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Series Editor: Colm O'Cofaigh

Helgi Björnsson

The Glaciers of Iceland

A Historical, Cultural and Scientific Overview

Atlantis Advances in Quaternary Science

Volume 2

Series editor

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A Historical, Cultural and Scientific Overview

Julian Meldon D'Arcy, University of Iceland:
English translation

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NÁTTÚRUVERNDARSJÓÐUR
PÁLMA JÓNSSONAR
STOFNANDA HAGKAUPS

The translation of the book was supported by the Icelandic Literature Center.

MIÐSTÖÐ ÍSLENSKRA BÓKMENNTA
ICELANDIC LITERATURE CENTER

I dedicate this book to my wife, Þóra Ellen Þórhallsdóttir, and my children Valgerður, Þórhallur, Ásdís, Björn and Svanhildur

Foreword

Glaciers are an essential part of the Icelandic identity. They hover in their beauty and magnificence on the horizons far and wide around the country, whatever their names: Snæfellsjökull, Öræfajökull, Eyjafjallajökull. These white giants play such an important role in creating Icelanders' self-image wherever they are found, as they majestically reign over the landscape, extending over 10% of Iceland. All true Icelanders are fascinated by glaciers from childhood, and many of those who live in the area of our capital on the southwest coast begin the day by looking out across the bay towards the glacier Snæfellsjökull, the old beacon for seamen on perilous fishing grounds. For those in the west of the country it is our own mystic mountain, our Fujiyama.

The quest for knowledge of these white giants, which serve as guides to where we are located in life, commenced here earlier than elsewhere in the world, for Iceland is truly a land of glaciers. Scientists and daring pioneers, both Icelanders and other foreign nationals, were determined to learn all about these glaciers at whatever the cost—for conditions were so harsh that their work was all but impossible in the early days. Accounts of what they achieved and endured sound incredible: their packhorses inch their way forward over slippery ice at the edge of a precipice, before tumbling into crevasses, where they wait patiently until they are hoisted to safety—or until they expire.

In an account of one of the first crossings of the great Vatnajökull glacier in the first years of the twentieth century, two Scottish pioneers were the first to record their impressions of the indefinable beauty of the white frozen wilderness, as they lay in a blizzard, imprisoned in their tent, reading Cervantes' *Don Quixote* and other masterpieces of world literature.

We owe a huge debt of gratitude to the scientists who have explored our glaciers, both past and present. They have brought to us vital knowledge about these white giants which will provide essential testimony in the great forthcoming trial concerning the potentially catastrophic case of global warming.

Glaciologist Helgi Björnsson is certainly a first among equals in the science of observing the life of our glaciers. His book, the fruit of four decades' work, is a unique testament to the history of Iceland's glaciers over countless centuries, and to their destiny. *The Glaciers of Iceland* is now finally available in English translation at a crucial time for the future of the world. It will be an important reference book on the beauty and magnificence of these phenomena of nature, which will not remain intact for ever, as we had so optimistically believed only a few years ago.

The glaciers of the world and of Iceland are no longer symbols of permanence and eternity—instead they remind us that everything in the world is transitory, even glaciers themselves—where beauty reigns alone, as our great writer Laxness expressed it in *World Light*. Glaciers are most certainly beacons of light in the world, and it is our profound wish that we may continue to live in their light, and not in the shadows.

