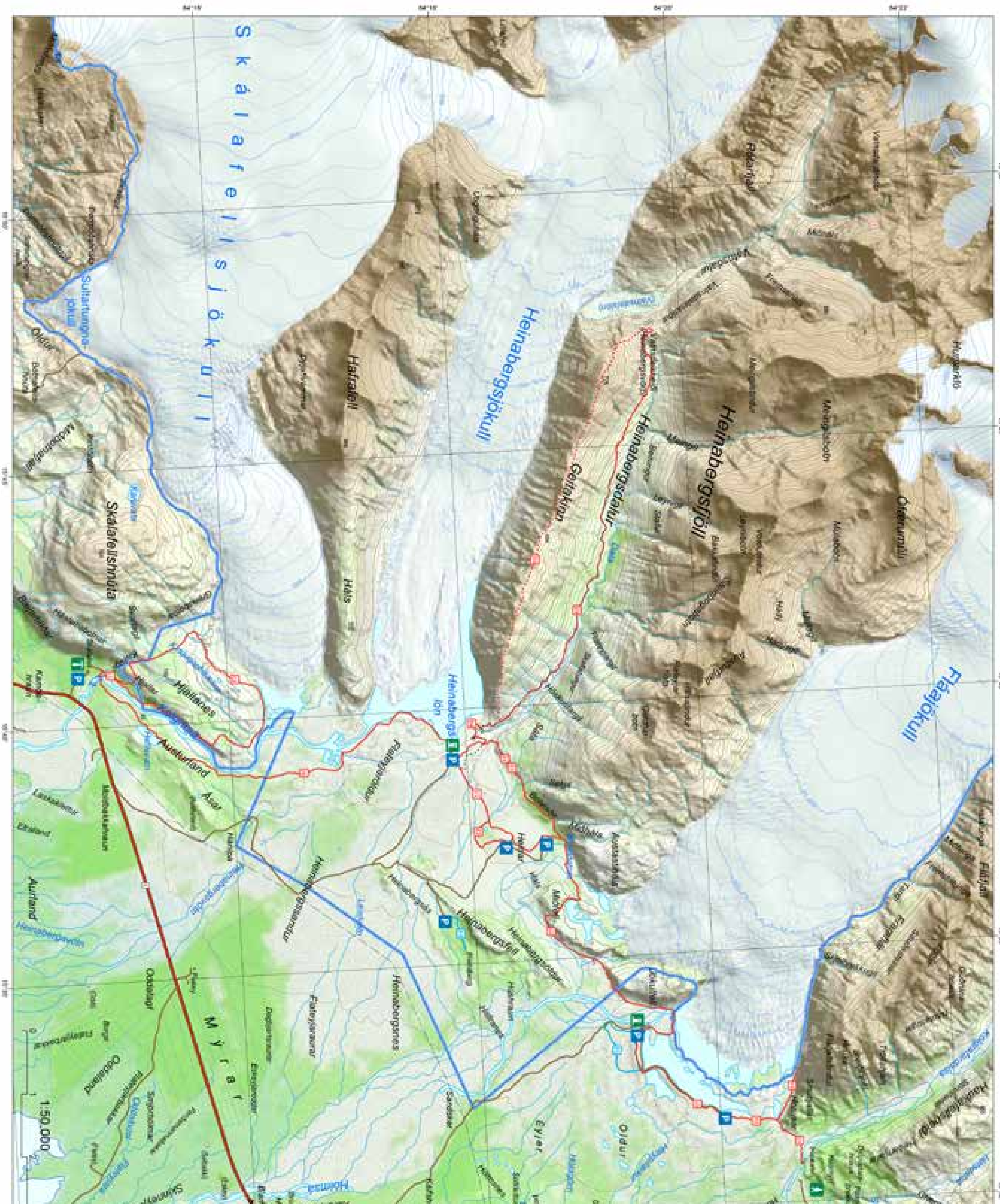

N
Bræðraalda
Svartalda
Laugarfell
Hafursfell
Sandfell
Ragnaborg
Hrakströnd
Hafursá
Keldudárlón
Folavatn
Eyjabakkar
Kofahraun
Múlahraun
Hraunin
Grjótárdalur
Syðri-Háalda
Nyrðri-Háalda
Sauðárvatn
Ytra-Dýjafell
Innra-Dýjafell
Tungufell
Tungufellsskáli
Þingvöllur
Suðurfell
Grenisöldur
Villingafell
Villingadalur
Sultarrani
Leirdæld
Polladæld
Innstaland
Jökulhæð
Nautagilstungur
Hnútufjöll
Norðurhnúta
Hnúta
Hnútuvatn
Eyjafell
Ljósafell
Kverkfell
Dökkafell
Geldingafell
Vesturdalsjökull
Brúarjökull
Vatnajökull
Blöndujökull
Grjótárhnjúkur
Móraudaurð
Keldá
Grjótá
Sauðahnjúkur
Stórihnjúkur
Þorgerðarstaðadalur
Snæfellsnes
Eyjafellsvatn
Suðurfell
Heiðarárbugar

The Southeast Region

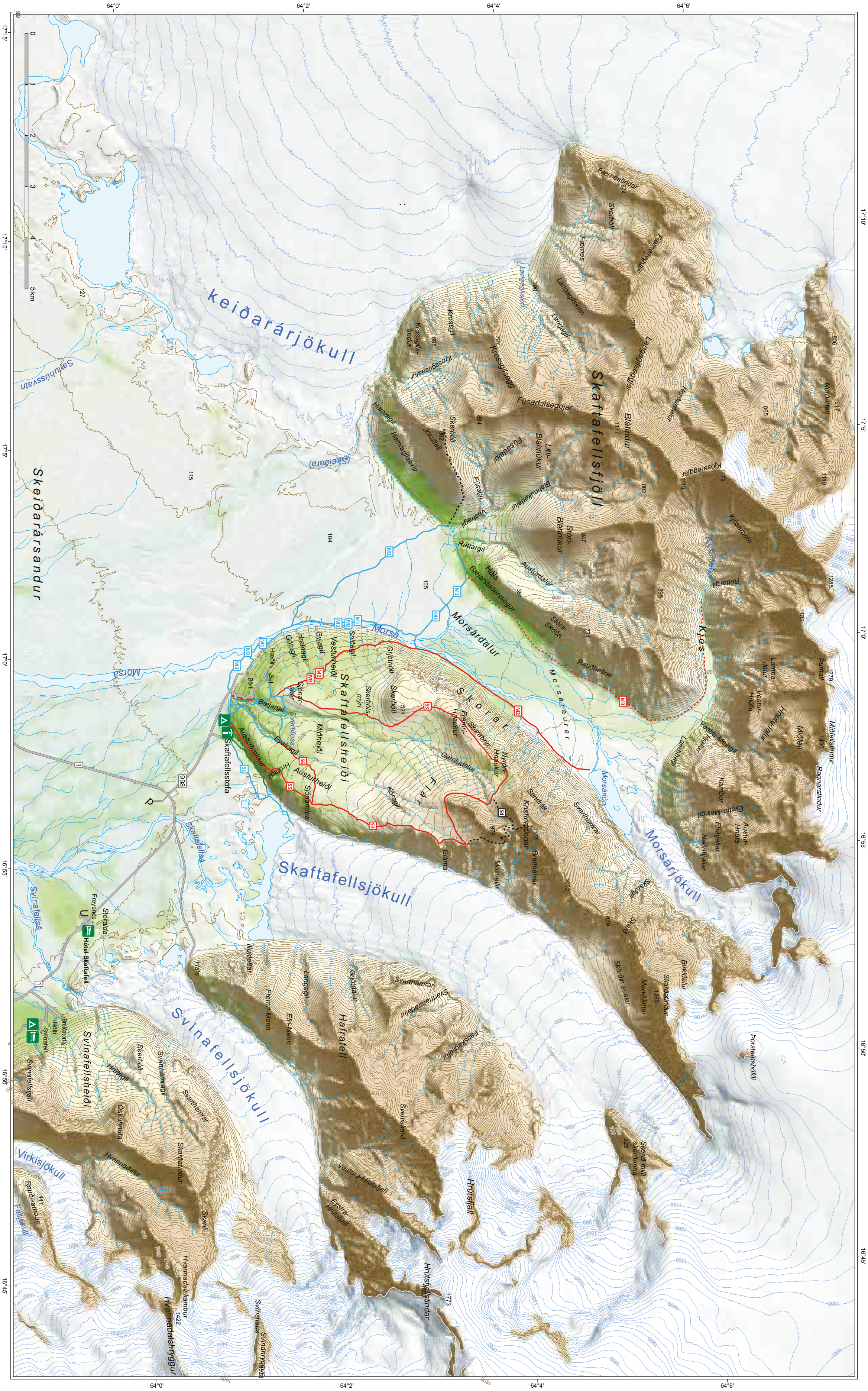


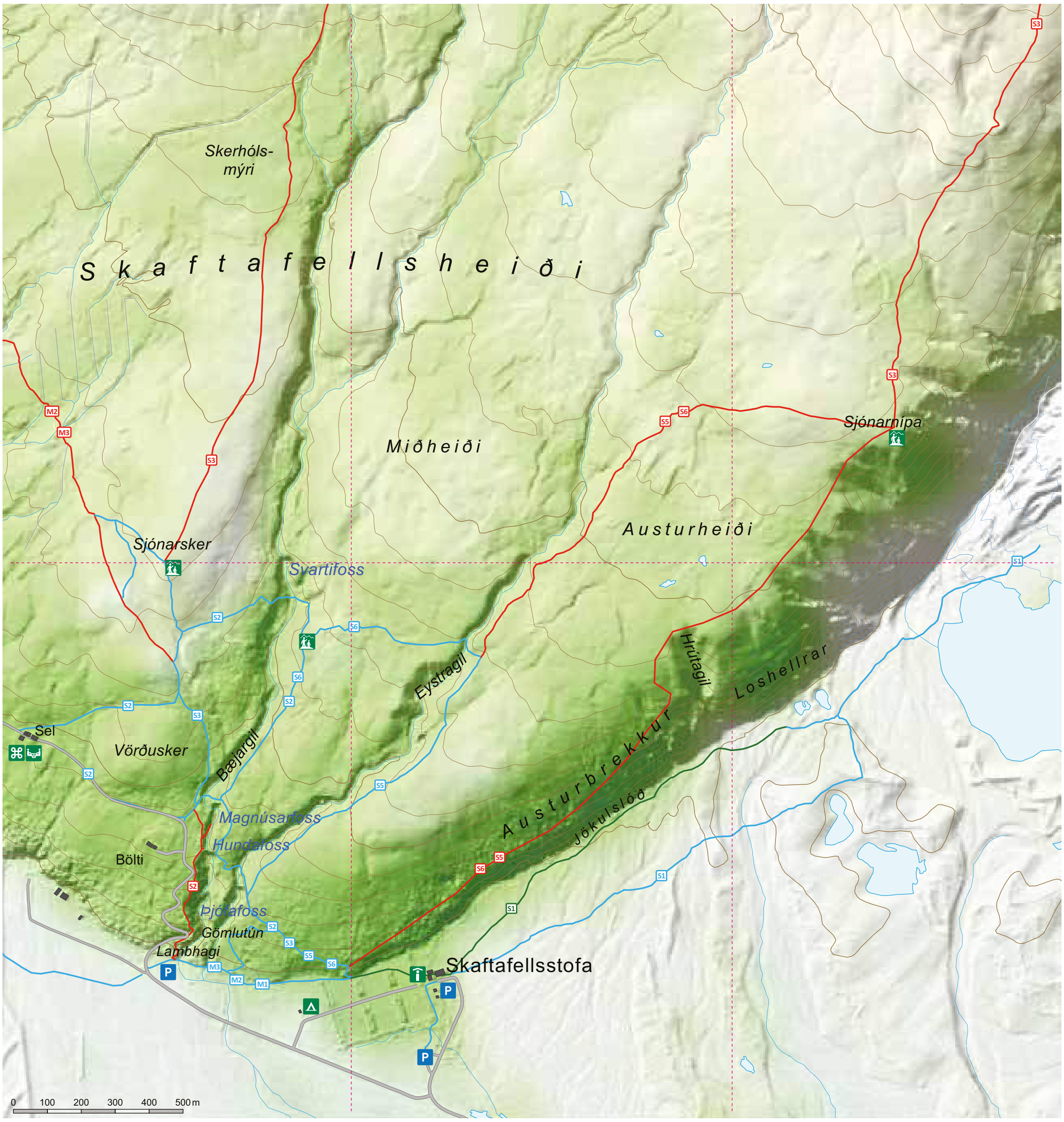
Skýringar - Legend :

- Upplýsingar innanhúss - Information indoors
- Salerni - Toilet
- Bílastæði - Parking
- Merkt gönguleið - Marked walking trail
- F905 Vegnúmer - Road number
- Göngubrú - Walkway
- Merkt gönguleið, auðveld - Marked trail, easy
- Merkt gönguleið, krefjandi - Marked trail, challenging
- Ómerkt gönguleið, krefjandi - Trail, challenging
- Ómerkt gönguleið, erfið - Trail, difficult
- Vegur, bundið slitlag - Paved road
- Vegur, malarborinn - Gravel road
- Illfær vegur - Difficult road
- Torleiði - Barely passable road
- Mörk Vatnajökulsþjóðgarðs - National park boundaries


Skálafellsjökull
Heinabergsjökull
Heinabergsfjöll
Fláajökull
Hafrafell
Heinabergslón
Mýrar
1:50.000

