World Geomorphological Landscapes

Colin K. Ballantyne
John E. Gordon *Editors*

Landscapes and Landforms of Scotland

Springer

World Geomorphological Landscapes

Series Editor

Piotr Migoń, Institute of Geography and Regional Development, University of Wrocław, Wrocław, Poland

Geomorphology – 'the Science of Scenery' – is a part of Earth Sciences that focuses on the scientific study of landforms, their assemblages, and surface and subsurface processes that moulded them in the past and that change them today. Shapes of landforms and regularities of their spatial distribution, their origin, evolution, and ages are the subject of geomorphology. Geomorphology is also a science of considerable practical importance since many geomorphic processes occur so suddenly and unexpectedly, and with such a force, that they pose significant hazards to human populations. Landforms and landscapes vary enormously across the Earth, from high mountains to endless plains. At a smaller scale, Nature often surprises us creating shapes which look improbable. Many geomorphological landscapes are so immensely beautiful that they received the highest possible recognition – they hold the status of World Heritage properties. Apart from often being immensely scenic, landscapes tell stories which not uncommonly can be traced back in time for millions of years and include unique events. This international book series will be a scientific library of monographs that present and explain physical landscapes across the globe, focusing on both representative and uniquely spectacular examples. Each book contains details on geomorphology of a particular country (i.e. The Geomorphological Landscapes of France, The Geomorphological Landscapes of Italy, The Geomorphological Landscapes of India) or a geographically coherent region. The content is divided into two parts. Part one contains the necessary background about geology and tectonic framework, past and present climate, geographical regions, and long-term geomorphological history. The core of each book is however succinct presentation of key geomorphological localities (landscapes) and it is envisaged that the number of such studies will generally vary from 20 to 30. There is additional scope for discussing issues of geomorphological heritage and suggesting itineraries to visit the most important sites. The series provides a unique reference source not only for geomorphologists, but all Earth scientists, geographers, and conservationists. It complements the existing reference books in geomorphology which focus on specific themes rather than regions or localities and fills a growing gap between poorly accessible regional studies, often in national languages, and papers in international journals which put major emphasis on understanding processes rather than particular landscapes. The World Geomorphological Landscapes series is a peer-reviewed series which contains single and multi-authored books as well as edited volumes.

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Series Editor Preface

Landforms and landscapes vary enormously across the Earth, from high mountains to endless plains. At a smaller scale, Nature often surprises us by creating shapes which look improbable. Many physical landscapes are so immensely beautiful that they have received the highest possible recognition—they hold the status of World Heritage properties. Apart from often being immensely scenic, landscapes tell stories which not uncommonly can be traced back in time for tens of millions of years and include unique events. In addition, many landscapes owe their appearance and harmony not solely to natural forces. For centuries, or even millennia, they have been shaped by humans who modified hillslopes, river courses, and coastlines, and erected structures which often blend with the natural landforms to form inseparable entities.

These landscapes are studied by Geomorphology—'the Science of Scenery'—a part of Earth Sciences that focuses on landforms, their assemblages, the surface and subsurface processes that moulded them in the past and that change them today. The shapes of landforms and the regularities of their spatial distribution, their origin, evolution, and ages are the subject of research. Geomorphology is also a science of considerable practical importance since many geomorphic processes occur so suddenly and unexpectedly, and with such a force, that they pose significant hazards to human populations and not uncommonly result in considerable damage or even casualties.

To show the importance of geomorphology in understanding the landscape, and to present the beauty and diversity of the geomorphological sceneries across the world, we have launched a new book series *World Geomorphological Landscapes*. It aims to be a scientific library of monographs that present and explain physical landscapes, focusing on both representative and uniquely spectacular examples. Each book will contain details on geomorphology of a particular country or a geographically coherent region. This volume is dedicated to Scotland, part of the world where modern geoscience was born in the late eighteenth century thanks to the insightful thinking of James Hutton; some of key sites first interpreted by Hutton are presented in this book, although in a more geomorphological context. As with most books in the series, this one also starts with chapters providing the geological and temporal context, setting the stage for systematic presentation of the geomorphology of specific regions of Scotland. The regional part is as comprehensive as possible, so that the reader can virtually visit the northern archipelagos of Shetland and Orkney, jump across the islands of the Hebrides, travel through the glacially moulded Scottish Highlands to the largely inherited landscape of Buchan, enjoy the glacial topography of the Midland Valley, be introduced to the less-known geomorphology of the Southern Uplands, and get acquainted with the diverse Scottish coasts. Even underwater landscapes around the Scottish landmass are covered. The effects of successive glaciations are the main theme in many regions, but we also learn about the pre-Quaternary roots of Scotland's topography, going back to really distant times of the Palaeozoic, as well as the evidence of the multitude of landscape changes that postdate the demise of the last ice sheet and glaciers.

The World Geomorphological Landscapes series is produced under the scientific patronage of the International Association of Geomorphologists—a society that brings together geomorphologists from all around the world. The IAG was established in 1989 and is an independent scientific association affiliated with the International Geographical Union and the International Union of Geological Sciences. Among its main aims are to promote geomorphology and to foster dissemination of geomorphological knowledge. I believe that this lavishly illustrated series, which sticks to the scientific rigour, is the most appropriate means to fulfil these aims and to serve the geoscientific community. To this end, my great thanks go to Colin Ballantyne and John Gordon, who agreed to coordinate the book and contributed many chapters themselves, based on their enormous experience in geomorphological research across the lowlands, highlands, and islands of Scotland. Their editorial work was absolutely first class, and they ensured that all geographical gaps were expertly filled. Reading many chapters brought back my own distant memories of seeing a fraction of Scotland's superb geomorphology, under expert guidance of Philip Ringrose and Michael Thomas, whose hospitality is also acknowledged here. I am also grateful to all the other contributors to the book, who agreed to add the task of writing chapters to their busy agendas and delivered high-quality final products. Collectively, they have shown us that Scottish geomorphological landscapes are some of the finest in the world and are, besides single malts, the key attractions of this part of the globe.