Vigdís Finnbogadóttir
Former President of Iceland

Preface

Wherever one looks in Iceland, its landscape bears witness to the impact of ice and fire. The terrain appears to be moulded either by a glacier that covered Iceland 18,000 years ago, or by lava which had flowed after the glacier had thawed. Long after glaciers had disappeared, extant landforms indicated their previous existence, for they have chiselled bedrock, scooped out corries, shattered cliff faces, and left behind massive and jagged sculptures and sharp mountain pinnacles. Glaciers have gouged deep and narrow fjords far out into Iceland's continental shelf, and hollowed out valley floors and troughs that are now full of lakes. Taking a closer look at the landscape, more refined pieces of evidence can be seen: striated rocks, serrated crags, polished whalebacks and erratic boulders. Glacial rivers have harrowed out ravines, often during catastrophic floods, and discharged sediments over outwash plains. In many places there are visible signs of volcanic eruptions beneath glaciers. Palagonite ridges rise above volcanic fissures and precipitous table mountains, some of the most magnificent in the country, tower high above their surroundings, bearing witness to the thickness of an ice-age glacier. Glacial moraines illustrate the power of previously advancing outlet glaciers, and both fresh-water lakes and the ocean have sediment strata which have been borne and dispersed there by glacial rivers. Iceland's flora still reveals signs of the vegetation which had been destroyed in a glacial age.

Glaciers now cover only about 10 % of Iceland and are retreating rapidly. Ancient glacial plains and valleys have become the country's most fertile agricultural areas. But there are signs of life left in the glaciers, nonetheless, they still sometimes expand and even surge forward, responding quickly to changes in the climate. The greatest rivers of the country flow from them into power stations, groundwater systems and the ocean, and they also provide the greatest storage facility for our fresh water. Glacial rivers continue to need bridging or containing with defensive levees. Huge outburst floods (jökulhlaups) still rush from proglacial lakes in geothermal areas and from subglacial volcanic eruptions.

By researching present-day glaciers we can discover the basic laws of their formation and behaviour and their relationship to climate change. Here, as in other geophysical sciences, the key to the future can be found in the past. Questions may be asked about glaciers as to when and how they originated, how large were they during the settlement of Iceland, and how did they thrive while the nation endured a long-term cold period? A knowledge of present-day glaciers is no less a key to the future. Will glaciers be able to grow again and advance in the coming years, or will they shrink and retreat so much that glacial rivers will run dry? What effect will that have on hydroelectric power stations, groundwater systems, and supplies of drinking water? What would the hitherto hidden mountains and valleys look like, should the glaciers that cover them disappear?

The aim of this book is to record a history of the knowledge and understanding of the origins, habitats and behaviour of glaciers and how we evaluate their role in nature. The first part traces this history from the first settlement of Iceland in the ninth century right up until modern science has revealed the island's hidden, subglacial terrain. It also reveals how research into remnants of ancient glaciers has made mankind realise how Earth's climate is in a constant state of fluctuation. The second part contains a detailed study of all of Iceland's major glaciers as they now are in the beginning of the twenty-first century.

In writing this book I have used a wide variety of historical and scientific sources, from the Sagas of the Icelanders to recent academic research, from pencil drawings to computer-generated and satellite images. I have tried to produce a text that, while avoiding an overuse of scientific discourse, can nonetheless present precise and valid explanations of glaciological phenomena and data in a lucid manner accessible to the general reader and geoscientists alike.

Glaciers are now rapidly receding all over the world and the surface of the ocean is rising and threatening our coastlines and Earth's hydrologic cycles, while global warming is stimulating increasingly volatile climate changes. The questions and answers relating to glaciers are thus of vital relevance to all of mankind for the foreseeable future.

Reykjavík, Iceland Helgi Björnsson

Translator's Note

In keeping with the spirit of Helgi Björnsson's multidisciplinary approach to the scientific, cultural and historical content of *The Glaciers of Iceland*, I have attempted to provide an English translation which, while retaining formal elements of glaciological and scholarly discourse, will hopefully remain accessible, informative, interesting and enjoyable to the general reader. All translations of Björnsson's Icelandic sources are mine, unless otherwise stated in the reference sections. Sources in English are, of course, quoted from the original texts.