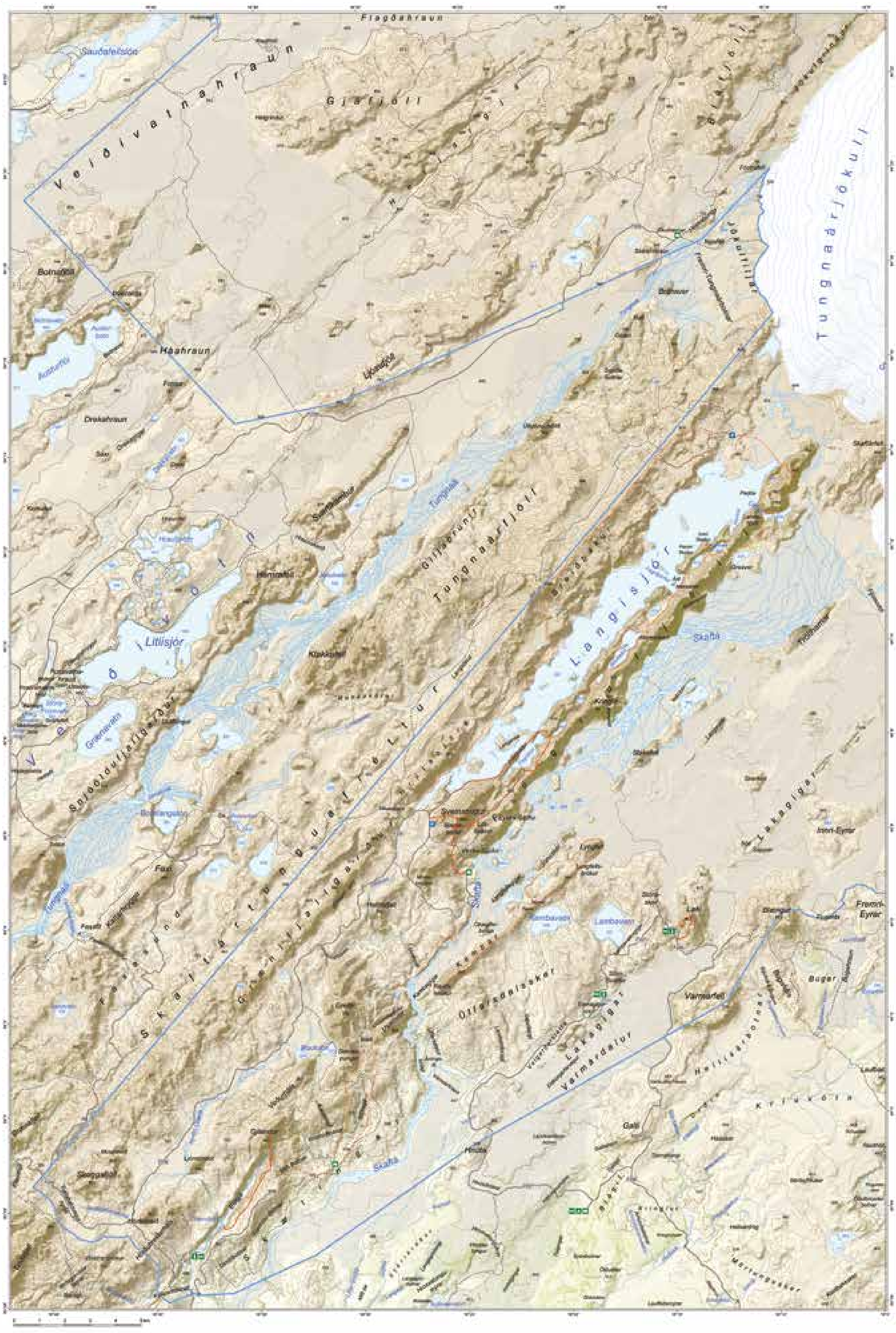
Skaftafell

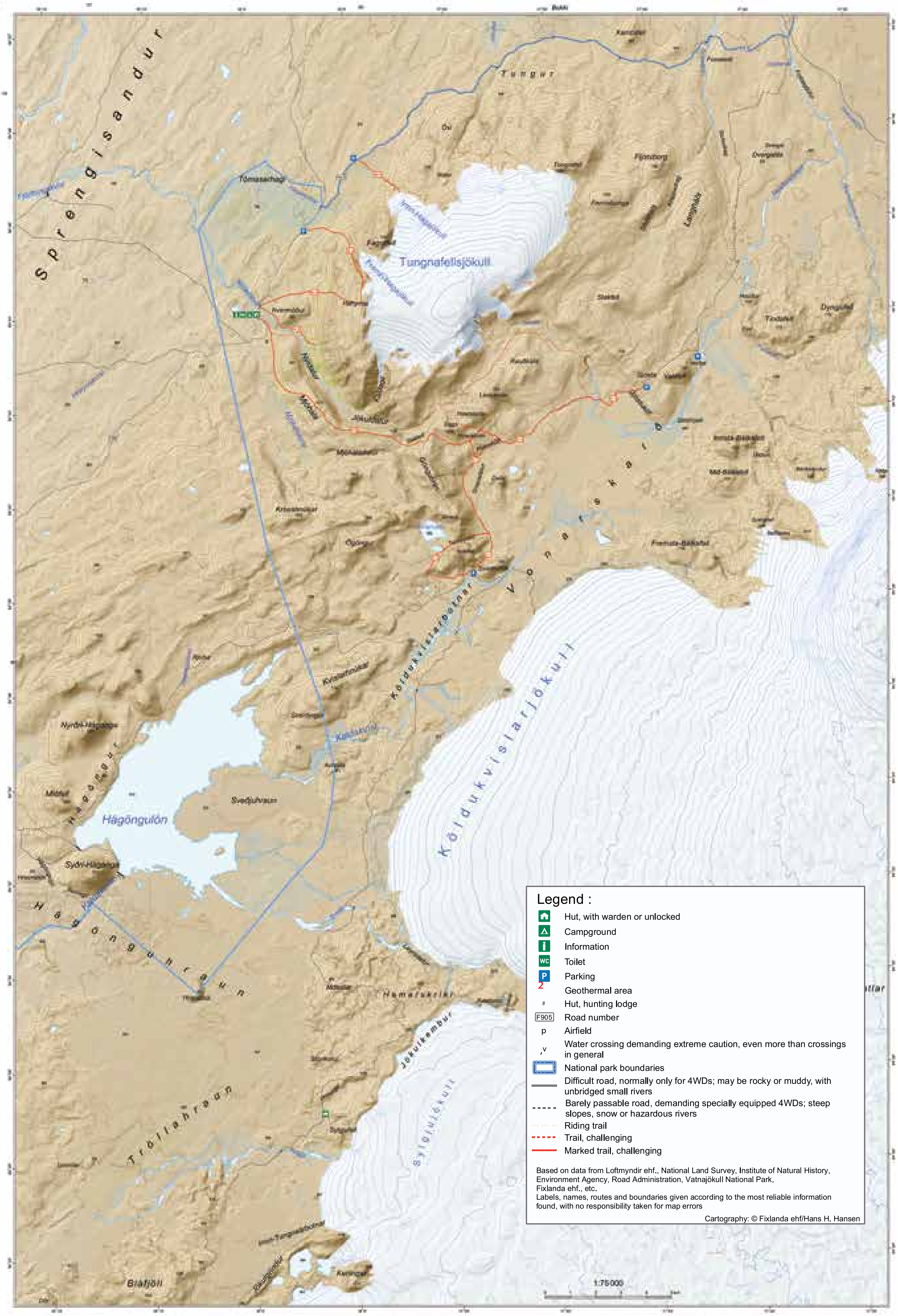

Skaftafellsfjöll
Skaftafellsheiði
Skaftafellsjökull
Morsárjökull
Svínafellsjökull
Svínafellsheiði
Skeiðarársandur
Morsárdalur
Kjós
Hafrafell
Skaftafellsstofa
Hótel Skaftafell



Skýringar :	Legend :
Merkt gönguleið	Marked walking trail
Tjaldsvæði	Campground
Veitingasala	Catering
Upplýsingar innanhúss	Information, indoors
Útsýni	Viewpoint
Athyglisverður staður	Place of interest
Áningarstaður	Rest area
Hjólastígur	Bicycle trail
Gisting	Lodging
Bílastæði	Parking
Eldsneytissala	Fuel station
Flugvöllur, lendingarstaður	Airfield
Vegur, bundið slitlag	Paved road
Vegur, malarborinn	Gravel road
Gönguleið fyrir hreyfihamlaða	Trail, for those with limited mobility
Ómerkt gönguleið, auðveld	Trail, easy
Merkt gönguleið, auðveld	Marked trail, easy
Ómerkt gönguleið, krefjandi	Trail, challenging
Merkt gönguleið, krefjandi	Marked trail, challenging
Ómerkt gönguleið, erfið	Trail, difficult

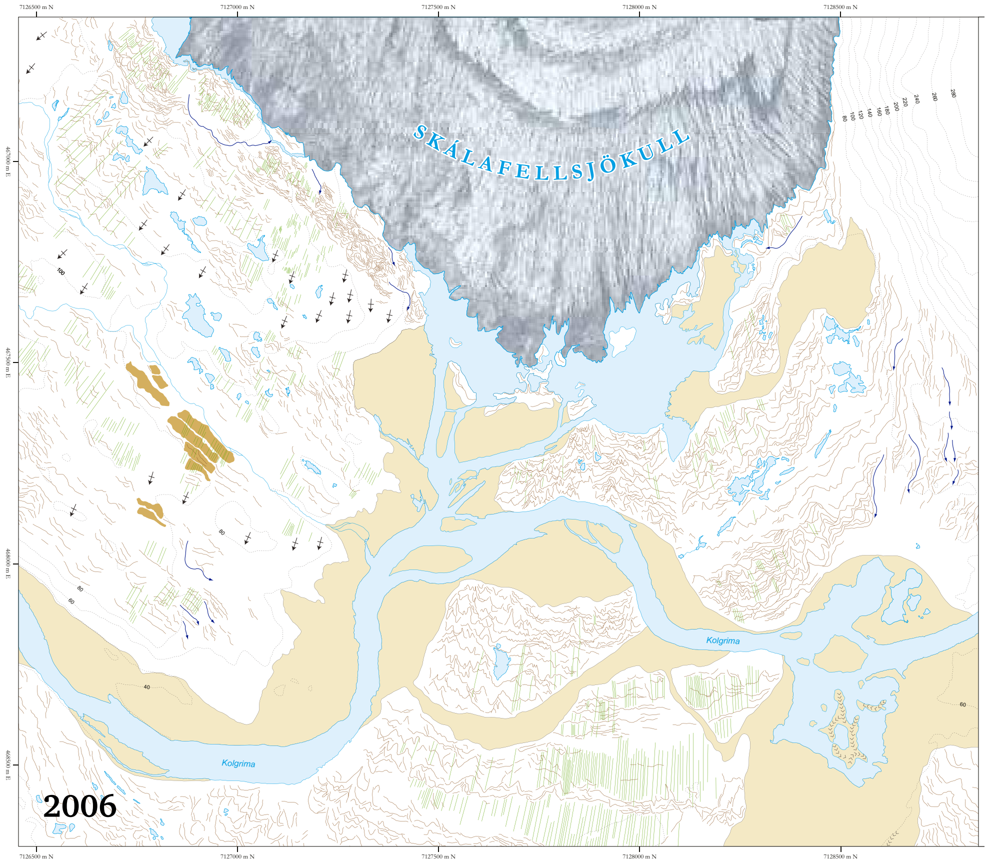
The Western Region

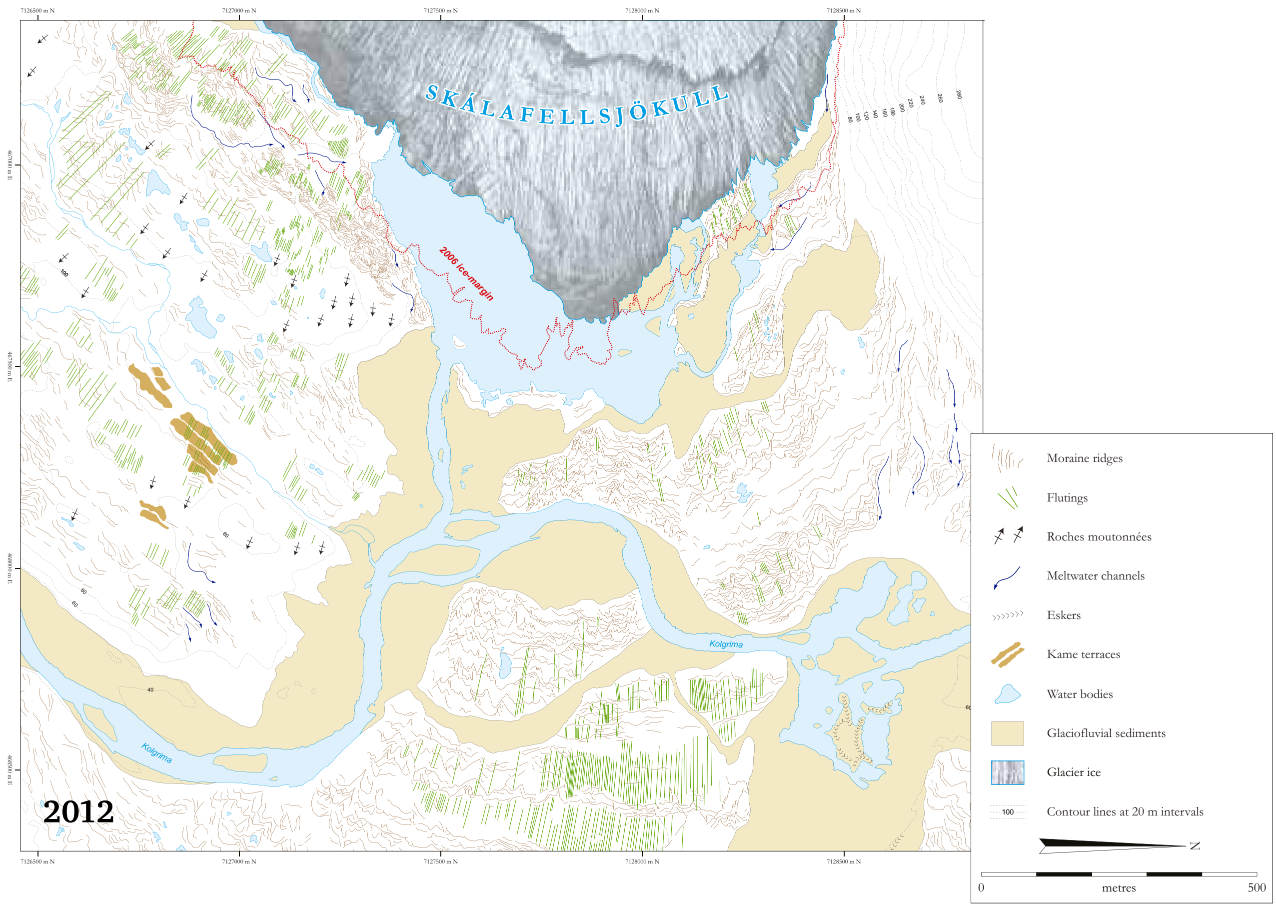



Sprengisandur
Tungnafellsjökull
Hágöngulón
Köldukvíslarjökull
Vonarskarð
Hágönguhraun
Tröllahraun
Legend :
Hut, with warden or unlocked
Campground
Information
Toilet
Parking
Geothermal area
Hut, hunting lodge
F905 Road number
Airfield
Water crossing demanding extreme caution, even more than crossings in general
National park boundaries
Difficult road, normally only for 4WDs; may be rocky or muddy, with unbridged small rivers
Barely passable road, demanding specially equipped 4WDs; steep slopes, snow or hazardous rivers
Riding trail
Trail, challenging
Marked trail, challenging
Based on data from Loftmyndir ehf., National Land Survey, Institute of Natural History, Environment Agency, Road Administration, Vatnajökull National Park, Fixlanda ehf., etc.
Labels, names, routes and boundaries given according to the most reliable information found, with no responsibility taken for map errors
Cartography: © Fixlanda ehf/Hans H. Hansen
1:75 000