Wrocław, Poland

Piotr Migoń
Series Editor

Foreword

Scotland is renowned for its landscapes of mountains, lowlands, islands, and its intricate coast. Within an hour or so, a visitor can travel from the rolling uplands and coastlands of the east to the steep and rocky mountains of the west, or from the gentle central lowlands to the open landscapes of the northwest with their isolated mountains rising above a rugged plain, or even from the sweeping beaches of the east to the fretted and dramatic coast of the fjords in the west. By bridge or ferry, the visitor can move to the world of islands, each with its own distinctive landscape. And if the visitor wonders at this remarkable variety within such a small area, then he or she enters the world of geomorphology, namely the study of landforms, their origins, and the processes that have shaped them in the past and are shaping them today.

Perhaps it is no surprise that Scotland's landscapes have stimulated scientists over the centuries and that several world-leading figures cut their teeth in Scotland. Indeed, in the late eighteenth century and nineteenth century, Scotland was a veritable hotbed of activity that transformed geomorphology. James Hutton, whose treatise *Theory of the Earth* was published in Edinburgh in 1788, is seen internationally as the founder of both geomorphology and geology. His ideas, developed by John Playfair, underpinned Charles Lyell's hugely influential three-volume *Principles of Geology* published in the 1830s. In 1864, James Croll was the first to develop the astronomical theory of the ice ages; no mean glaciologist and fluvial geomorphologist himself, Croll was stimulated by the wish to understand Scotland's glacial landforms and interglacial sediments. The Geikie brothers were notable for their demonstration of how field studies could link with theory to aid geomorphological understanding. In 1865, Archibald Geikie published what was probably the first-ever regional geomorphology, *The Scenery of Scotland*. A few years later in 1874, James Geikie produced his book on *The Great Ice Age*, a path-breaking study of Scotland's glacial deposits that reflected the vicissitudes of the last ice age. And even Charles Darwin was involved, although it must be admitted that his marine explanation of the Parallel Roads of Glen Roy has since been rejected!

This book, entitled the *Landscapes and Landforms of Scotland*, consists of 29 chapters, each written by authors with expertise and empathy for particular topics or regions and reflecting the latest research. The book begins with early chapters on the geological evolution and the evolving physical environment of Scotland. Here we learn that Scotland first became a geological entity ~420 million years ago. There are rocks telling of the glacial, desert, and humid tropical climates experienced as Scotland migrated from near the South Pole to its present mid-latitude location in the Northern Hemisphere. The main outlines of the present topography and drainage have evolved in the last 65 million years, first under fluvial conditions and then in the last 2.6 million years, through successive glaciations. Currently, we learn how Scotland is being moulded by rivers, frost, mass movements, wind, and the sea.

Many chapters in the book are devoted to particular regions of iconic interest. These will be a boon to geomorphologists, teachers, students, visitors, and all those with an interest in the landscape of Scotland. Thus in the west and north, there are regional chapters covering the geomorphology of Shetland, Orkney and Caithness, the Outer Hebrides, and the islands of Skye, Mull, Rùm, Arran, Islay, Jura, Colonsay, Tiree, and Coll; for the western mainland, there are chapters on the far northwest and Wester Ross. Other regional chapters cover the Grampian Highlands (east, central and west), the uplands of the Southern Uplands, and the Solway coast and lowlands. There are chapters devoted to the Midland Valley, a glacially streamlined landscape punctuated by upstanding volcanic plugs such as that crowned by Edinburgh Castle and another that is home to the gannets on Bass Rock. Visitors to iconic mainland sites will be pleased to find a chapter covering Loch Ness in the Great Glen, one on the Parallel Roads of Glen Roy, one on Loch Lomond, and one on the Cairngorm Mountains in the heart of the national park of the same name. In the last location, the juxtaposition of tor-studded ancient uplands with dramatic cliffs bounding glacially scoured corries and troughs is a wonderful example of selective erosion by ice sheets and a dramatic contrast to the glacially dissected landscape of western Scotland.

Other chapters cover specific geomorphological topics. Thus, we can read of landslides in the Northwest Highlands, fluvial landforms in Glen Feshie, the origin of the ancient palaeo-surface of Northeast Scotland, glacifluvial landforms in the Midland Valley, and beaches and dunes of Eastern Scotland, especially along the Moray coast and from Aberdeenshire to East Lothian. Of special interest is one chapter that opens up a new world; it describes and interprets the geomorphology of the extensive continental shelf surrounding Scotland. Here, the surveys associated with the petroleum and fishing industries have revolutionised our understanding of Scotland's geomorphological evolution. For example, we can now see that the last ice sheet extended to the Atlantic margin of the continental shelf, with a huge outlet glacier flowing in a trough from The Minch in Northwest Scotland and depositing a large fan of debris at the shelf edge. The final chapter in the book focuses on the geomorphological heritage in Scotland and its conservation. Overall, the book is a powerful statement of the importance of geomorphology in underpinning so much of what makes Scotland's landscapes so special.