I have followed the common practice of translating all Icelandic personal and place-names in their original Icelandic spelling in the nominative case, except in instances where a place-name (on maps) is specifically declined, e.g. the river Jökulsá á Fjöllum. Although I sometimes attempt to indicate the kind of geographical entity certain place-names imply (hill, spur, tongue, bog, etc.), many common and frequently used suffixes are not continually repeated in English, and it is hoped the reader will quickly grasp the meaning of most of them. These include, most importantly, the following: ***-jökull*** = glacier, outlet glacier; ***-fjörður*** = fjord; ***-flói*** = bay; ***-fjall***, ***-fell*** = mountain (***-fjöll***, pl. mountains); ***-heiði*** = highland moor, mountain; ***-á***, ***-fljót***, ***-kvísl*** = river; ***-vatn, -lón*** = lake, reservoir; ***-dalur*** = valley, dale; ***-hraun*** = lava field; ***-sandur*** = outwash or gravel plain; ***-öræfi*** = wilderness. The Icelandic ***jökulhlaup*** (for pro- or subglacial outburst flood) has been internationally accepted as the scientific term for this phenomenon.

A rough guide to the pronunciation of the consonants and vowels special to the Icelandic alphabet, as compared to general, standard RP English pronunciation, is as follows: The non-diacritic vowels a, e, i, o and u, are very similar to those in English (bat, bed, bid, bog, bun), the Icelandic medial 'r' is often trilled, and the double 'll' is usually pronounced 'tl' as in kettle or the Welsh 'll' in Llangollen; Þ þ = unvoiced 'th' as in: Beth, bath, path (always at beginning of words); ð is a voiced 'th' as in: then, this, that (always in middle or end of words); Á á = 'ou' as in bound, found, round; É é = 'ye' as in yet, yellow, yesterday; Í í = 'ee'/'ea' as in seen, keen, lean, mean; Ó ó = 'o'/'oe' as in go, no, foe, doe; Ú ú = 'oo' as in moon, boon, doom; Ö ö = 'ur' as in burn, turn, urn; Æ æ = 'i' as in bite, kite, trite.

I would like to thank Helgi Björnsson for his boundless patience and assistance with geophysical and glaciological terminology, and to express my gratitude to the Pálmi Jónsson Nature Preservation Fund and the Icelandic Literature Centre for grants towards this translation.

Julian Meldon D'Arcy
University of Iceland

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Many photographers have allowed me the use of their photographs. Sven Þ. Sigurðsson gave me permission to use photographs from his father's collection (Sigurður Þórarinsson). The National and University of Iceland Library, the National Museum of Iceland, the Árni Magnússon Institute, and The Royal Library in Copenhagen have all allowed me the use of photographs from their collections. Hagþenkir supported the writing of the Icelandic version, which was published by Opna. I am grateful to the publishers Sigurður Svavarsson and Guðrún

Magnúsdóttir and to their layout and graphic designers Líba Ásgeirsdóttir and Björn Valdimarsson.

Finally, I would like to thank the Pálmi Jónsson Conservation Fund and the Icelandic Literature Center for helping fund the translation of this book. I am also extremely grateful to Prof. Julian Meldon D'Arcy of the University of Iceland both for translating the text into English and for his continuous encouragement.

Contents

Abbreviations

AMI	The Árni Magnússon Institute for Icelandic Studies, Reykjavík
CLIMAP	Climate: Long range Investigation, Mapping, and Prediction (project)
COHMAP	Cooperative Holocene Mapping Project
DCPEM	Department of Civil Protection and Emergency Management (Almannavarnir)
DGI	Danish Geodetic Institute
DGS	Danish General Staff
EPICA	European Project for Ice Coring in Antarctica
GPS	Global Positioning System
HB	Helgi Björnsson (photographs)
HSD	Hydrological Service Division of NEAI
ICAA	Icelandic Civil Aviation Administration (Flugmálastjórn)
IESUI	Institute of Earth Sciences of the University of Iceland (Jarðvísindastofnun Háskóla Íslands)
IGS	Iceland Glaciological Society (Jöklarannsóknafélag Íslands)
IMO	Iceland Meteorological Office (Veðurstofa Íslands)
IPCC	Intergovernmental Panel on Climate Change
IRCA	Iceland Road and Coastal Administration (Vegagerð Ríkisins)
ISRC	Icelandic State Research Council
ITA	Iceland Touring Association (Ferðafélag Íslands)
LM	Loftmyndir (Aerial photographs)
MODIS	Moderate Resolution Imaging Spectroradiometer (NASA)
NEA	National Energy Authority (of Iceland) (Orkustofnun)
NLSI	National Land Survey of Iceland (Landmælingar Íslands)
NMI	National Museum of Iceland (Þjóðminjasafn)
NPCI	National Power Company of Iceland (Landsvirkjun)
NULI	National and University Library of Iceland (Lands- og Háskólabókasafns Íslands)