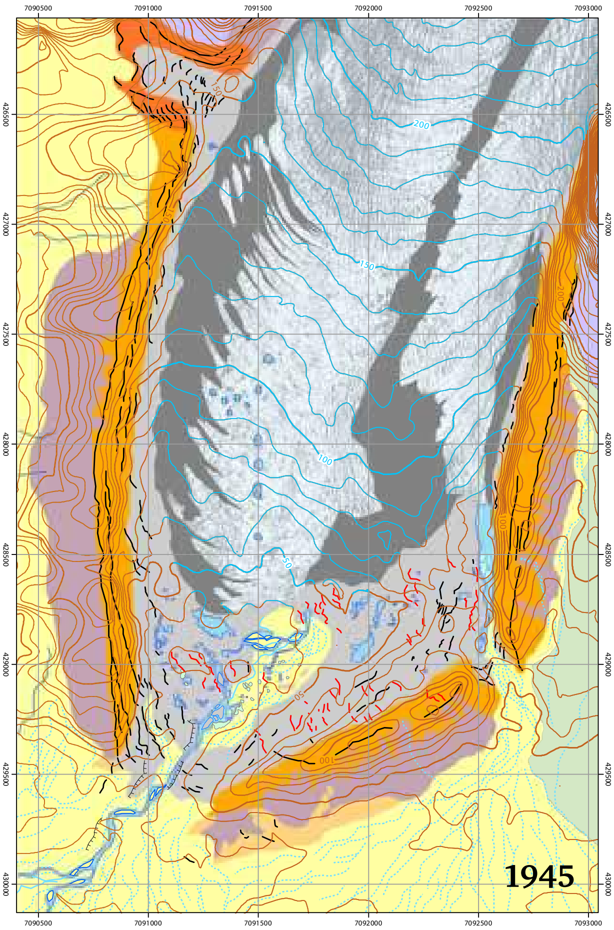
Appendix 1.3: Glacial geomorphology maps

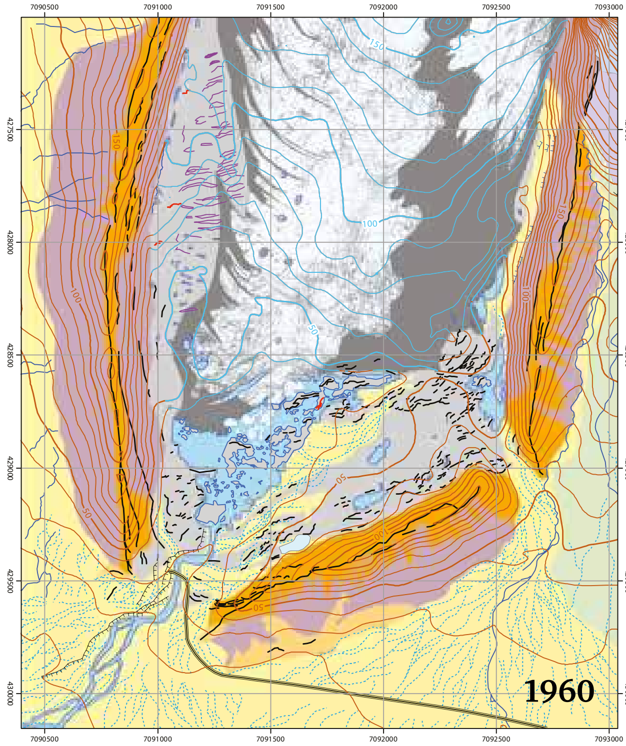
Skálafellsjökull. From Chandler et al., 2016a.

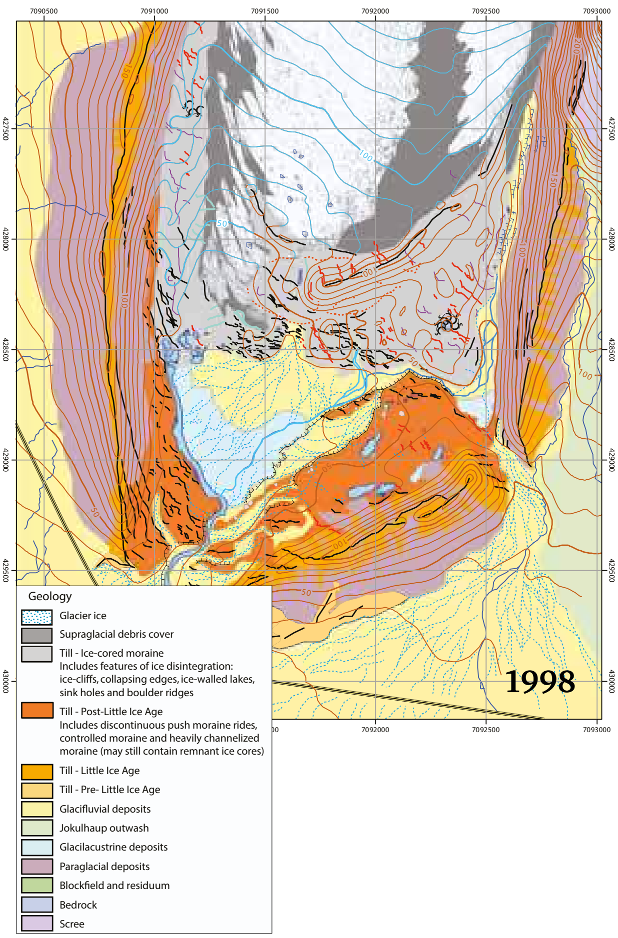


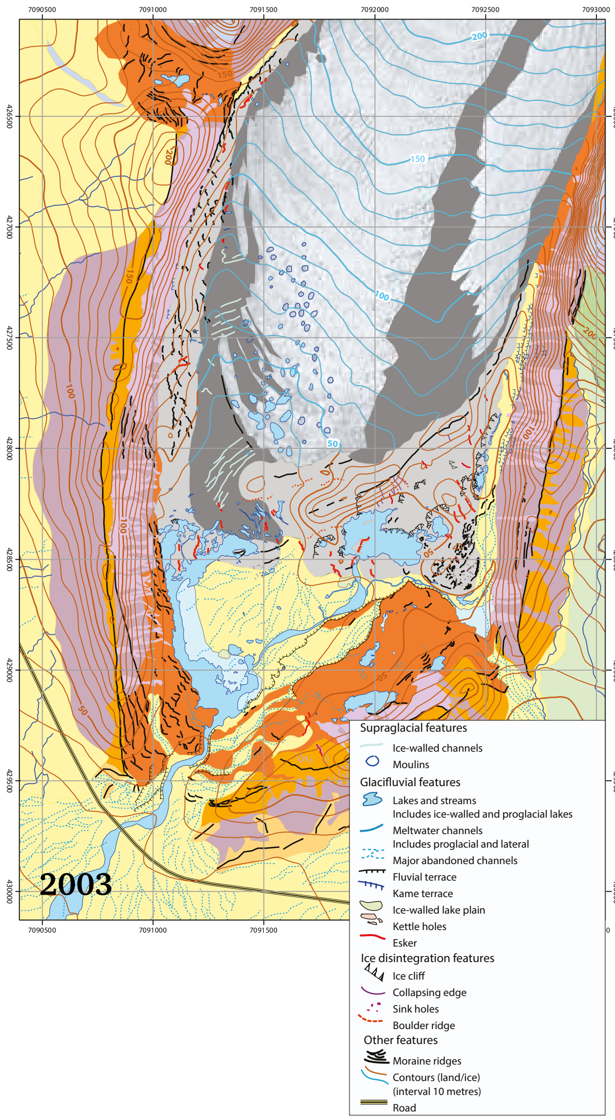


Kvíárjökull. From Bennett et al., 2010.