I would like to end with a note on behalf of future readers to thank all those authors who have contributed to chapters and also to the editors, Colin K. Ballantyne and John E. Gordon, who have organised and contributed to such a significant volume. I hope readers and visitors will enjoy learning about the geomorphology of Scotland, especially since it comes with the privilege of learning from experts who have devoted so much of their energy to its study. The book is significant not only for the subject of geomorphology, but also as a wider inspiration to those who treasure the landscape and culture of Scotland.

David Sugden
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We wish to thank the editor of the World Geomorphological Landscapes series, Piotr Migoń, for his excellent guidance and advice during the compilation of this book. Piotr reviewed every chapter and made perceptive comments on each one; we particularly valued his continuous support and remarkably rapid turnaround of all submitted material. We also owe a great debt to Graeme Sandeman, formerly cartographer at the University of St Andrews, for producing many of the maps and diagrams in the book; without his skill and forbearance, the final production of several chapters would have been greatly delayed. Finally, we thank Emeritus Professor David Sugden of the University of Edinburgh for agreeing to write the Foreword to this volume. David is the doyen of geomorphology and glaciology in Scotland, and we are honoured to have his endorsement.

An edited volume such as this would not be possible without the commitment of our 21 contributing authors, who have persevered in producing their chapters despite the difficult circumstances and pressures arising from the 2020 coronavirus pandemic. These authors have themselves added hugely to our understanding of the landscapes and landforms of Scotland, and we are privileged to have received their contributions. We particularly thank them for their patience as each chapter evolved through successive reviews and edits and for responding positively to our numerous queries and suggestions.

The chapters in this book were externally peer reviewed by a small but distinguished group of individuals, and we are delighted to acknowledge the contributions of Riccardo Arosio, Doug Benn, Clare Boston, John Brown, Ben Chandler, Rodger Connell, Simon Cook, Pete Coxon, Roger Crofts, Rob Ferguson, Andrew Finlayson, Callum Firth, Con Gillen, Martin Kirkbride, Stephen Livingstone, Jon Merritt, Julian Orford, Brice Rea, Jim Rose, and David Smith to the review process, which resulted in substantial improvements to many of the draft chapters.

We also thank the staff at Springer Nature, in particular Manjula Saravanan and Banu Dhayalan, and project manager Madanagopal Deenadayalan and the team at Scientific Publishing Services, Chennai, India, for overseeing and expediting the production of the book on behalf of Springer Nature.

The editors would like to express their unanimity and solidarity in co-editing this book, which has benefitted greatly from equal sharing of editorial tasks and responsibilities. Writing, editing, and compilation of this volume took over 18 months, and it was not always straightforward. We are both fortunate in having understanding wives, Rebecca Trengove and Janet Gordon, who are inured by experience to having husbands who spend long hours closeted in their studies. Rebecca and Janet provided vital support throughout and deserve our warmest thanks of all.

Colin K. Ballantyne
John E. Gordon

Contents

Editors and Contributors

About the Editors

Colin K. Ballantyne is Emeritus Professor of Physical Geography at the University of St Andrews and Fellow of the Royal Society of Edinburgh, the Royal Scottish Geographical Society, the Geological Society, and the British Society for Geomorphology. He has published over 200 papers on various aspects of geomorphology and Quaternary science, many of which concern Scotland. His recent books include *The Quaternary of Skye* (2016), *Periglacial Geomorphology* (2018), and *Scotland's Mountain Landscapes: A Geomorphological Perspective* (2019). He is Honorary Life Member of the Quaternary Research Association and Recipient of the Clough Medal of the Edinburgh Geological Society, the Saltire Earth Science Medal, the Gordon Warwick Medal and Wiley Award of the British Society for Geomorphology, the President's Medal, Coppock Research Medal and Newbigin Prize of the Royal Scottish Geographical Society, and the Lyell Medal of the Geological Society.

John E. Gordon is Honorary Professor in the School of Geography and Sustainable Development at the University of St Andrews, Scotland. His research interests include geoconservation, the Quaternary of Scotland, and mountain geomorphology and glaciation in North Norway and South Georgia. He has published many academic papers and popular articles in these fields and is co-author/co-editor of books including *Quaternary of Scotland* (1993), *Antarctic Environments and Resources* (1998), *Earth Science and the Natural Heritage* (2001), *Land of Mountain and Flood: the Geology and Landforms of Scotland* (2007) and *Advances in Scottish Quaternary Studies*, a special issue of *Earth and Environmental Science Transactions of the Royal Society of Edinburgh* (2019). He is a Fellow of the Royal Scottish Geographical Society, an Honorary Member of the Quaternary Research Association, and a Deputy Chair of the Geoheritage Specialist Group of the IUCN World Commission on Protected Areas.

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1 Landscapes and Landforms of Scotland: A Geomorphological Odyssey

John E. Gordon and Colin K. Ballantyne

Abstract

The landscapes and landforms of Scotland are renowned for their outstanding geodiversity, the outcome of a long and complex geological evolution, Cenozoic uplift and etchplanation, and modification by glacial and interglacial processes during the Quaternary. The Scottish landscape has provided the stimulus for over two centuries of groundbreaking research in geology and geomorphology, beginning with the seminal work of James Hutton (1726–1797) and the subsequent development of uniformitarianism as a geological paradigm by Charles Lyell (1797–1875). From 1840, Scottish researchers played a major part in the recognition of the role of Quaternary glaciation in fashioning the landscape, and other nineteenth-century Scottish pioneers developed such concepts as glacio-isostasy, multiple Pleistocene glaciations and the astronomical theory of climate change. We trace the subsequent history of key geomorphological developments in Scotland before outlining the rationale for the chapters in this book: (i) four systematic chapters that set the context and chronology for those that follow; (ii) 17 regionally focused chapters that encompass particular landscapes; and (iii) six thematic-based chapters that highlight particular aspects of Scotland's geomorphology. The final chapter addresses geoconservation, and the approach and measures adopted to protect Scotland's exceptional geoheritage.