RLC	Royal Library of Copenhagen
SCSI	Soil Conservation Service of Iceland (Landgræðsla Ríkisins)
SIUI	Science Institute of the University of Iceland
SPOT	French: Satellite Pour l'Observation de la Terre. (Satellite for observation of Earth)
USAMS	US Army Map Service

Part I
The Origins and History of Glaciers and Glaciology

Chapter 1
Origins and Nature of Glaciers

> 'Out of whose womb came the ice? And the hoary frost of heaven, who hath gendered it?' Job 38:29.

Abstract A knowledge of the nature of glaciers and ice sheets is required to understand their important role in the Earth's hydrologic cycle. The glaciers of today provide an insight into both past and future glaciers and climate changes. In this chapter, the basic concepts and terminology of glaciers and glaciology are presented as an introduction to the accounts of Icelandic glaciers in the later sections of the book. This includes an explanation of how ice masses are formed from snow, which falls and settles in an accumulation zone, hardens into firn snow and consequently glacial ice, and then flows downward and across the equilibrium line into an ablation zone, where it melts. The mechanics of how ice masses move are outlined, as well as the occurrence of surges and the formation of crevasses, ogives, and moulins. The effects of subglacial, geothermal and volcanic activity on glaciers are also explained, particularly the formation of ice cauldrons and ice-dammed lakes, along with the reasons for the phenomenon of outburst floods, or jökulhlaups, from glaciers. The landforms resulting from glacial movements and fluvial processes are also defined, e.g. moraines, canyons, and gravel outwash plains.

1.1 The Frozen World and Its Imprints

Glaciers cover polar landmasses and the highest mountains of all the continents of the world, with the exception of Australia, and blanket about a tenth of the Earth's land surface. Their influence extends even further than this, however, for glacial rivers flow through land to the sea, ice shelves break up in the seas around the world's polar regions, and icebergs and ice floes are borne by ocean currents into shipping lanes. Glaciers were previously much larger than they are now and almost every part of the world's land mass has been covered by glacial ice at some time in its history. The evidence glaciers leave behind bear witness to this (Figs. 1.1, 1.2 and 1.3). They have chiselled at the toughest bedrock, gnawed out mountains and basins, broken up cliff faces, and carved out pointed summits, leaving behind sharp,

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Fig. 1.1 The sharp edges of Veðurárdalsfjöll mountains bear witness to the erosives powers of glaciers. Breiðamerkurjökull descends south along the mountains towards Jökulsárlón lagoon on the outwash plain Breiðamerkursandur (see Sect. 8.5). In the centre of the photograph, a glacier in the wide valley of Svöludalur has pushed up a curvilinear moraine, Veðurárdalsrönd. The North Atlantic can be seen in the far distance. HB, September 1994

Fig. 1.2 Hvalfjörður, a 35-km-long fjord abraded by an ice-age glacier. View down Botnsdalur valley over Botnsvogur inlet, Þyrilsnes peninsula, Hvammsvík bay and Reyniháls ridge. Furthest away is Mt. Akrafjall. HB, September 1997

Fig. 1.3 The glacially eroded valley Fossadalur on the left of Lambatungnajökull, a present day outlet of the eastern parts of Vatnajökull. In the *top left* corner can be seen the nunataks (mountain peaks protruding through a glacier's surface) in Hofellsjökull (Sect. 8.6). HB

craggy peaks, and huge, jagged rock sculptures. They have gouged out deep and narrow fjords far out onto continental shelves, eroded broad valley basins and large trenches now filled by lakes, and levelled out and polished uneven ground in the lowlands. Erratic boulders are scattered far and wide, and if one looks closer, more refined traces can be found: glacially striated rocks, grooves in boulders, smooth roches moutonnées (Fig. 1.4). In glacial forefields, terminal moraines stand alone as silent witnesses to the former might of the glaciers. Further afield, glacial rivers have gouged out ravines and their contents created gravel plains and sediment strata in both lakes and the sea. This is the manner in which glaciers have left behind traces that tell us the history of climate change, even long after the glaciers themselves have disappeared.