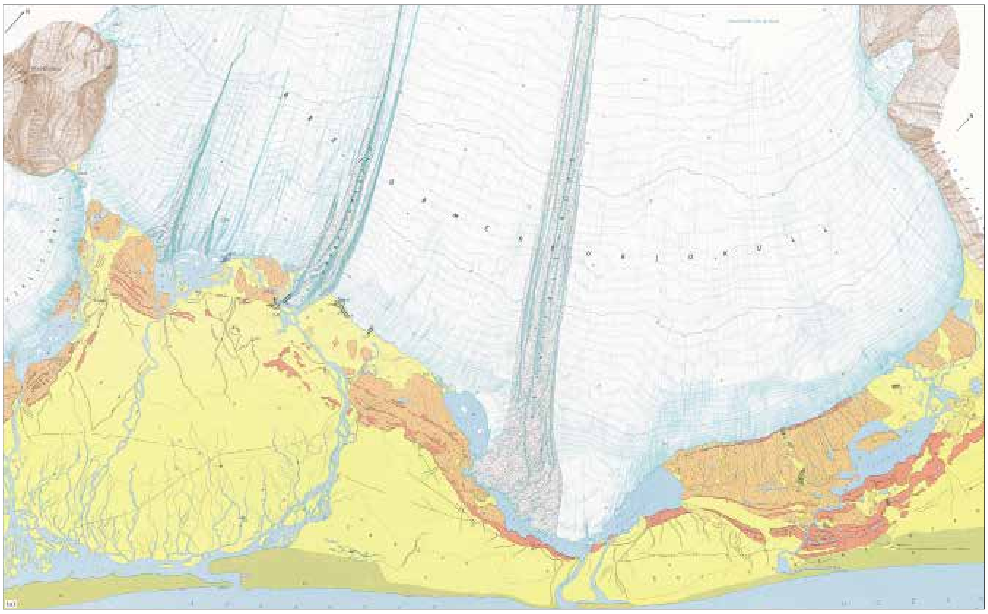


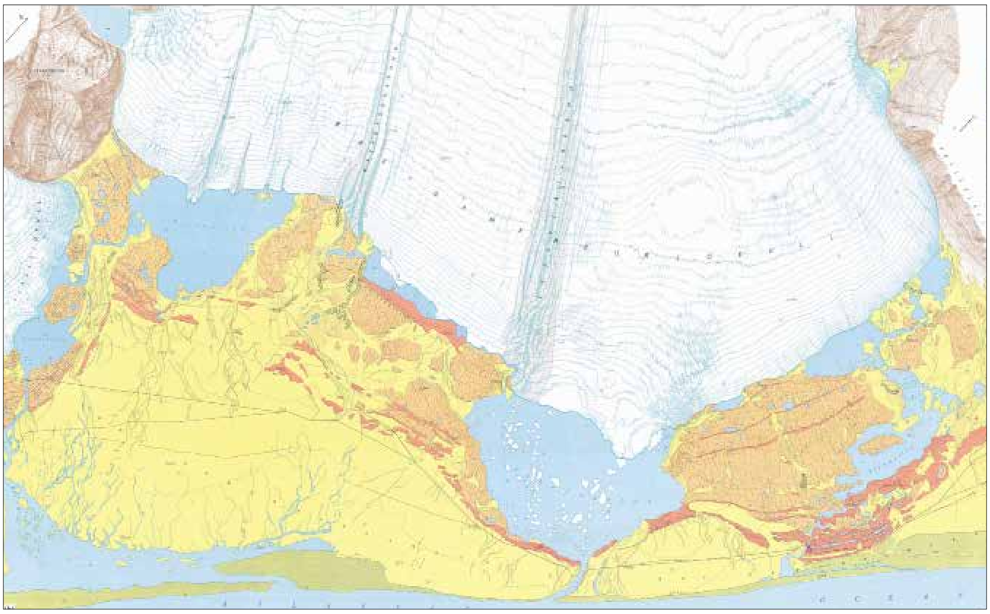


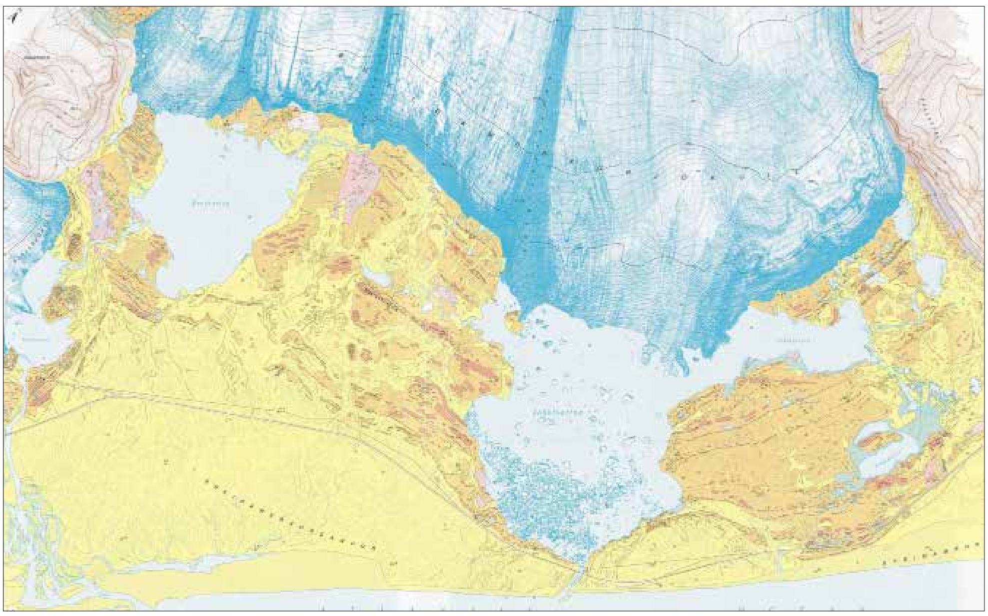




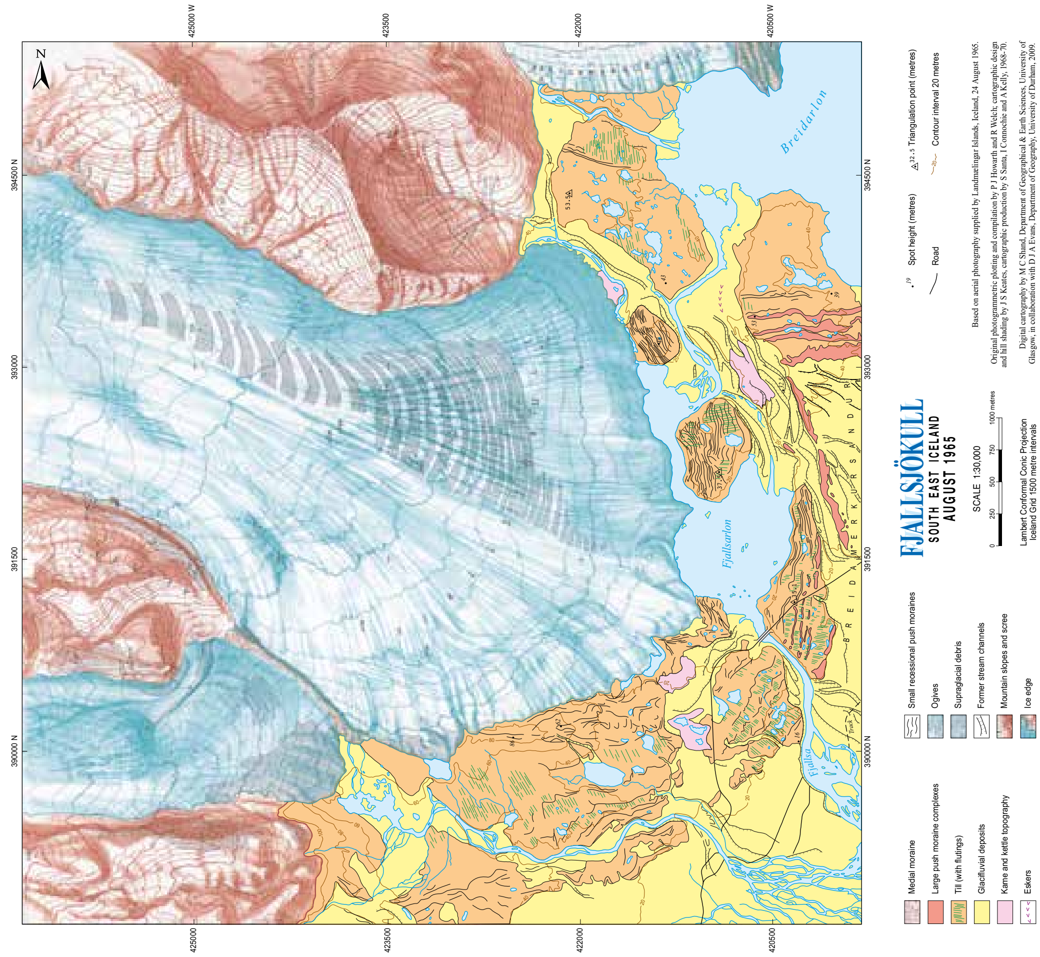
From Evans & Twigg, 2002.