Keywords

Geomorphology • Geology • Geodiversity • Geoheritage • Scotland • Landscape • History of geomorphology

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1.1 Introduction: The Landscapes of Scotland

The story of the origin of our scenery … leads us back into the past farther than imagination can well follow … Archibald Geikie (1865), p. 351.

Scotland is renowned for the great variety of its scenery. In the far northwest, monolithic sandstone inselbergs surmount a platform of Archaean gneiss; on the Isle of Skye, serrated battlements of Palaeogene gabbro rise above deeply gouged glacial troughs, and huge basalt landslides descend to the sea; on the granite of the Cairngorms, glacial troughs carve through an ancient tor-studded plateau scalloped by cirques; and even the lowlands of central Scotland are interrupted by steep lava scarps, sills and volcanic plugs; whilst at the coast, sandy beaches and bays backed by dunes and raised (emerged) beaches contrast starkly with rocky promontories and spectacular cliffs (Fig. 1.1). This remarkable landscape diversity occurs within a small country only 80,240 km^2 in extent; few (if any) parts of the Earth's surface encompass such variety within an equivalent area.

Such landscape heterogeneity is the outcome of not only a long and complex geological evolution that spans the Archaean to the Cenozoic, but also the varied processes that have operated over the past 400 Ma to mould the land surface to its present form. Most of the large-scale elements of Scotland's relief had evolved by the end of the Neogene Period (2.59 Ma), but the detailed form of the landscape was radically modified during the multiple glacial-interglacial cycles of the Quaternary (2.59 Ma to the present). Successive episodes of icefield or ice-sheet glaciation reshaped much of the pre-glacial landscape, carving alpine landforms across the western Highlands and Hebrides, selectively incising older palaeosurfaces in the Eastern Grampian Highlands and Southern Uplands, scouring the basement gneisses of the far northwest and depositing a mantle of glacigenic deposits over the sedimentary rocks of the Midland Valley. During ice-free intervals, the landscaping

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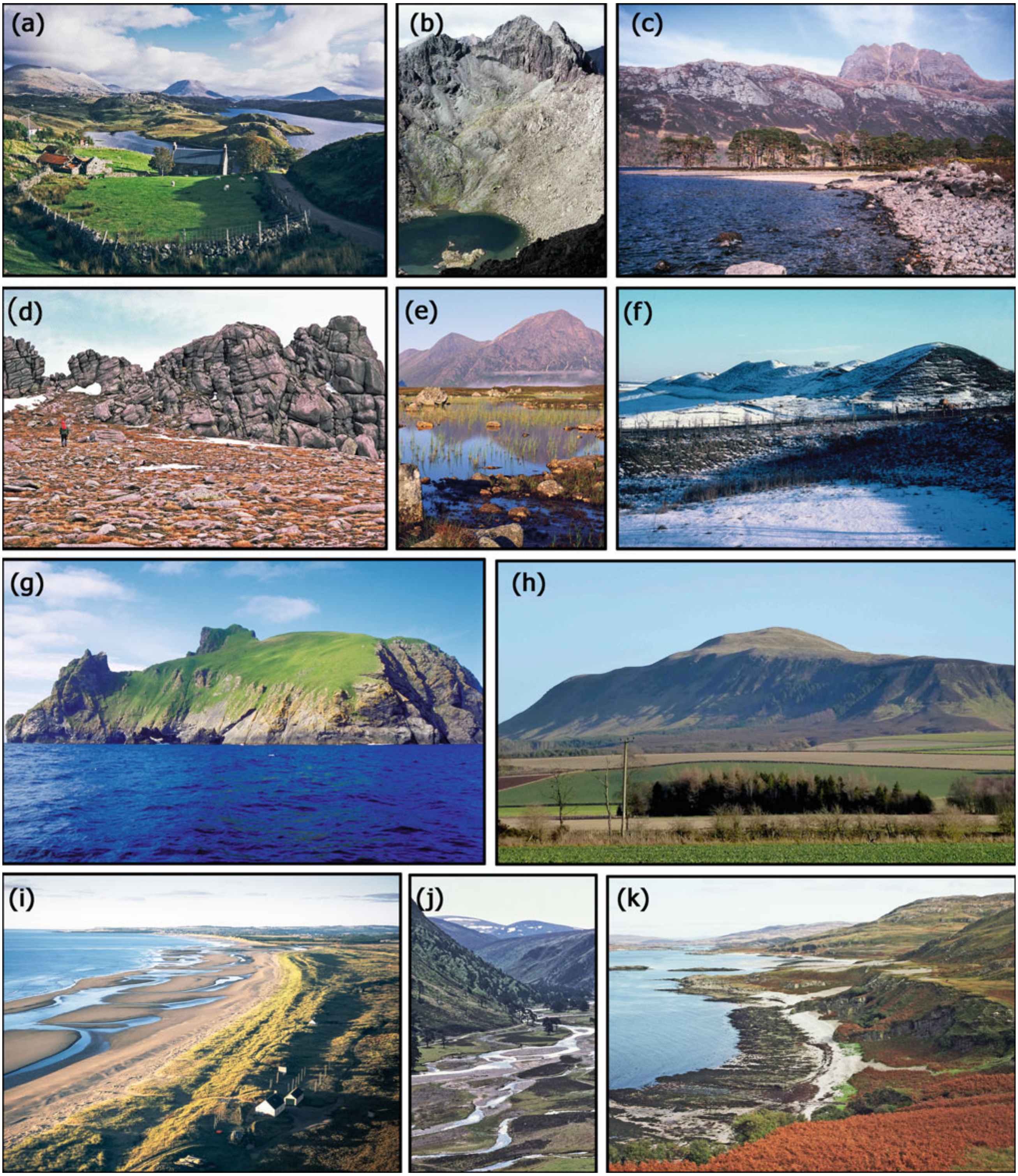