1.2 Understanding Ice in the Global Environment

Glaciers and ice sheets are an important link in the Earth's hydrologic cycle (Fig. 1.5). Their existence and size is determined by climate, the transport of moisture and warmth around the globe through atmospheric and oceanic currents, the locations and levels of seas, and Earth's crustal movements. Ice masses adjust

Fig. 1.4 Scraped and grooved roches moutonnées just to the north of Gullfoss waterfall (see Chap. 6). The striation marks show the direction of the flow of the ice-age glacier. The grinding tools are still strewn all over the bedrock. Vegetation protected the roches moutonnées for thousands of years, but since Iceland has been settled, wind erosion has removed all flora and the topsoil. HB, July 1997

rapidly to changes in climate, but they may also influence the climate themselves. Glaciers contain the largest reservoirs of fresh water on Earth, storing water as ice during cold periods over timescales of hundreds to thousands of years. In the short term, they gather snow during winters and supply meltwater through the summers, providing water to plants, animals and humans when other sources may be scant during dry times.

Knowledge of the origins, existence and nature of glaciers is thus important for a full comprehension of the global environment. Such an understanding comes to a great extent from research into modern-day glaciers, for the nature of glaciers is the same now as it was in the past, and as it will be, for as long they exist: the present is a key to the past and the future. This applies to how ice masses expanded and once shaped continents, as well as to what their responses might be to climate change in the future. Moreover, the glaciers of today preserve a long history of climate, and evidence of changes in the composition of the Earth's atmosphere can be found in both the chemical composition of their layers of ice and in their frozen air bubbles.

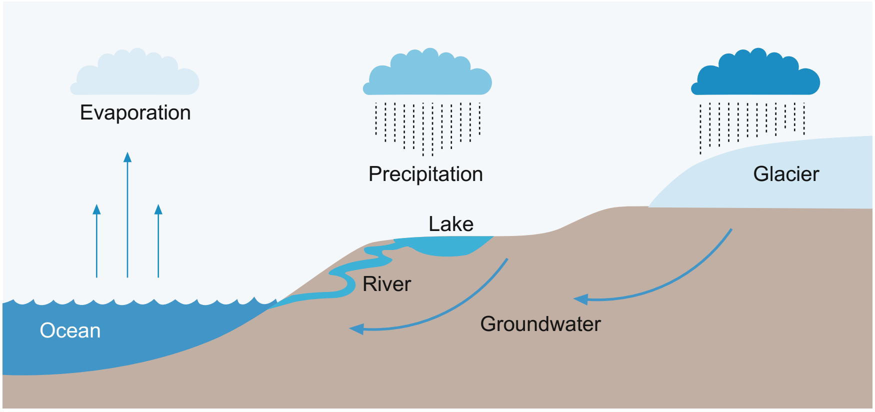


Fig. 1.5 Glaciers in the Earth's hydrologic cycle. Earth has been called both the Blue Planet, because 70 % of its surface is covered with ocean, and the Frozen Planet, because about 10 % of the land masses are covered with ice. It can even be said that we still live in an ice age, for the triple point of water, whereby it can coexist in all three of its phases, water vapour, liquid water, and frozen ice, is 0 °C. Ice masses on Earth are important for their influence on the climate and its fluctuations, the flow of meltwater to rivers, and Earth's sea levels. Water remains longest in its glacial forms during its global cycle