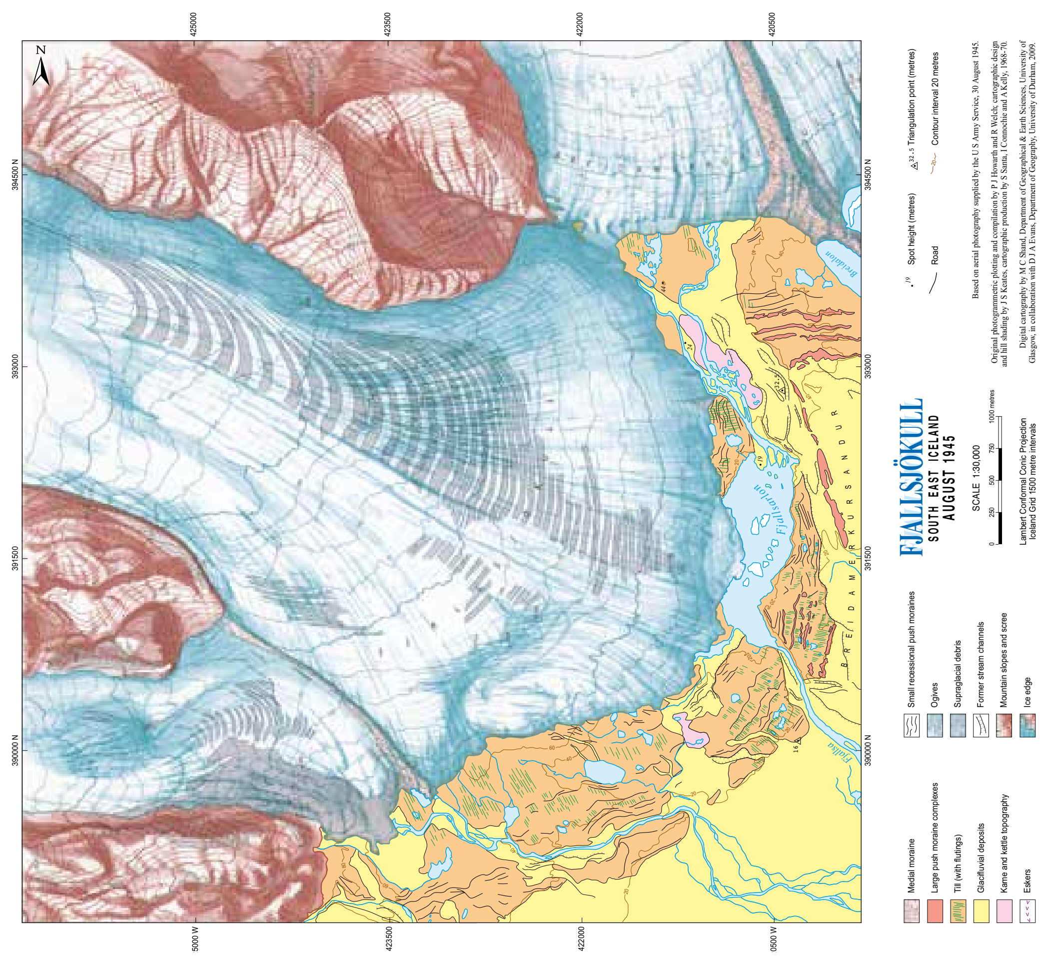




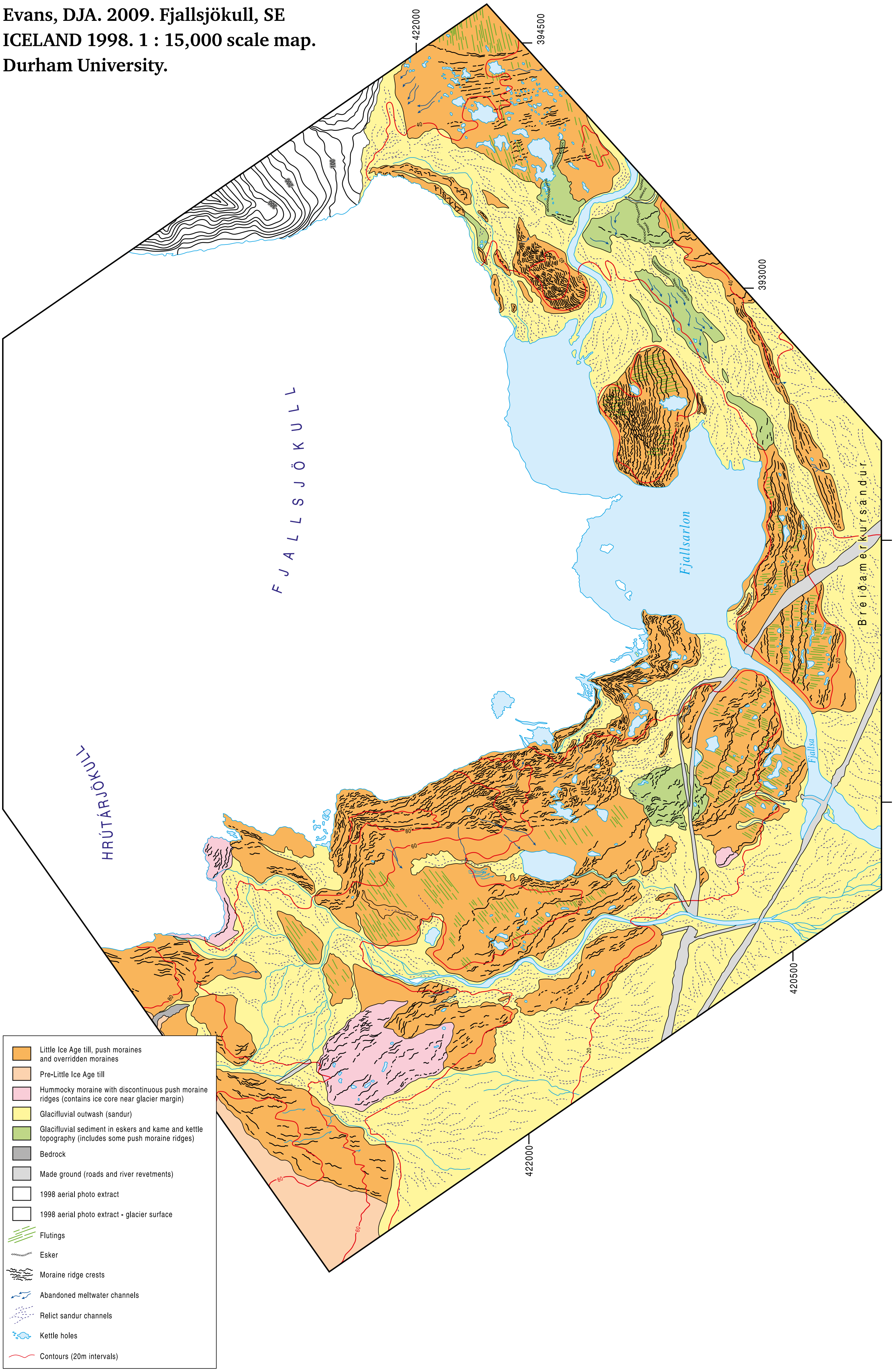


Evans et al., 2009

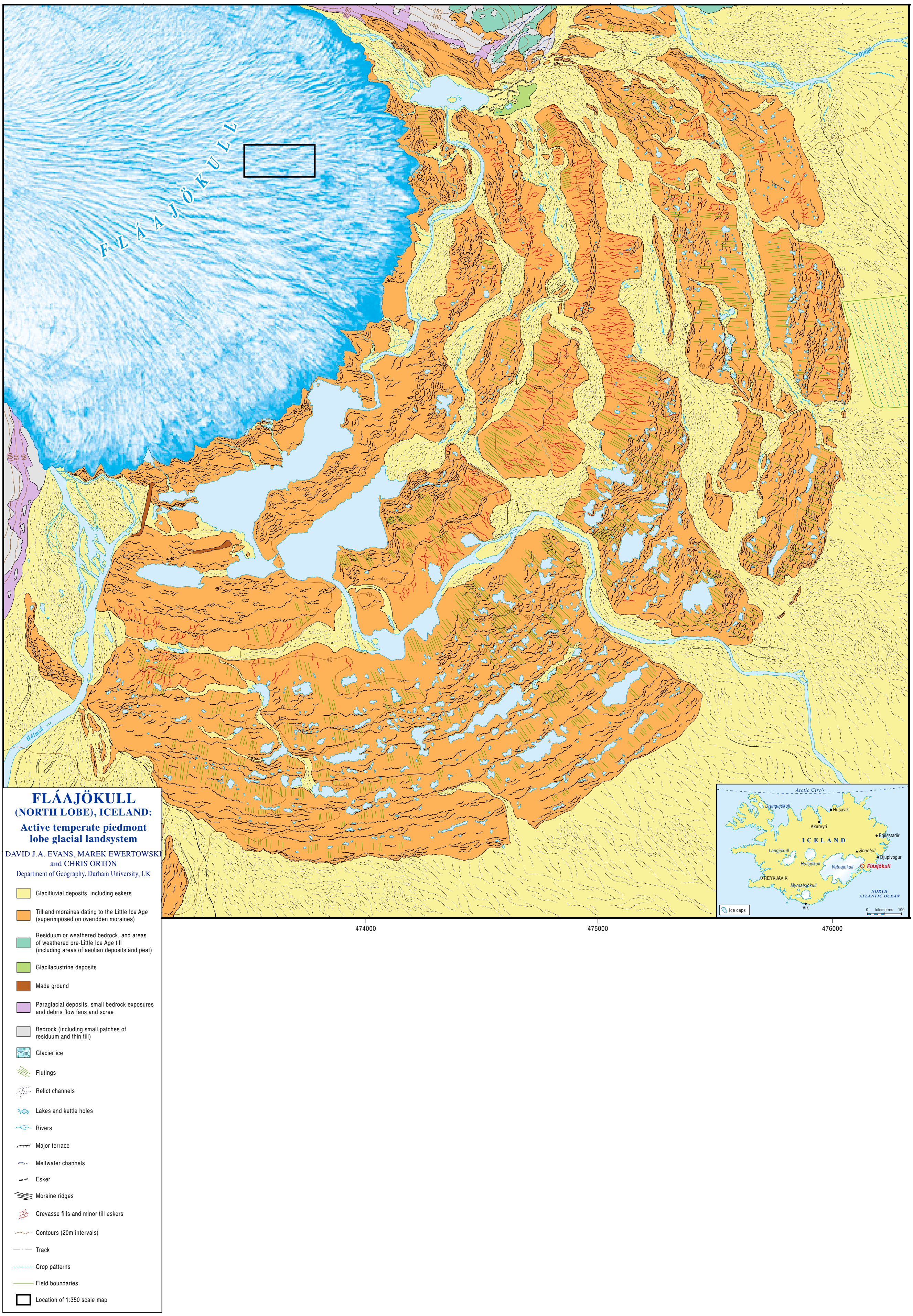




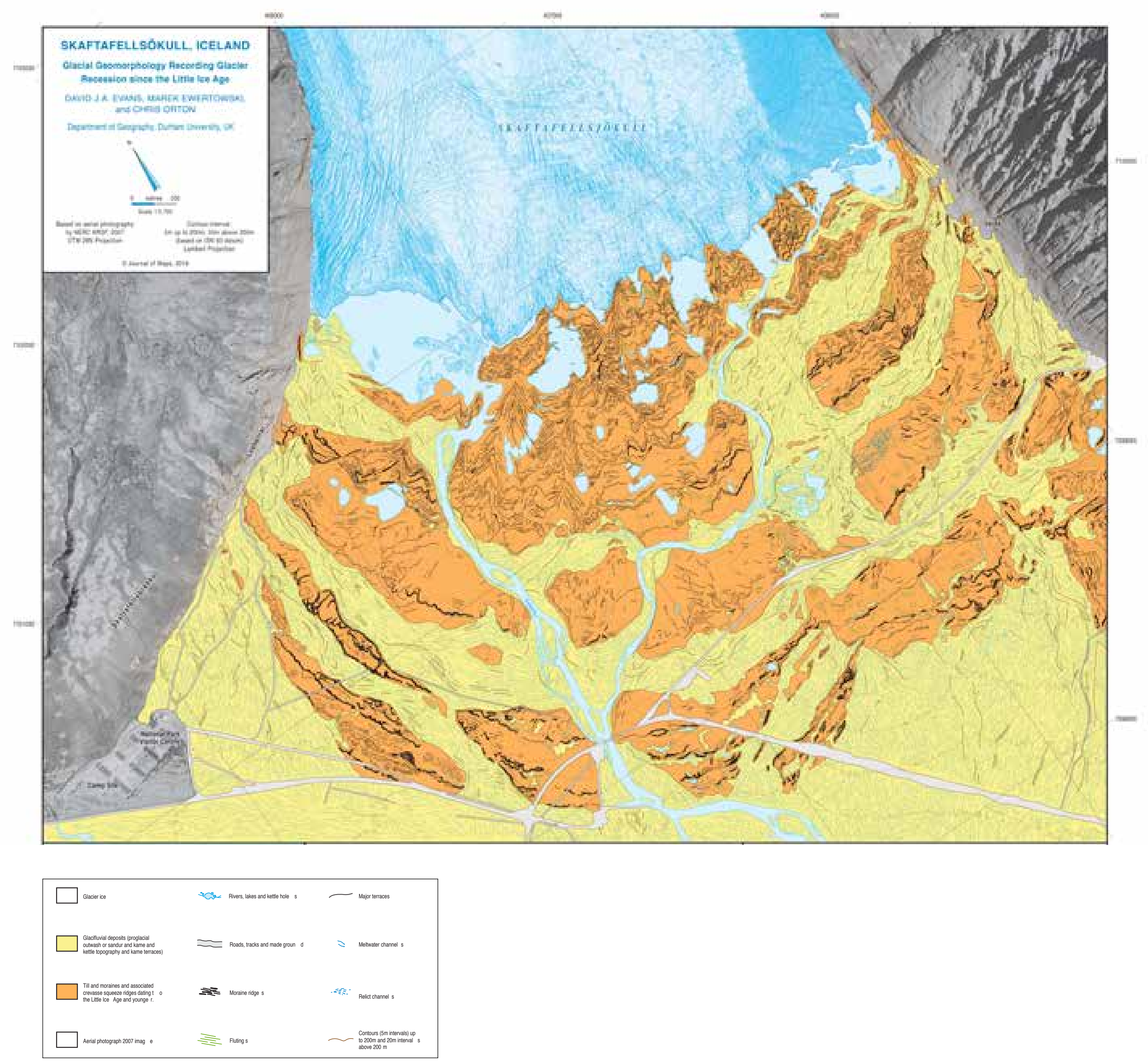
Evans, DJA. 2009. Fjallsjökull, SE ICELAND 1998. 1 : 15,000 scale map. Durham University.



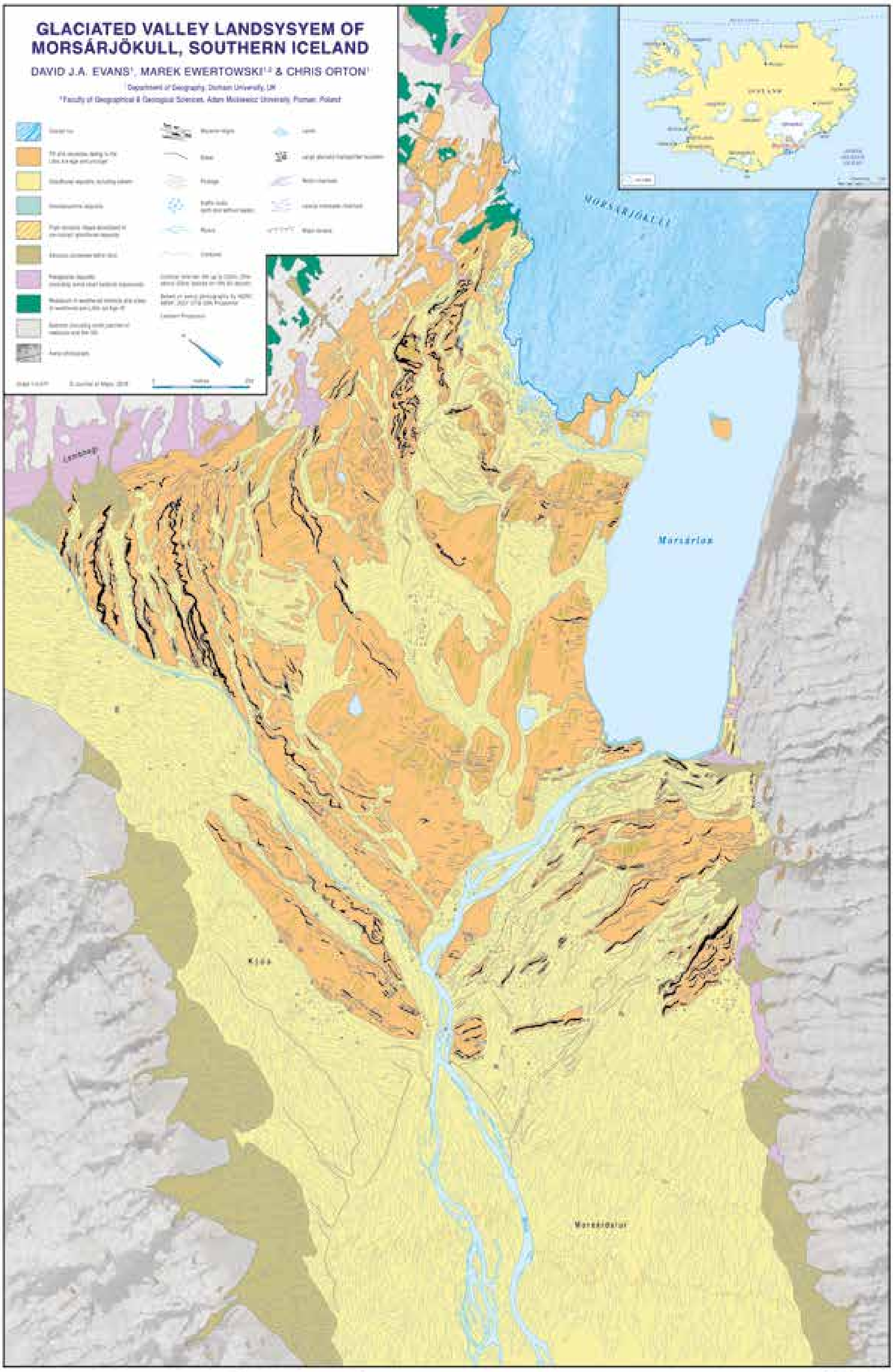
Evans et al., 2016.



Evans et al., 2016.



Evans et al., 2017.



Appendix 2: Inventory of Property

Appendix 2.1: Breeding birds

Gavia stellata	Red-throated diver
Podiceps auritus VU	Slavonian grebe
Fulmarus glacialis	Northern fulmar
Cygnus cygnus	Whooper swan
Anser brachyrhynchus	Pink-footed goose
Anser anser VU	Graylag goose
Branta leucopsis EN	Barnacle goose
Anas platyrhynchos	Mallard
Anas penelope	European widgeon
Anas crecca	European teal
Anas acuta	Northern pintail
Aythya fuligula	Tufted duck
Aythya marila	Greater scaup
Somateria mollissima	Common eider
Clangula hyemalis	Long-tailed duck
Histrionicus histrionicus LC	Harlequin duck
Bucephala islandica EN *	Barrow's Goldeneye
Mergus serrator	Red-breasted merganser
Mergus merganser VU	Common merganser
Haliaeetus albicilla EN **	White-tailed eagle
Falco columbarius	Merlin
Falco rusticolus VU	Gyrfalcon
Lagopus muta	Rock ptarmigan
Haematopus ostralegus	Eurasian oystercatcher
Charadrius hiaticula	Ringed plover
Pluvialis apricaria	Golden plover
Calidris maritima	Purple sandpiper
Calidris alpina	Dunlin
Gallinago gallinago	Common snipe
Scolopax rusticola	Eurasian woodcock
Limosa limosa islandica	Black-tailed godwit
Numenius phaeopus	Whimbrel
Tringa totanus	Redshank
Phalaropus lobatus	Red-necked phalarope
Phalaropus fulicarius EN **	Gray phalarope
Stercorarius parasiticus	Parasitic jaeger
Stercorarius skua	Great skua
Larus ridibundus	Black-headed gull
Larus marinus VU	Great black-backed gull
Larus argentatus	Herring gull
Nyctea scandiaca CR *	Snowy owl
Asio flammeus VU	Short-eared owl
Sterna paradisaea	Arctic tern
Anthus pratensis	Meadow pipit
Motacilla alba	White wagtail
Regulus regulus	Goldcrest
Troglodytes troglodytes	Eurasian wren
Oenanthe oenanthe	Northern wheatear
Turdus merula *	Common blackbird
Turdus iliacus	European redwing
Corvus corax VU	Raven
Fringilla montifringilla	Brambling
Carduelis flammea	Redpoll
Plectrophenax nivalis	Snow bunting

Species status: CR= Critically Endangered; EN= Endangered; VU= Vulnerable; LC= Least Concern; DD= Data Deficient

* Occasional breeder ** Previous breeder

Appendix 2.2: Vascular Plants

Seedless plants (club mosses, horsetails and ferns)

Lycopodiacea	
Diphasiastrum alpinum	Alpine clubmoss
Huperzia appressa	Appalachian firmoss
Lycopodium annotinum ssp. Alpestre	Interrupted clubmoss
Selqaginellaceae	
Selaginella selaginoides	Lesser clubmoss
Equisetaceae	
Equisetum arvense	Field horsetail
Equisetum arvense ssp. Alpestre	
Equisetum hyemale	Rough horsetail
Equisetum palustre	Marsh horsetail
Equisetum pratense	Shady horsetail
Equisetum variegatum	Variegated horsetail
Ophioglossaceae	
Botrychium lunaria	Common moonwort
Botrychium minganense	Mingan moonwort
Botrychium simplex	Glossy moonwort
Ophioglossum azoricum LC	Small adder's tongue
Botrychium simplex var. Tenebrosum DD	Little grapefern
Botrychium lanceolatum	Lance-leaved moonwort
Asplenaceae	
Asplenium trichomanes EN	Maidenhair spleenwort
Asplenium viride LC	Green spleenwort
Woodsiaceae	
Woodsia alpina	Alpine woodsia
Woodsia ilvensis	Oblong woodsia
Cystopteridaceae	
Cystopteris fragilis	Brittle bladder-fern
Gymnocarpium dryopteris	Oak fern
Dryopteridaceae	
Dryopteris filix-mas	Male-fern
Athyraceae	
Athyrium distentifolium	Alpine lady-fern
Polystichum lonchitis	Holly fern
Polypodiaceae	
Polypodium vulgare	Common polypody

Seed Plants

Coniferopsida/Conifers

Cupressaceae	
Juniperus communis ssp. Communis	Common juniper
Juniperus communis ssp. Nana	Dwarf juniper

Magnoliopsida/Dicots

Dicots

Salicaceae	
Salix herbacea	Dwarf willow
Salix lanata	Woolly willow
Salix phylicifolia	Tea-leaved willow
Salix viminalis *	Basket willow
Betulaceae	
Betula nana	Dwarf birch
Betula pubescens	Downy birch
Polygonaceae	
Bistorta vivipara	Alpine bistort
Koenigia islandica	Iceland-purslane
Oxyria digyna	Mountain sorrel
Polygonum aviculare	Knotgrass
Rheum rhabarbarum **	Rhubarb
Rumex acetosa	Common sorrel
Rumex acetosella	Sheep's sorrel
Rumex longifolius	Northern dock
Montiaceae	
Montia fontana	Blinks
Plumbaginaceae	
Armeria maritima	Thrift
Caryophyllaceae	
Arenaria norvegica	Arctic sandwort
Cerastium alpinum	Alpine mouse-ear
Cerastium cerastoides	Starwort mouse-ear
Cerastium fontanum	Common mouse-ear
Cerastium glomeratum	Sticky mouse-ear
Cerastium nigrescens	Arctic mouse-ear
Honckenya peploides	Sea sandwort
Lychnis flos-cuculi	Alpine catchfly
Minuartia biflora	Northern sandwort
Minuartia rubella	Mountain sandwort
Minuartia stricta	Teesdale sandwort
Sagina caespitosa LC	Tufted pearlwort
Sagina nivalis	Snow pearlwort
Sagina nodosa ssp. Borealis	Knotted pearlwort
Sagina procumbens	Procumbent pearlwort
Sagina saginoides	Alpine pearlwort
Silene acaulis	Moss campion
Silene uniflora	Sea campion
Spergula arvensis	Corn spurrey
Stellaria crassifolia	Fleshy stitchwort
Stellaria graminea *	Lesser stitchwort
Stellaria humifusa	Saltmarsh stitchwort
Stellaria media	Common chickweed
Viscaria alpina	Alpine catchfly
Ranunculaceae	

Species status: CR= Critically Endangered; EN= Endangered; VU= Vulnerable; LC= Least Concern; DD= Data Deficient

* Naturalised ** Casual *** Invasive

*Anemone nemorosa **	Wood anemone
Caltha palustris	Marsh-marigold
Ranunculus confervoides	Thread-leaved water-crowfoot
Ranunculus glacialis	Glacier buttercup
Ranunculus hyperboreus	Arctic buttercup
Ranunculus pygmaeus	Pigmy buttercup
Ranunculus reptans	Creeping spearwort
Ranunculus subborealis	Arctic buttercup
Ranunculus subborealis ssp. Pumilus	Arctic buttercup
Ranunculus subborealis ssp. Villosus	Meadow buttercup
Thalictrum alpinum	Alpine meadow-rue
Papaveraceae	
Papaver radicatum	Arctic poppy
Brassicaceae	
Arabidopsis lyrata ssp. Petrea	Northern rock-cress
Arabis alpina	Alpine rock-cress
Capsella bursa-pastoris	Shepherd's purse
Cardamine bellidifolia	Alpine bittercress
Cardamine hirsuta	Hairy bittercress
Cardamine pratensis ssp. Angustifolia	Cuckoo flower
Cochlearia groenlandica	Greenland scurvygrass
Cochlearia officinalis ssp. Islandica	Common scurvygrass
Draba incana	Hoary whitlowgrass
Draba nivalis	Snow whitlowgrass
Draba norvegica	Rock whitlowgrass
Draba oxycarpa	Alpine whitlowgrass
Draba verna	Common whitlowgrass
Rorippa islandica	Northern yellowcress
Subularia aquatica	Awlwort
Crassulaceae	
Rhodiola rosea	Roseroot
Sedum acre	Biting stonecrop
Sedum annuum	Annual stonecrop
Sedum villosum	Hairy stonecrop
Parnassiaceae	
Parnassia palustris	Grass-of-Parnassus
Saxifragaceae	
Saxifraga aizoides	Yellow saxifrage
Saxifraga cernua	Drooping saxifrage
Saxifraga cespitosa	Tufted saxifrage
Saxifraga cotyledon	Pyramidal saxifrage
Saxifraga hirculus	Marsh saxifrage
Saxifraga hypnoides	Mossy saxifrage
Saxifraga nivalis	Alpine snow saxifrage
Saxifraga oppositifolia	Purple saxifrage
Saxifraga paniculata	Silver saxifrage
Saxifraga rivularis	Alpine brook saxifrage
Saxifraga rosacea	Irish saxifrage
Saxifraga stellaris	Starry saxifrage
Saxifraga tenuis	Slender snow saxifrage