Fig. 1.1 Landscapes and landforms of Scotland, a land of outstanding geodiversity. **a** Ice-scoured landscape on Archaean Lewisian gneiss, with Cambrian quartzite inselbergs in the background, NW Sutherland. **b** Landscape of mountain glacier erosion with cirques and arêtes in Palaeogene volcanic rocks, Cuillin Hills, Isle of Skye. **c** Inselberg in Proterozoic Torridonian sandstone resting on an ancient erosion surface on Archaean Lewisian gneiss, Wester Ross. **d** Granite tor, Cairngorm Mountains. **e** Ice-scoured montane basin of Rannoch Moor, Western Grampian Highlands. **f** Carstairs Kames esker system, Midland Valley. **g** Coastal cliffs in Palaeogene volcanic rocks, St Kilda. **h** Scarp of the Carboniferous Midland Valley Sill, Lomond Hills, Fife. **i** Beach and dune coastal landscape, St Cyrus, Montrose Bay, eastern Scotland. **j** Wandering gravel-bed river, River Feshie, Strath Spey. **k** Raised and intertidal shore platforms, Isle of Jura. (Images: **a**–**d**, **f**, **i**–**k** John Gordon; **e** Lorne Gill/NatureScot; **g** David Donnan/NatureScot; **h** Colin Ballantyne)

effects of glaciation were modulated by periglacial activity, renewed rock weathering, rivers, paraglacial landslides and coastal processes. These changes occurred against a backdrop of fluctuations in sea level and changes in vegetation cover, from tundra and cold desert to boreal forest and, during interglacials, temperate deciduous forest. Moreover, the impact of successive glaciations was uneven: in the west, fast-flowing, erosive glaciers fed by abundant snowfall extensively dissected the pre-glacial terrain, whereas in the east some areas exhibit only limited and selective modification of the pre-glacial landscape. Nowhere is this better illustrated than on the Scottish coastline: the west coast is fretted by glacially deepened fjords and sounds and fringed by hundreds of islands and islets, but such features are lacking along Scotland's eastern seaboard.

1.2 Exploring Scotland's Geodiversity

1.2.1 The Scottish Pioneers

Given its remarkable geological and geomorphological diversity, it is not surprising that the Scottish landscape has stimulated a vast body of research for more than two centuries and continues to yield findings of global significance for geoscience. Perhaps the most fundamental of these appeared in 1788 in volume one of the *Transactions of the Royal Society of Edinburgh* under the title *Theory of the Earth; or an investigation of the laws observable in the composition, dissolution and restoration of land upon the globe.* The author of this ambitious exposition was James Hutton (1726–1797; Fig. 1.2a), now regarded by many as the father of modern geology. Hutton's claim to geological paternity rests not merely on his formidable skills in interpreting the rock record in various parts of Scotland, but in his realization that the rocks and landforms of Scotland represent not some past cataclysm, but the slow operation through aeons of time of the processes presently acting on and within the Earth: the paradigm, later termed *uniformitarianism,* that underpins all subsequent geological and geomorphological research. This insight required rejection of the then-accepted biblical timescale of creation some 6000 years ago and enabled Hutton to stare into the depths of deep time; his treatise concludes with the stirring words: 'the result, therefore of our present enquiry is, that we find no vestige of a beginning, no prospect of an end'.

Hutton was a prolix writer, but his ideas were promoted after his death with the publication of the splendid *Illustrations of the Huttonian Theory of the Earth* (1802) by his disciple, John Playfair (1748–1819), and formed much of the basis of the hugely influential three-volume *Principles of Geology*, published by another Scot, Charles Lyell (1797–1875; Fig. 1.2b), between 1830 and 1833. This monumental treatise formed the bedrock of geological enquiry across the world for half a century (the final edition appeared in 1875) and exhibits a keen appreciation of the role of surface processes in the fashioning of landforms and landscapes. With its demonstration of the great age of the Earth, Lyell's *Principles* played a fundamental role in influencing Charles Darwin's ideas on the evolution of species.