Glaciers are all similar in nature even though they may have dissimilar shapes, sizes and appearances (Fig. 1.6), and can be found all over the world, from the polar regions to the equator. They are all created from snow, but their development and behaviour can vary according to the amount of snow they accumulate, how cold and hard the ice is, how they discharge their meltwater, and if they creep forward over hard bedrock or soft basal sediments. Glaciers expand or recede in accordance with alterations to their mass balance, but their responses to climate change can vary from one glacier to another and their dynamics may be affected by

MAIN GROUPS	SUBCATEGORIES
Fig. 1.6a Ice sheets Move in all directions from their centres and over land, which is already mostly covered by ice; the surface does not usually reflect the subglacial topography.	**Continental glaciers, inland ice** The largest ice sheets like those existing today in Greenland and Antarctica. **Ice caps** Smaller and thinner than continental glaciers, e.g. the main ice masses in Iceland (Ch. 3) such as Vatnajökull, Hofsjökull, Mýrdalsjökull and Eiríksjökull. Also common on islands in the Arctic Ocean and in the southern part of Alaska.

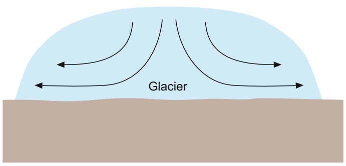
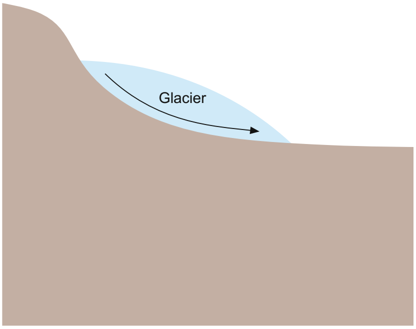


Fig. 1.6 Glaciers may be divided into three main categories according to their geomorphological shape and size

Fig. 1.6b Outlet glaciers
Move in one direction, determined by the landscape. Can be branches of an ice sheet.



Piedmont glaciers.
Glaciers that spread out like a fan once they reach lowland plains, e.g. Skeiðarárjökull (Ch. 8) and Múlajökull (Ch. 6) and Malaspina in Alaska.

Valley glaciers. Glaciers in valleys, e.g. Svínafellsjökull in Öræfi and Fláajökull in Austur-Skaftafell County.

Valley-head glaciers. Glaciers limited to the head of a valley, e.g. Bægisárjökull (Ch. 7).

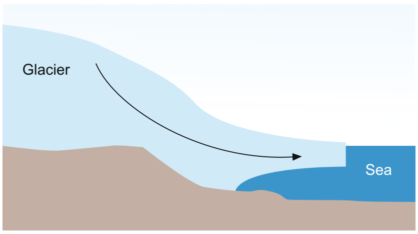
Cirques (corries). Glaciers in rounded valley hollows, e.g. Barkárdalsjökull.

Hanging glaciers. Glaciers in hanging valleys, e.g. above the main valley on Tröllaskagi peninsula (Ch. 7).

Ice aprons. Ice carapaces on mountain sides, e.g. in the highest reaches of Tröllaskagi (Ch. 7).

Mixed glaciers. Glacial tracts in the highlands broken up by nunataks, e.g. to the north of Öræfajökull towards Mávabyggðir and Esjufjöll (Ch. 8.5).

Fig. 1.6c Ice shelves.
The part of a glacier that floats on the sea or a lake and calves at its precipitous margins.



The largest ice shelves of Antarctica, e.g. the Ross Ice Shelf and the Filchner-Ronne Ice Shelf.

The ice cover on Lake Grímsvötn and the blue snout of Breiðamerkurjökull, which breaks up (calves) into the Jökulsárlón lagoon (see Ch. 8).

Fig. 1.6 (continued)

processes that are not directly related to climate, e.g. glaciers that surge on land or calve icebergs into the sea. A detailed description of the complex nature of glaciers will not be addressed here, but an overview of basic glaciology will follow below. For further details see Sharp (1991), Paterson (1994), Knight (1999), Hambrey and Alean (2004), Hooke (2005), Cuffey and Paterson (2010), Benn and Evans (2010), van der Veen (2013).