Rosaceae	
Alchemilla alpina	Alpine lady's mantle
Alchemilla faeroensis	Faeroeic lady's mantle
Alchemilla filicaulis	Hairy lady's mantle
Alchemilla glomerulans	Clustered lady's mantle
Alchemilla wichurae	Rock lady's mantle
Argentina anserina	Silverweed
Comarum palustre	Marsh cinquefoil
Dryas octopetala	Mountain avens
Filipendula ulmaria	Meadowsweet
Fragaria vesca	Wild strawberry
Geum rivale	Water avens
Potentilla crantzii	Alpine cinquefoil
Rubus saxatilis	Stone bramble
Sibbaldia procumbens	Creeping sibbaldia
Fabaceae	
Lathyrus japonicus ssp. Maritimus	Beach pea
Lathyrus pratensis	Meadow vetchling
*Lupinus nootkatensis ****	Nootka lupin
*Trifolium hybridum **	Alsike clover
*Trifolium pratense **	Red clover
Trifolium repens	White clover
Vicia cracca	Tufted vetch
Geraniaceae	
Geranium sylvaticum	Wood crane's-bill
Linaceae	
Linum catharticum	Fairy flax
Violaceae	
Viola canina	Heath dog-violet
Viola epipsila	Northern marsh violet
Viola palustris	Marsh violet
Viola tricolor	Wild pansy
Onagraceae	
Chamerion angustifolium	Rosebay willowherb
Chamerion latifolium	Arctic riverbeauty
Epilobium alsinifolium	Chickweed willowherb
Epilobium anagallidifolium	Alpine willowherb
Epilobium collinum	Cliff willowherb
Epilobium hornemannii	Hornemann's willowherb
Epilobium lactiflorum	Milky willowherb
Epilobium palustre	Marsh willowherb
Haloragaceae	
Myriophyllum alterniflorum	Alternate water-milfoil
Apiaceae	
Angelica archangelica	Garden angelica
Angelica sylvestris	Wild angelica
Carum carvi	Caraway
Pyrolaceae	
Pyrola grandiflora	Arctic wintergreen
Orthilia secunda	One-sided wintergreen
Ericaceae	
Arctostaphylos uva-ursi	Bearberry
Calluna vulgaris	Heather

Harrimanella hypnoides	Moss bell heather
Loiseleuria procumbens	Trailing azalea
Orthilia secunda	Serrated wintergreen
Vaccinium myrtillus	Bilberry
Vaccinium uliginosum	Bog bilberry
Empetraceae	
Empetrum nigrum	Crowberry
Primulaceae	
Trientalis europaea	Chickweed wintergreen
Gentianaceae	
Comastoma tenellum	Slender gentian
Gentiana nivalis	Alpine gentian
Gentianella amarella ssp. Septentrionalis	Autumn gentian
Gentianella aurea	Golden dwarfgentian
Gentianella campestris ssp. Islandica	Field gentian
Lomatogonium rotatum	Marsh felwort
Rubiaceae	
Galium boreale	Northern bedstraw
Galium normanii	Slender bedstraw
Galium uliginosum	Fen bedstraw
Galium verum	Lady's bedstraw
Callitricaceae	
Callitriche hermaphroditica	Autumnal water-starwort
Boraginaceae	
Myosotis arvensis	Field forget-me-not
Lamiaceae	
Lamium album *	White dead-nettle
Prunella vulgaris	Selfheal
Thymus praecox ssp. Arcticus	Wild thyme
Scrophulariaceae	
Limosella aquatica	Mudwort
Lentibulariaceae	
Pinguicula vulgaris	Common butterwort
Orobanchaceae	
Bartsia alpina	Alpine bartsia
Euphrasia frigida	Cold eyebright
Euphrasia stricta var. Tenuis	Drug eyebright
Pedicularis flammea	Red-tipped lousewort
Rhinanthus minor	Yellow-rattle
Rhinanthus minor ssp. Groenlandicus	Little yellow-rattle
Plantaginaceae	
Veronica alpina	Alpine speedwell
Veronica fruticans	Rock speedwell
Veronica officinalis	Common speedwell
Veronica scutellata	Marsh speedwell
Veronica serpyllifolia	Thyme-leaved speedwell
Callitriche palustris	Vernal water-starwort
Hippuris vulgaris	Mare's tail
Plantago maritima	Sea plantain
Caprifoliaceae	
Valeriana officinalis *	Common valerian

Campanulaceae	
Campanula rotundifolia	Harebell
Asteraceae	
Achillea millefolium	Yarrow
Achillea ptarmica	Sneezewort
Antennaria alpina	Alpine everlasting
Erigeron borealis	Alpine fleabane
Erigeron humilis	Arctic alpine fleabane
Erigeron uniflorus	Oneflower fleabane
Gnaphalium uliginosum	Marsh cudweed
Hieracium acidotoides	
Hieracium alpinum	Alpine hawkweed
Hieracium anglicum	English hawkweed
Hieracium aquiliforme	Hearth hawkweed
Hieracium arctocerinthe	
Hieracium cretatum	
Hieracium demissum	
Hieracium holopleurum	Bush hawkweed
Hieracium lygistodon	
Hieracium macrocomum	
Hieracium microdon	
Hieracium phrixoclonum	
Hieracium pullicalicitum	
Hieracium stictophyllum	Stain-leaved hawkweed
Hieracium stroemfeltii	
Hieracium thaectolepium	Hillside hawkweed
Leontodon autumnalis	Autumn hawkbit
Omalotheca norvegica	Highland cudweed
Omalotheca supina	Dwarf cudweed
Omalotheca sylvatica	Heath cudweed
Pilosella islandica	Icelandic hawkweed
Taraxacum	Dandelion
Tripleurospermum maritimum ssp.Phaeocephalum	Sea mayweed
Liliopsida / Monocots	
Potamogetonaceae	
Potamogeton alpinus	Red pondweed
Potamogeton berchtoldii	Small pondweed
Potamogeton gramineus	Various-leaved pondweed
Potamogeton praelongus	Long-stalked pondweed
Stuckenia filiformis	Slender-leaved pondweed
Zannichellia palustris	Horned pondweed
Typhaceae	
Sparganium hyperboreum	Northern bur-reed
Sparganium natans	Least bur-reed
Tofeldiaceae	
Tofieldia pusilla	Scottish asphodel
Melanthiaceae	
Paris quadrifolia LC	Herb-Paris
Orchidaceae	
Coeloglossum viride	Frog orchid
Corallorhiza trifida	Coralroot orchid
Dactylorhiza maculata	Heath spotted orchid

Listera cordata Lesser Twayblade
Listera ovata LC Common twayblade
Platanthera hyperborea Northern green orchid
Pseudorchis straminea Small white orchid
Juncaceae
Juncus alpinoarticulatus Alpine rush
Juncus arcticus Arctic rush
Juncus arcticus ssp. Intermedius
Juncus articulatus Jointed rush
Juncus biglumis Two-flowered rush
Juncus bufonius Toad rush
Juncus bulbosus Bulbous rush
Juncus castaneus Chestnut rush
Juncus ranarius Frog rush
Juncus trifidus Three-leaved rush
Juncus triglumis Three-flowered rush
Luzula arcuata Curved wood-rush
Luzula confusa Northern woodrush
Luzula multiflora Heath wood-rush
Luzula spicata Spiked wood-rush
Luzula sudetica Sudetan wood-rush
Juncaginaceae
Triglochin palustris Marsh Arrowgrass
Cyperaceae
Carex atrata Black alpine-sedge
Carex bicolor Bicoloured sedge
Carex bigelowii ssp. Rigida Stiff sedge
Carex brunnescens Brownish sedge
Carex canescens Silvery sedge
Carex capillaris ssp. Capillaris Hair sedge
Carex capillaris ssp. Fuscidula Hair sedge
Carex capitata Capitate sedge
Carex chordorrhiza String sedge
Carex diandra Lesser tussock-sedge
Carex dioica Dioecious sedge
Carex glacialis Glacier sedge
Carex glareosa Lesser saltmarsh sedge
Carex krausei Krause's sedge
Carex lachenalii Hare's-foot sedge
Carex limosa Common bog-sedge
Carex lyngbyei Lyngbye's sedge
Carex maritima Curved sedge
Carex microglochin Bristle sedge
Carex nardina Nard sedge
Carex nigra Common sedge
Carex norvegica Close-headed alpine-sedge
Carex panicea Carnation sedge
Carex rariflora Mountain bog-sedge
Carex rostrata Bottle sedge
Carex rufina Reddish sedge
Carex rupestris Rock sedge
Carex saxatilis Russet sedge
Carex vaginata Sheathed sedge
Carex viridula Small-fruited yellow-sedge
Eleocharis acicularis Needle spike-rush
Eleocharis palustris ssp. Palustris Common spike-rush
Eleocharis quinqueflora Few-flowered spike-rush
Eleocharis uniglumis Slender spike-rush
Eriophorum angustifolium Common cottongrass
Eriophorum scheuchzeri Scheuchzer's cottongrass
Kobresia myosuroides Bellard's kobresia
Trichophorum caespitosum Deergrass
Poaceae
Agrostis capillaris Common bent
Agrostis stolonifera Creeping bent
Agrostis vinealis Brown bent
Alopecurus aequalis Orange Foxtail
Alopecurus geniculatus Marsh foxtail
Alopecurus pratensis * Meadow foxtail
Anthoxanthum odoratum Sweet vernal grass
Avenella flexuosa Wavy hair-grass
Calamagrostis neglecta Narrow small-reed
Catabrosa aquatica Whorlgrass
Dactylis glomerata Cock's-foot
Deschampsia alpina Alpine hair-grass
Deschampsia cespitosa Tufted hair-grass
Elytrigia repens Common couch
Festuca rubra ssp. Richardsonii Arctic fescue
Festuca rubra ssp. Rubra * Red fescue
Festuca vivipara Viviparous sheep's-fescue
Hierochloe odorata Holygrass
Leymus arenarius Lyme-grass
Milium effusum Wood millet
Nardus stricta Mat-grass
Phippsia algida Icegrass
Phleum alpinum Alpine cat's-tail
Phleum pratense Timothy
Poa alpina Alpine meadow-grass
Poa annua Annual meadow-grass
Poa flexuosa Wavy meadow-grass
Poa glauca Glaucous meadow-grass
Poa nemoralis Wood meadow-grass
Poa pratensis ssp. Alpigena Smooth meadow-grass
Poa trivialis Rough meadow-grass
Poa x jemtlandica Jemtland meadow-grass
Puccinellia maritima Northern saltmarsh-grass
Secale cereale ** Rye
Trisetum spicatum ssp. Spicatum Narrow false oat
Trisetum triflorum Three-flowered false oat

Appendix 2.3: Bryophytes

Marchantyophyta/Liverworts

Anastrophyllum minutum	Comb notchwort
Aneura pinguis	Small greasewort
Anthelia julacea	Alpine silverwort
Anthelia juratzkana	Juratzka's silverwort
Asterella gracilis	Graceful asterella
Barbilophozia atlantica	Atlantic pawwort
Barbilophozia hatcheri	Hatcher's pawwort
Barbilophozia kunzeana	Kunze's pawwort
Barbilophozia lycopodioides	Greater pawwort
Barbilophozia quadriloba	Four-fingered pawwort
Blasia pusilla	Common kettlewort
Calypogeia sphagnicola	Bog pouchwort
Cephalozia bicuspidata	Two-horned pincewort
Cephalozia pleniceps	Blunt pincewort
Cephaloziella divaricata	Common threadwort
Cephaloziella hampeana	Hampe's threadwort
Cephaloziella varians	Fann ekkert
Diphyscium foliosum	Nut-moss
Diplophyllum albicans	Common fold-leaf liverwort
Diplophyllum taxifolium	Alpine earwort
Fossombronia foveolata	Pitted frillwort
Frullania dilatata	Dilated scalewort
Frullania tamarisci	Tamarisk scalewort
Gymnomitrion apiculatum	Pointed frostwort
Gymnomitrion concinnatum	Braided frostwort
Gymnomitrion corallioides	Coral frostwort
Harpanthus flotovianus	Great mountain plapwort
Hygrobiella laxifolia	Lax notchwort
Jungermannia borealis	Northern flapwort
Jungermannia exsertifolia	Cordate flapwort
Jungermannia gracillima	Crenulated flapwort
Jungermannia hyalina	Transparent flapwort
Jungermannia obovata	Egg flapwort
Jungermannia pumila	Dwarf flapwort
Jungermannia sphaerocarpa	Round-fruited flapwort
Leiocolea bantriensis	Bantry notchwort
Leiocolea gillmanii	Gillman's notchwort
Leiocolea heterocolpos	Ragged notchwort
Lejeunia cavifolia	Micheli's least pouncewort
Lophozia debiliformis	Weak notchwort
Lophozia excisa	Capitate notchwort
Lophozia grandiretis	Purple-lobed notchwort
Lophozia obtusa	Obtuse notchwort
Lophozia sudetica	Hill notchwort
Lophozia ventricosa	Tumid notchwort
Lophozia wenzelii	Wenzel's notchwort
Marchantia polymorpha	Common liverwort
Marsupella adusta	Schorched rustwort
Marsupella brevissima	Snow rustwort
Marsupella condensata	Compact rustwort
Nardia breidleri	
Nardia geoscyphus	Book flapwort
Odontoschisma macounii	Earth-cup flapwort
Pellia neesiana	Macoun's flapwort
Peltolepis quadrata	Ring pellia
Plagiochila porelloides	
Pleurocladula albescens	Lesser featherwort
Preissia quadrata	Snow threadwort
	Narrow mushroom-headed
Ptilidium ciliare	liverwort
Radula complanata	Ciliated fringewort
Riccia beyrichiana	Even scalewort
Sauteria alpina	Purple crystalwort
Scapania brevicaulis	Snow lungwort
Scapania calcicola	Short-stemmed earwort
Scapania curta	Calcicolous earwort
Scapania cuspiduligera	Least earwort
Scapania hyperborea	Untidy earwort
Scapania irrigua	
Scapania lingulata	Heath earwort
Scapania mucronata	Tongue earwort
Scapania obcordata	
Scapania paludosa	Patch earwort
Scapania scandica	Floppy earwort
Scapania subalpina	Norwegian earwort
Scapania undulata	Northern earwort
Tritomaria polita	Water earwort
Tritomaria quinquedentata	Flush notchwort
Tritomaria scitula	Lyon's notchwort
	Mountain notchwort