Recognition that Scotland had been glaciated was first anticipated by Robert Jameson (1774–1854; Fig. 1.2c), Professor of Natural History at the University of Edinburgh. In lectures Jameson presented in 1827 that were recorded in the notes of his student, James Forbes (1809–1868; Fig. 1.2d), Jameson referred to the existence of moraines as evidence of former Scottish glaciers (Cunningham 1990). Vindication of his views came in 1840 when Swiss glaciologist, Louis Agassiz, travelled by stagecoach from Glasgow to Fort William in the western Highlands in the company of William Buckland, president of the Geological Society. As their coach rumbled slowly northwards, Agassiz noted countless examples of the landforms that he had observed on the forelands of Swiss glaciers: moraines, erratics, roches moutonnées and striae. Their journey culminated in Glen Roy, where three shorelines or 'parallel roads' cut across both valley sides. Dismissing Darwin's interpretation of these features as the uplifted products of marine erosion, Agassiz concluded that they represented shorelines formed at the margin of an ancient glacier-dammed lake, an interpretation that implies the former existence of a glacier hundreds of metres thick in neighbouring Glen Spean. Agassiz dashed off a brief account that was published in *The Scotsman* newspaper, noting that he had seen near Ben Nevis '…the most distinct morains and polished rocky surfaces' and concluding that '…the existence of glaciers in Scotland at early periods can no longer be doubted' (Agassiz 1840, p. 3). Whilst Agassiz travelled onwards to Ireland, Buckland visited Lyell at the latter's estate in Angus. Lyell was quickly converted to what became known as the Glacial Theory and together with Buckland conducted an energetic search for further evidence of glaciation in Scotland.

Agassiz, Buckland and Lyell presented papers on their momentous findings at meetings of the Geological Society in November and December 1840 but met with a critical response, so much so that Lyell recanted. But the seed was sown: only six years later the pioneering Scottish glaciologist James Forbes published an account of glacial phenomena on the Isle of Skye (Forbes 1846), and by the 1870s, few geologists were in any doubt that glaciers had not only occupied Scotland, but had formerly extended over extensive tracts of Europe and North America.

Fig. 1.2 Key figures in the history of geomorphology in Scotland. **a** James Hutton. **b** Charles Lyell. **c** Robert Jameson. **d** James Forbes. **e** Archibald Geikie. **f** James Geikie. **g** John Horne (left) and Ben Peach (right). **h** Andrew Ramsay. **i** James Croll. **j** Thomas Jamieson. **k** Brian Sissons. (Images: **a** Sir Henry Raeburn, *James Hutton, 1726–1797. Geologist*, National Galleries of Scotland. Purchased with the aid of the Art Fund and the National Heritage Memorial Fund 1986. Image rights: Copyright National Galleries of Scotland, photography by AIC photography services. **b** Photograph by John Watkins. Wellcome Collection. Attribution 4.0 International (CC BY 4.0). **c** Stipple engraving by J. Jenkins, 1847, after K. Macleay. Wellcome Collection. Attribution 4.0 International (CC BY 4.0). **d** Unattributed engraving from Shairp et al. (1873). **e** Unattributed photo. Wellcome Collection. Attribution 4.0 International (CC BY 4.0). **f** Photo by Gutebrunst from Newbiggin and Flett (1917); **g** Courtesy of the British Geological Survey, UKRI sourced: https://geoscenic.bgs.ac.uk/asset-bank/action/quickSearch?CSRF=D5QFYdsKdJtoS2OixvJW&newSearch=true&quickSearch=true&includeImplicitCategoryMembers=true&keywords=P008682. **h** Photograph by D. Hains from Geikie (1895). **i**: Unattributed photo from Irons (1896); **j** Courtesy of the University of Aberdeen from 'Wilson's Aberdeen Portraits, George Washington Wilson and Co', L fAa Y24 Wil; **k** Murray Gray)

1.2.2 1865–1914: Archibald Geikie, James Geikie and the Geological Survey of Scotland

The year 1865 marked the publication of a remarkable book entitled *The Scenery of Scotland, Viewed in Connexion with its Physical Geology*. This book has a claim to be the first to focus on the geomorphology of any part of the Earth. It contains not only an analysis of the role played by geology in determining the shape of the land surface, but also over 100 pages devoted to glacial landforms and deposits, together with detailed descriptions of the contribution of rock weathering, frost, soil erosion, rivers and coastal processes in the evolution of the Scottish landscape. The final edition, published in 1901, brilliantly encompasses the sum of nineteenth-century understanding of the geomorphology of Scotland.

The author of this book was Archibald Geikie (1835–1924; Fig. 1.2e). Like his equally eminent brother, James Geikie (1839–1915; Fig. 1.2f), Archibald Geikie was not only a geologist of the first rank, but also an innovative geomorphologist, whose understanding of glacigenic deposits and their representation in the stratigraphic record provided a foundation for much later work. James Geikie authored several seminal books on geological topics, but his crowning achievement was *The Great Ice Age* (1874; third edition 1894), which drew heavily on his research in Scotland and demonstrated that the stratigraphic complexity of glacial deposits implied that the Quaternary Period incorporated multiple glacial stages separated by intervening temperate intervals. Together, the Geikie brothers not only employed the diversity of Scottish landscapes to illustrate and enrich their research, but also established a tradition of geomorphological enquiry that persists to the present. They were also pioneers in learning from modern glacier environments, conducting a Geological Survey expedition to Norway in 1865 (Worsley 2006). Another Scot, Andrew Crombie Ramsay (1814–1891; Fig. 1.2h), was a strong influence on Archibald Geikie. Ramsay, who worked for many years with the Geological Survey in Wales, was a key figure in recognizing and promoting the role of glacial erosion in shaping the landscape, and particularly in forming glacial troughs, rock basins, cirques, fjords and the lochans in knock-and-lochan topography, including many classic examples in Scotland (Ramsay 1862).

The establishment of the Geological Survey of Scotland in 1867, with Archibald Geikie as its first director, lent impetus to the mapping and understanding of Scotland's geology and landscape. Early work focused on the Midland Valley and adjacent areas, but in 1875 attention turned to the Highlands. The complexities of Highland geology were unravelled by a remarkable team of survey geologists, including James Geikie, Charles Clough (1852–1916) and two individuals who collaborated extensively, Ben Peach (1842–1926) and John Horne (1848–1928; Fig. 1.2g). Peach and Horne not only resolved the 'Highland controversy' by demonstrating thrust-faulting of Moine rocks across the stable foreland of the Hebridean terrane, but also made major contributions to Quaternary geology, notably on Orkney, Shetland and the Northwest Highlands, paralleled by pioneering research on the Outer Hebrides by Geikie and the landscape of Argyll by Clough. The manager of records at the Survey was James Croll (1852–1916; Fig. 1.2i), the father of the orbital theory of glacial-interglacial oscillations, subsequently enshrined as the Croll-Milanković theory and now widely accepted as representing the pacemaker of climate change during the Quaternary. Also briefly associated with the Scottish Survey was the Irishman, William Bourke Wright (1876–1939), who contributed innovative work on the coastal platforms and igneous rocks of the Hebrides, and whose book *The Quaternary Ice Age* (1914; second edition 1936) became the standard reference text on the Quaternary for nearly half a century and makes frequent reference to the glacial landforms and deposits of Scotland, and to the pattern of isostatic recovery of the land surface.

Another pioneering Scottish figure in the nineteenth century was Thomas Francis Jamieson (1829–1913; Fig. 1.2j), factor of Ellon Castle Estate north of Aberdeen and Fordyce Lecturer in Agriculture at the University of Aberdeen. Jamieson is credited with establishing the principle of glacio-isostasy from his work on the carse deposits in the Forth valley and was an early advocate of glacial erosion in shaping the landscape. He also made significant contributions to understanding the glaciation of NE Scotland and was the first to work out in detail the sequence of formation of the ice-dammed lakes and Parallel Roads of Glen Roy.

1.2.3 The Twentieth Century (1914–2000)

The interwar years (1918–1939) saw the publication of further maps and memoirs by the Geological Survey of Scotland, notably the prescient work of Edward Bailey (1881–1965) on the Tertiary Igneous Province in the Inner Hebrides and the igneous rocks of the Glen Coe and Ben Nevis region. During this period, only a handful of papers addressed Scotland's geomorphology, notably a 1923 study of the Moray Firth coast by the Scottish geographer, Alan G. Ogilvie (1887–1954). A focus on Scottish geomorphology was reignited after the Second World War by David Linton (1906–1971); although Linton is best remembered for his work on long-term landscape evolution (then termed 'denudation chronology'), he published a dozen seminal papers on river capture, glacial erosion and tors in Scotland, some of which have continued resonance today. Interest in the later Quaternary was reawakened by a survey of the Lateglacial history of Scotland (1955) by John Kaye Charlesworth (1889–1972), whose magisterial two-volume book *The Quaternary Era* (1957) also refers to copious Scottish examples. A particularly outstanding (and still much-cited) contribution to the post-war study of geomorphology in Scotland was made by the French geomorphologist, Alain Godard, whose eclectic doctoral thesis, *Recherches de Géomorphologie en Écosse du Nord-Ouest* (1965), encompassed the influence of lithology on landscape evolution, identification of palaeosurfaces, recognition of the influence of pre-glacial weathering, neotectonics, the effects of successive Pleistocene glaciations and postglacial landscape modification by periglacial activity and landslides. Notable contributions to the documentation of Scotland's coastal geomorphology during the second half of the century included publication of *The Coastline of Scotland* (1963) by J. Alfred Steers and the *Beaches of Scotland* surveys commissioned by the Countryside Commission for Scotland between 1969 and 1984 (Ritchie and Mather 1984).

The most influential figure in the development of geomorphology in Scotland in the second half of the twentieth century was Brian Sissons (1926–2018; Fig. 1.2k). Between 1958 and 1982, he published some 80 papers on aspects of Scottish geomorphology, together with two influential books: *The Evolution of Scotland's Scenery* (1967) and a briefer update, *The Geomorphology of the British Isles: Scotland* (1976). His principal achievements included a re-evaluation of the significance of meltwater channels and associated glacifluvial landforms, deciphering the complex sequence of raised and buried shorelines in eastern Scotland and the significance of rock platforms along the western seaboard, and detailed reconstruction of the extent and palaeoclimatic implications of the glaciers that formed in Scotland during the Loch Lomond (≈Younger Dryas) Stade of ~12.9–11.7 ka, as well as reassessment of the sequence of Lateglacial events associated with the ice-dammed lake sequence in Glen Roy (Ballantyne and Gray 1984). Equally importantly, he nurtured a school of over 30 Ph.D. students, many of whom continued to contribute research on aspects of the geomorphology and Quaternary history of Scotland, and some of whom remain active at present.

This period also saw a significant expansion in studies of modern glacier environments by geomorphologists based in Scotland. Among these, Chalmers Clapperton, Robert Price and David Sugden applied knowledge gained from their work on glacier processes in Iceland, Greenland, Alaska, Svalbard and the Antarctic to provide new insights into the formation of Scotland's glacial landforms and landscapes, both in their research and teaching (Price 1973, 1983; Sugden and John 1976).