Bryophyta/True mosses

Andraeaceae	
Andreaea rupestris	Black rock-moss
Bryaceae	
Abietinella abietina	Fir-tamarisk moss
Abietinella abietina	Fir-tamarisk moss
Amblyodon dealbatus	Short-tooth hump-moss
Amblystegium serpens	Creeping feather-moss
Amphidium lapponicum	Lapland yoke-moss
Amphidium mougeotii	Mougeot's yoke-moss
Anoectangium aestivum	Summer-moss
Anomobryum julaceum	Slender silver-moss
Aongstroemia longipes	Sprig-moss
Archidium alternifolium	Clay earth-moss
Arctoa anderssonii	Andersson's arctoa moss
Arctoa fulvella	Arctic fork-moss
Aulacomnium palustre	Bog groove-moss
Aulacomnium turgidum	Mountain groove-moss
Bartramia ithyphylla	Straight-leaved apple-moss
Blepharostoma trichophyllum	Hairy treadwort
Brachythecium albicans	Whitish feather-moss
Brachythecium glaciale	Snow feather-moss
Brachythecium latifolium	

Species status: CR= Critically Endangered; EN= Endangered; VU= Vulnerable; LC= Least Concern; DD= Data Deficient

Brachythecium plumosum	Rusty feather-moss
Brachythecium reflexum	Reflexed feather-moss
Brachythecium rivulare	River feather-moss
Brachythecium salebrosum	Smooth-stalk feather-moss
Brachythecium turgidum	Turgid brachythecium moss
Brachythecium velutinum	Velvet feather-moss
Bryoerythrophyllum ferruginascens	Rufous beard-moss
Bryoerythrophyllum recurvirostrum	Red beard-moss
Bryoxiphium norvegicum	Sword moss
Bryum algovicum	Drooping thread-moss
Bryum archangelicum	Archangelic thread-moss
Bryum arcticum	Arctic thread-moss
Bryum argenteum	Silver-moss
Bryum axel-blyttii	Blytt's bryum moss
Bryum calophyllum	Blunt bryum
Bryum creberrimum	Tight-tufted thread-moss
Bryum curvatum	Bryum moss
Bryum cyclophyllum	Round-leaved bryum
Bryum dichotomum	Bicoloured bryum
Bryum imbricatum	Small-mouthed thread-moss
Bryum knowltonii	Knowlton's thread-moss
Bryum pallens	Pale thread-moss
Bryum pallescens	Tall-clustered thread-moss
Bryum pseudotriquetrum	Marsh bryum
Bryum purpurascens	Bryum moss
Bryum rutilans	
Bryum vermigerum EN	Oblong bryum moss
Bryum weigelii Spreng.	Duval's thread-moss
Calliergon giganteum	Giant spear-moss
Calliergon richardsonii	Richardson's spear-moss
Calliergonella cuspidata	Pointed spear-moss
Campyliadelphus chrysophyllus	Golden feather-moss
Campylium protensum	Dull starry feather-moss
Campylium stellatum	Yellow starry feather-moss
Campylopus schimperi	Schimper's swan-neck moss
Catoscopium nigritum	Down-looking moss
Ceratodon purpureus	Redshank
Cinclidium stygium	Lurid cupola-moss
Climacium dendroides	Tree-moss
Conardia compacta	Compact feather-moss
Conostomum tetragonum	Helmet-moss
Cratoneuron filicinum	Fern-leaved hook-moss
Ctenidium molluscum	Chalk comb-moss
Dichodontium pellucidum	Transparent fork-moss
Dicranella rufescens	Rufous forklet-moss
Dicranella schreberiana	Schreber's forklet-moss
Dicranella subulata	Awl-leaved forklet-moss
Dicranoweisia crispula	Mountain pincushion
Dicranum bonjeanii	Crisped fork-moss
Dicranum flexicaule	Bendy fork-moss
Dicranum scoparium	Broom fork-moss
Dicranum spadiceum	Dicranum moss
Didymodon asperifolius	Rough-leaved beard-moss
Didymodon icmadophilus	Slender beard-moss
Didymodon insulanus	Cylindric beard-moss
Distichium capillaceum	Fine distichium
Distichium inclinatum	Inclined distichium
Ditrichum flexicaule	Bendy ditrichum
Ditrichum gracile	Slender ditrichum
Ditrichum heteromallum	Curve-leaved ditrichum
Ditrichum lineare	Dark ditrichum
Ditrichum pusillum	Brown ditrichum
Drepanocladus aduncus	Kneiff's hook-moss
Drepanocladus polygamus	Fertile feather-moss
Encalypta alpina	Alpine extinguisher-moss
Encalypta ciliata	Fringed extinguisher-moss
Encalypta procera	Extinguisher-moss
Encalypta rhaptocarpa	Ribbed extinguisher-moss
Encalypta streptocarpa	Spiral extinguisher-moss
Entodon concinnus	Montagne's cilynder-moss
Eurhynchium pulchellum	Elegant feather-moss
Fissidens bryoides	Lesser pocket-moss
Fissidens osmundoides	Purple-stalked pocket-moss
Fontinalis antipyretica	Greater water-moss
Grimmia donniana	Donn's grimmia
Grimmia funalis	String grimmia
Grimmia longirostris	North Grimmia
Grimmia montana	Sun grimmia
Grimmia ovalis	Flat-rock grimmia
Grimmia reflexidens	
Grimmia torquata	Twisted grimmia
Gymnostomum aeruginosum	Verdigris tufa-moss
Helodium blandowii	Blandow's tamarisk-moss
Hennediella heimii	Heim's pottia
Homalothecium sericeum	Silky wall feather-moss
Hygrohypnum alpestre	Hygrohypnum moss
Hygrohypnum luridum	Drab brook-moss
Hygrohypnum ochraceum	Claw brook-moss
Hylocomium splendens	Glittering wood-moss
Hymenostylium recurvirostrum	Hook-beak tufa-moss
Hypnum bambergeri	Golden plait-moss
Hypnum cupressiforme	Cypress-leaved plait-moss
Hypnum hamulosum	Hook-leaved plait-moss
Hypnum lacunosum	Great plait-moss
Hypnum lindbergii	Lindberg's plait-moss
Hypnum revolutum	Revolute plait-moss
Hypnum vaucheri	Vaucher's plait-moss
Isopterygiopsis pulchella	Neat silk-moss
Kiaeria blyttii	Blytt's fork-moss
Kiaeria falcata	Sickle-leaved fork-moss
Kiaeria glacialis	Snow fork-moss
Kiaeria starkei	Starke's fork-moss
Leptobryum pyriforme	Golden thread-moss
Lescuraea incurvata	Brown mountain leskea
Lescuraea patens	Patent leskea
Lescuraea radicosa	Pseudoleskea moss
Leucodon sciuroides	Squirrel-tail moss
Meesia triquetra	Three-ranked hump-moss

Meesia uliginosa	Broad-nerved hump-moss
Mnium blyttii	Blytt's thyme-moss
Mnium marginatum	Bordered thyme-moss
Mnium spinosum	Spinose thyme-moss
Mnium stellare	Starry thyme-moss
Mnium thomsonii	Short-beaked thyme-moss
Myurella julacea	Small mouse-tail moss
Myurella tenerrima	Dwarf mouse-tail moss
Neckera complanata	Flat neckera
Oncophorus virens	Green spur-moss
Oncophorus wahlenbergii	Wahlenberg's spur-moss
Orthothecium chryseon	Golden erect-capsule moss
Orthothecium intricatum	Fine-leaved leskea
Orthotrichum laevigatum	Orthotrichum moss
Orthotrichum rupestre	Rock bristle-moss
Orthotrichum speciosum	Showy bristle-moss
Orthotrichum stramineum VU	Straw bristle-moss
Orthotrichum striatum VU	Shaw's bristle-moss
Paludella squarrosa	Tufted fen-moss
Palustriella commutata	Curled hook-moss
Palustriella decipiens	Lesser curled hook-moss
Palustriella falcata	Claw-leaved hook-moss
Philonotis fontana	Fountain apple-moss
Philonotis tomentella	Woolly apple-moss
Plagiobryum zieri	Zierian hump-moss
Plagiomnium cuspidatum	Woodsy thyme-moss
Plagiomnium ellipticum	Marsh thyme-moss
Plagiothecium denticulatum	Dented silk-moss
Plagiothecium succulentum	Juicy silk-moss
Platydictya jungermannioides	Spruce's leskea
Platyhypnidium riparioides	Long-beaked water feather-moss
Pohlia andalusica	Gravel thread-moss
Pohlia annotina	Pale-fruited thread-moss
Pohlia cruda	Opal thread-moss
Pohlia drummondii	Drummond's thread-moss
Pohlia elongata	Long-fruited thread-moss
Pohlia eruda	
Pohlia filum	Fat-bud thread-moss
Pohlia obtusifolia	Blunt-leaved thread-moss
Pohlia proligera	Bent-bud thread-moss
Pohlia wahlenbergii	Pale glaucous thread-moss
Pseudobryum cinclidioides	River thyme-moss
Pseudocalliergon angustifolium	
Pseudocalliergon trifarium	Three-ranked spear-moss
Pseudocalliergon turgescens	Turgid scorpion-moss
Pterigynandrum filiforme	Capillary wing-moss
Racomitrium aciculare	Yellow fringe-moss
Racomitrium canescens	Hoary fringe-moss
Racomitrium elongatum	Long fringe-moss
Racomitrium ericoides	Dense fringe-moss
Racomitrium fasciculare	Green mountain fringe-moss
Racomitrium heterostichum	Bristly fringe-moss
Racomitrium lanuginosum	Woolly fringe-moss
Racomitrium microcarpon	
Racomitrium sudeticum	Slender fringe-moss
Rhizomnium magnifolium	Large-leaf thyme-moss
Rhizomnium pseudopunctatum	Felted thyme-moss
Rhizomnium punctatum	Dotted thyme-moss
Rhodobryum roseum	Rose-moss
Rhytidiadelphus squarrosus	Springy turf-moss
Rhytidiadelphus triquetrus	Big shaggy-moss
Rhytidium rugosum	Wrinkle-leaved feather-moss
Saelania glaucescens	Blue dew-moss
Sanionia georgico-uncinata	
Sanionia orthothecioides	St. Kilda hook-moss
Sanionia uncinata	Sickle-leaved hook-moss
Schistidium agassizii	Water grimmia
Schistidium flexipile	
Schistidium frigidum	Frigid grimmia
Schistidium papillosum	Rough grimmia
Schistidium platyphyllum	Broadleaf grimmia
Schistidium rivulare	River grimmia
Schistidium strictum	Upright brown grimmia
Schistidium venetum VU	Bluish bloom moss
Scorpidium cossonii	Intermediate hook-moss
Scorpidium revolvens	Rusty hook-moss
Scorpidium scorpioides	Hooked scorpion-moss
Splachnum vasculosum	Rugged collar-moss
Straminergon stramineum	Straw spear-moss
Syntrichia norvegica	Norway screw-moss
Syntrichia ruralis	Great hairy screw-moss
Tayloria lingulata	Tongue-leaved gland-moss
Thuidium assimile	Philibert's tamarisk-moss
Timmia austriaca	Sheathed timmia
Timmia norvegica	Norway timmia
Tomentypnum nitens	Wooly feather-moss
Tortella fragilis	Brittle crisp-moss
Tortella tortuosa	Frizzled crisp-moss
Tortula euryphylla	Hoppe's screw-moss
Tortula subulata	Awl-leaved screw-moss
Warnstorfia exannulata	Ringless hook-moss
Warnstorfia sarmentosa	Twiggy spear-moss
Warnstorfia tundrae	Tundra warnstorfia moss
Weissia controversa	Green-tufted stubble-moss
Polytrichaceae	
Atrichum angustatum VU	Lesser smoothcap
Atrichum tenellum CR	Slender smoothcap
Atrichum undulatum	Common smoothcap
Oligotrichum hercynicum	Hercynian haircap
Pogonatum urnigerum	Urn haircap
Polytrichum alpinum	Alpine haircap
Polytrichum commune	Common haircap
Polytrichum juniperinum	Juniper haircap
Polytrichum piliferum	Bristly haircap
Polytrichum sexangulare	Northern haircap
Polytrichum sphaerothecium	
Sphagnaceae	
Sphagnum girgensohnii	Girgensohn's bog-moss
Sphagnum teres	Rigid bog-moss
Sphagnum warnstorfii	Warnstorf's bog-moss

Appendix 2.4: Lichens

Macro lichens (fruticose and foliose)

Alectoria ochroleuca	Yellow-green witch's hair	*Nephroma expallidum*	Alpine kidney lichen
Alectoria sarmentosa	Witch's hair	*Nephroma laevigatum*	Mustard kidney lichen
Allantoparmelia alpicola	Rock grubs	*Nephroma parile*	Powdery kidney lichen
Bryoria chalybeiformis	Horsehair lichen	*Nephroma resupinatum* VU	Pimpled kidney lichen
Catapyrenium cinereum	Earthscale lichen	*Neuropogon sphacelatus*	Beard lichen
Cetraria aculeata	Spiny heath lichen	*Parmelia saxatilis*	Grey crottle
Cetraria islandica	Iceland moss	*Parmelia sulcata*	Powdered crottle
Cetraria muricata	Spiny heath lichen	*Peltigera aphthosa*	Common freckle pelt
Cetraria sepincola	Chestnut wrinkle-lichen	*Peltigera britannica*	Flaky freckle pelt
Cetrariella delisei	Snow-bed Iceland lichen	*Peltigera canina*	Dog lichen
Cladonia arbuscula	Reindeer lichen	*Peltigera collina*	Floury dog lichen
Cladonia borealis	Boreal pixie-cup	*Peltigera didactyla*	Imperfectly-veined lichen
Cladonia cariosa	Split-peg lichen	*Peltigera extenuata*	Dwarf dog lichen
Cladonia cervicornis	Buck's-horn cup lichen	*Peltigera hymenina*	
Cladonia cervicornis	Ladder lichen	*Peltigera kristinssonii*	Dark-veined pelt
Cladonia chlorophaea	Mealy pixie-cup	*Peltigera lepidophora*	Scaly pelt
Cladonia coccifera	Scarlet cup lichen	*Peltigera leucophlebia*	Ruffled freckle pelt
Cladonia furcata	Many-forked cladonia	*Peltigera malacea*	Veinless pelt
Cladonia gracilis	Smooth cladonia	*Peltigera membranacea*	Membranous dog lichen
Cladonia islandica		*Peltigera neckeri*	Black saddle lichen
Cladonia luteoalba		*Peltigera polydactylon*	Many-fruited pelt
Cladonia macroceras		*Peltigera ponojensis*	Pale-bellied dog lichen
Cladonia macrophyllodes	Large-leaved cladonia	*Peltigera praetextata*	Scaly dog lichen
Cladonia mitis	Green reindeer lichen	*Peltigera rufescens*	Field dog lichen
Cladonia pocillum	Rosette pixie-cup	*Peltigera venosa*	Fan lichen
Cladonia pyxidata	Pebbled pixie-cup	*Phaeophyscia endococcina*	Wreath lichen
Cladonia stricta		*Phaeophyscia sciastra* DD	Dark shadow lichen
Cladonia subcervicornis		*Physcia caesia*	Blue-gray rosette lichen
Cladonia subulata	Antlered powderhorn	*Physcia dubia*	Powder-tipped rosette lichen
Cladonia symphycarpa	Cup lichen	*Physconia muscigena*	Ground frost lichen
Cladonia trassii	Spotted black-foot	*Placidium lachneum*	Stipplescale lichens
Cladonia turgida	Crazy-scale lichen	*Platismatia glauca* VU	Varied rag lichen
Collema flaccidum	Squamiform jelly lichen	*Polychidium muscicola*	Moss-thorns lichen
Collema glebulentum	Jelly lichen	*Pseudephebe minuscula*	Coarse rockwool
Dermatocarpon miniatum	Common stippleback	*Pseudephebe pubescens*	Fine rockwool
Enchylium tenax		*Rusavsia elegans*	
Flavocetraria nivalis	Crinkled snow lichen	*Scytinium gelatinosum*	
Gowardia nigricans		*Scytinium lichenoides*	
Hypogymnia physodes LC	Monk's-hood lichen	*Solorina bispora*	Chocolate chip lichen
Hypogymnia tubulosa LC	Powder-headed tube lichen	*Solorina crocea*	Orange chocolate chip lichen
Lathagrium undulatum		*Solorina saccata*	Common chocolate chip lichen
Leptogium saturninum	Bearded jelly skin	*Solorina spongiosa*	Fringed chocolate chip lichen
Massalongia carnosa	Rockmoss rosette lichen	*Stereocaulon alpinum*	Alpine soil foam
Melanelia agnata		*Stereocaulon arcticum*	Arctic snow lichen
Melanelia hepatizon	Rimmed camouflage lichen	*Stereocaulon botryosum*	Snow lichen
Melanohalea exasperata	Warty brown-shield	*Stereocaulon capitellatum*	
Melanohalea infumata	Salted brown-shield	*Stereocaulon glareosum*	Glare snow lichen

Species status: CR= Critically Endangered; EN= Endangered; VU= Vulnerable; LC= Least Concern; DD= Data Deficient

Stereocaulon rivulorum	Snow foam lichen
Stereocaulon spathuliferum	
Stereocaulon tomentosum	Wooly foam lichen
Stereocaulon vesuvianum	Vesuvius snow lichen
Stereocaulon ! uliginosum VU	Snow lichen
Thamnolia vermicularis	Whiteworm lichen
Tuckermannopsis chlorophylla	Powdered wrinkle lichen
LR	Ashen rock tripe lichen
Umbilicaria aprina	Arctic navel lichen
Umbilicaria arctica	Fringed rock tripe lichen
Umbilicaria cylindrica	Netted rock tripe
Umbilicaria decussata	Blistered rock tripe lichen
Umbilicaria hyperborea	Fringed button lichen
Umbilicaria proboscidea	Punctured rock tripe lichen
Umbilicaria torrefacta	Blushing rock tripe lichen
Umbilicaria virginis EN	Beard lichen
Usnea subfloridana VU	Shrubby starburst lichen
Xanthoria candelaria	

Micro lichens(crustose)

Acarospora badiofusca EN	Cracked lichen
Acarospora hospitans	
Amandinea punctata	Tiny button lichen
Amygdalaria consentiens	Amygdalaria lichen
Amygdalaria panaeola	Powdery almond lichen
Amygdalaria pelobotryon	Norman amygdalaria lichen
Arthonia fuscopurpurea VU	Dot lichens
Arthonia peltigerina	
Arthonia pelveti	
Arthonia punctiformis	
Arthonia stereocaulina	
Arthrorhaphis alpina	Alpine arthrorhaphis lichen
Aspicilia cinerea	Cinder lichen
Athallia holocarpa	
Bacidia bagliettoana	Baglietto's dotted lichen
Baeomyces rufus	Brown beret lichen
Bellemerea alpina	Alpine bellemerea lichen
Bellemerea subsorediza	Bellemerea lichen
Biatora subduplex	Biatora lichens
Bilimbia lobulata	
Blastenia ammiospila	
Brigantiaea fuscolutea	Brigantiaea lichen
Bryonora castanea	Bryonora lichen
Bryoplaca tetraspora	
Buellia insignis	Button lichens
Caloplaca alboatrum	Firedot lichens
Caloplaca cf. festivella VU	
Caloplaca approximata	Approximate orange lichen
Caloplaca caesiorufella	Orange lichen
Caloplaca cerina	Firedot lichens
Calvitimela armeniaca	
Calvitimela melaleuca	
Candelariella borealis	Goldspeck lichens
Candelariella kuusamoënsis	Goldspeck lichens
Candelariella vitellina	Eggyolk lichen
Carbonea supersparsa VU	Carbonea lichens
Carbonea vitellinaria	
Carbonea vorticosa	
Catillaria contristans	Catillaria lichens
Cercidospora epipolytropa	Cercidospora lichen
Cercidospora thamnoliicola	Cercidospora lichens
Chaenotheca cinerea EN	Old man's whiskers
Cliostomum corrugatum VU	Cliostomum lichens
Corticifraga peltigerae	Corticifraga lichens
Cystocoleus ebeneus	
Dibaeis baeomyces	Pink earth lichen
Diploschistes gypsaceus	Cowpie lichen
Endococcus perpusillus VU	Endococcus lichen
Endococcus propinquus	Endococcus lichen
Epilichen scabrosus	Rugged-shielded sulphur lichen
Euopsis pulvinata	Pulvinate euopsis lichen
Fuscopannaria praetermissa	Moss shingle lichen
Gyalecta foveolaris	Dimple lichen
Gyalolechia flavorubescens	
Henrica theleodes VU	
Hymenelia arctica	Hymenelia lichens
Illosporium carneum	
Ionaspis odora	Ionaspis lichen
Ionaspis ventosa	
Lasiosphaeriopsis stereocaulicola	
Lecanora epibryon	Rim lichen
Lecanora frustulosa	
Lecanora hagenii	Hagen's rim lichen
Lecanora intricata	Intricate rim lichen
Lecanora polytropa	Granite-speck rim lichen
Lecidea atrobrunnea	Brown tile lichen
Lecidea auriculata	Lecidea lichen
Lecidea confluens	Confluent shielded lichen
Lecidea lapicida	Lecidea lichen
Lecidea lapicida	Gray-orange disc lichen
Lecidea lapicida	
Lecidea olivascens	Lecidea lichen
Lecidea praenubila	
Lecidea tesselata	Tile lichen
Lecidella carpathica	Lecidella lichen
Lecidella elaeochroma	
Lecidella euphorea	
Lecidella stigmatea	Disk lichen
Lecidella wulfenii	Wulfen's lecidella lichen
Leciophysma finmarkicum LC	
Lempholemma isidioides DD	Lempholemma lichen
Lempholemma polyanthes	Thousand-fruited jelly lichen
Lepraria incanarino	Dust lichens
Leptosphaerulina peltigerae	
Megaspora verrucosa	False sunken-disc lichen
Micarea assimilata	Dot lichen
Micarea incrassata	
Micarea leprosula	

Micarea lignaria	
Miriquidica garovaglioi	Miriquidica lichens
Miriquidica nigroleprosa	
Muellerella pygmaea	Dwarf muellerella lichen
Muellerella ventosicola VU	Muellerella lichens
Mycobilimbia berengeriana	Berenger's mycobilimbia lichen
Mycobilimbia tetramera	Dot lichens
Ochrolechia frigida	Cold crab's-eye lichen
Ochrolechia grimmiae	Grimmia crab's-eye lichen
Ochrolechia xanthostoma	
Odontotrema santessonii	
Opegrapha stereocaulicola	Scribble lichens
Pannaria hookeri	Hookerian lichen
Parvoplaca tiroliensis	
Pertusaria corallina	White coral-crusted lichen
Pertusaria coriacea	Leathery pore lichen
Pertusaria oculata	Pore lichen
Phaeorrhiza nimbosa EN	Brown fuzz lichen
Pilophorus dovrensis	Matchstick lichens
Placopsis gelida	Bull's-eye lichen
Placopsis lambii	Pink bull's-eye lichen
Placynthium asperellum	Lilliput ink lichen
Placynthium rosulans	Ink lichens
Polyblastia borealis	Polyblastia lichens
Polyblastia schisticola	
Polycoccum islandicum	Polycoccum lichens
Polycoccum vermicularium	
Polysporina lapponica	Lapland polysporina lichen
Porpidia cf. soredizodes	Porpidia lichens
Porpidia cinereoatra	
Porpidia crustulata	Concentric boulder lichen
Porpidia flavicunda	Orange boulder lichen
Porpidia macrocarpa	Porpidia lichens
Porpidia melinodes	
Porpidia superba	Superb porpidia lichen
Porpidia tuberculosa	Porpidia lichens
Pronectria robergei	
Pronectria solorinae	
Protoblastenia siebenhaariana	Orange dot lichens
Protomicarea limosa	
Protopannaria pezizoides	Brown-gray moss shingle
Protoparmelia badia	Chocolate rim lichens
Protothelenella santessonii	Protothelenella lichens
Psilolechia leprosa	
Psora decipiens	Blushing scale lichen
Psora rubiformis	Rusty alpine psora
Psoroma hypnorum var. hypnorum	Green moss shingle lichen
Psoroma tenue var. boreale	Bowl lichen
Pyrenocollema bryospilum	Pyrenocollema lichens
Raciborskiomyces peltigericola	
Rhagadostoma lichenicola	
Rhizocarpon chioneum EN	Snowy map lichen
Rhizocarpon copelandii	Copeland's map lichen

Rhizocarpon expallescens	Map lichens
Rhizocarpon geographicum	Yellow map lichen
Rhizocarpon intermediellum	Map lichens
Rhizocarpon lavatum	
Rhizocarpon norvegicum	Norwegian map lichen
Rhizocarpon parvum	
Rhizocarpon reductum	
Rhizocarpon sublavatum	
Rhizocarpon superficiale	Superficial map lichen
Rimularia fuscosora	Rimularia lichens
Rinodina archaea	Pepper-spore lichens
Rinodina gennarii	Gennar's rinodina lichen
Rinodina mniaraea	Pepper-spore lichens
Rinodina olivaceobrunnea	
Rinodina turfacea	Tundra pepper-spore lichen
Rostania ceranisca	
Scoliciosporum umbrinum	Scoliosporum lichen
Sporastatia polyspora	Sporastatia lichen
Sporastatia testudinea	Copper patch lichen
Sporodictyon schaererianum	
Sporodictyon terrestris	
Staurothele arctica	Arctic wart lichen
Staurothele areolata	Wart lichens
Staurothele fissa	Lakezone lichen
Stereocaulon tornense	
Stigmidium conspurcans	Stigmidium lichens
Stigmidium gyrophorarum	Stigmidium lichens
Toninia sedifolia	Earth wrinkles
Toninia squalida	Squalid bruised lichen
Tremolecia atrata	Rusty-rock lichen
Verrucaria aethiobola	Wart lichen
Verrucaria nigrescens	Wart lichen

Appendix 2.5: Photographs and audiovisual image inventory and authorization form

Name (region)	Date (d.mo.yr)	Photographer and copyright holder	Contact detail*	Session of rights
A. Inventory of photographs – all provided in electronic (jpg) format.				
1. Ásbyrgi (N)	29.06.16	Snorri Baldursson	VNP	Yes
2. Hljóðaklettar (N)	29.06.16	Snorri Baldursson	VNP	Yes
3. Dettifoss (N)	13.08.17	Snorri Baldursson	VNP	Yes
4. Mt. Herðubreið (N)	13.08.17	Snorri Baldursson	VNP	Yes
5. Askja caldera lake	13.08.17	Snorri Baldursson	VNP	Yes
6. Trölladyngja lava shield (N)	19.09.14	Snorri Baldursson	VNP	Yes
7. Mt. Snæfell (E)	25.10.03	Skarphéðinn Þórisson	EINRC	Yes
8. Vesturöræfi (E)	10.08.15	Skarphéðinn Þórisson	EINRC	Yes
9. Kverkfjallarani (E)	13.08.17	Snorri Baldursson	VNP	Yes
10. Kverkfjöll (E)	13.08.17	Snorri Baldursson	VNP	Yes
11.Krepputunga (E)	17.0816	Snorri Baldursson	VNP	Yes
12. Skaftafell (S)	30.07.16	Snorri Baldursson	VNP	Yes
13. Fjallsárlón (S)	31.07.16	Snorri Baldursson	VNP	Yes
14. Falljökull (S)	06.10.12	Þorvarður Árnason	UIRCH	Yes
15. Öræfajökull (S)	21.02.15	Þorvarður Árnason	UIRCH	Yes
16. Hoffelsjökull	13.07.16	Þorvarður Árnason	UIRCH	Yes
17. Fláajökull	05.05.16	Þorvarður Árnason	UIRCH	Yes
18. Lakagígar (W)	14.09.15	Snorri Baldursson	VNP	Yes
19. Eldgjá (W)	22.09.10	Snorri Baldursson	VNP	Yes
20. Langisjór	01.07.11	Snorri Baldursson	VNP	Yes
21. Tungnaáröræfi	25.07.11	Snorri Baldursson	VNP	Yes
22. Kambar (W)	22.09.10	Snorri Baldursson	VNP	Yes
23. Laki lava flow & Mt. Uxatindar (W)	17.07.12	Snorri Baldursson	VNP	Yes
24. Vonarskarð (W)	20.07.10	Snorri Baldursson	VNP	Yes
B. Video				
1.Vatnajökull National Park – running time 50 min.	2013	Valdimar Leifsson	Lífsmynd	Partly**

*VNP= Vantanjökull National Park, Klapparstíg 25-27, 100, snorri@vjp.is ; EINRC = East Iceland Nature Research Centre, Mýrargötu 10, 740 Neskaupstaður, skarphedinn@na.is ; UIRCH = University of Iceland's Research Centre in Hornafjörður, Litlubrú 2, 880 Höfn, thorrvarn@h.is: Lífsmynd c/o Valdimar Leifsson, Tryggvagötu 10, 101 Reykjavík, lifsmynd@lifsmynd.is.
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Ministry for the Environment and Natural Resources
Ministry of Education, Science and Culture