The status of research at the end of the twentieth century on aspects of the geomorphology and Quaternary evolution of Scotland was summarized in the Quaternary, coastal, fluvial, mass-movement, and karst and caves volumes of the Geological Conservation Review (Gordon and Sutherland 1993; Waltham et al. 1997; Werritty and McEwen 1997; May and Hansom 2003; Cooper 2007). These encapsulated contemporary understanding of glaciation, Quaternary environmental changes, postglacial landscape evolution and modern coastal and river processes, with detailed accounts of key sites.

1.2.4 Recent Research

The geomorphological themes explored by Sissons and others have continued to engage geomorphologists working in Scotland over the past 40 years, with increasingly sophisticated research on raised shorelines and sea-level change, and the landforms, dimensions and dynamics of Loch Lomond Stadial glaciers, but new or revigorated research has also addressed many other aspects of Scotland's landscape evolution during this period, often reflecting technological advances in geochronology and remotely-sensed data. There have, *inter alia*, been groundbreaking discoveries regarding Cenozoic landscape evolution and the geomorphology of the continental shelf; a revolution in our understanding of the dimensions and dynamics of the last Scottish Ice Sheet; rigorous re-examination and formal classification of Quaternary stratigraphy; a growing awareness of the importance of paraglacial landscape modification; enhanced understanding of river processes and channel changes, and coastal sediment budgets; and heightened appreciation of the importance of geoheritage and geoconservation. Many of these topics were reviewed in a recent journal issue edited by Gordon and Werritty (2019) and permeate the chapters of this book. Several recent books also offer introductions to the geological framework and geomorphology of Scotland, notably Trewin (2002), McKirdy et al. (2007), Gillen (2013), Upton (2015) and Ballantyne (2019). The pace of recent research on the landscapes and landforms of Scotland is relentless; though with James Hutton we can identify the beginning, there is certainly no immediate prospect of an end.

1.3 Revealing Scotland's Geodiversity: The Structure of This Book

As with other volumes in this series, this account of Scotland's landscapes and landforms contains three categories of chapters, each with a different focus: (i) systematic chapters that set the context and chronology for those that follow;

(ii) regionally focused chapters that encompass particular landscapes; and (iii) thematic-based chapters that focus on particular aspects of Scotland's geomorphological heritage (Fig. 1.3).

The systematic chapters begin with an account of Scotland's diverse geology and geological evolution, which extends from the Archaean to the Cenozoic (Chap. 2). Scotland contains some of the oldest rocks in Europe, dating back to ~3.2 Ga, and evidence of several subsequent orogenic events; the present landmass of Scotland did not exist as a single geological entity until ~420 Ma, near the end of the Caledonian Orogeny. Rocks or sediments of all of the Phanerozoic geological periods are represented, from Cambrian to Quaternary, either onshore or in offshore basins. The rock record developed under a range of climates from glacial to hot desert and humid tropical as those parts of the crust that now form Scotland migrated from near the South Pole in Neoproterozoic times, across the Equator to Scotland's present latitude of 55–61°N. Although some of the major relief elements in Scotland may have developed as early as 400 Ma, the present configuration of the Scottish landscape owes much to magmatic activity, crustal uplift, deep weathering and erosion operating under humid subtropical to temperate conditions during the Palaeogene and Neogene Periods (65.5–2.59 Ma). These processes produced the present broad patterns of relief and drainage and are locally manifest in the survival of palaeosurfaces and evidence for etchplanation (Chap. 3). Radical transformation of the end-Neogene landscape occurred during the dramatic climatic shifts of the Quaternary Period, when Scotland experienced the alternation of recurrent glacial and interglacial stages. Cold periods were dominated by the effects of glaciation and periglaciation, and each return to temperate conditions was characterized by paraglacial landscape response, renewed weathering and the operation of slope, fluvial and coastal processes. As Chap. 4 demonstrates, our understanding of events prior to the last ice-sheet glaciation is limited, but the last ice-sheet glaciation (~35–14 ka) and more limited glaciation during the ensuing Loch Lomond Stade (~12.9–11.7 ka) provide analogues of glacial events earlier in the Quaternary. Similarly, geomorphological changes during the Holocene Epoch (present interglacial) provide insights into the nature of landscape evolution during earlier interglacials. Finally, Chap. 5 briefly considers the geomorphological processes that are affecting the Scottish landscape at present, and how these are responding to climate change.

Selection of regions for inclusion in the chapters that follow (Fig. 1.3) was guided primarily by their diversity: all differ in their geomorphological attributes. In part, these differences reflect the influence of geology and geological evolution: Scotland encompasses five major geological terranes, each of which is geologically and geomorphologically distinct, and representation of these terranes partly guided selection of the regional chapters. A second consideration was geographical: Scotland's major archipelagos, for example, exhibit great diversity of geology, relief and landscape, and deserve individual chapters. A final criterion that guided selection of key regions was the literature base: whereas some parts of Scotland are generously endowed with recent publications covering a wide range of landforms, others are relative *terra incognita* in terms of the publication record.

At less than a third of the size, the present land area of Scotland is dwarfed by the area of adjacent offshore shelves (~286,500 km^2). Drawing on a wealth of recent high-resolution marine geophysical and bathymetric data, Chap. 6 explores the geomorphology of this submarine realm, including moraines, grounding-zone wedges, tunnel valleys, streamlined bedforms, iceberg ploughmarks, pockmarks and submarine landslides, and it highlights the importance of submarine landforms in unravelling the glacial history of the last and earlier Scottish ice sheets. Chapters 7–11 are devoted to the iconic geomorphology of Scotland's main islands and archipelagos, beginning with the northern isles of Shetland and Orkney, the visible manifestation of the much larger (but largely submerged) Orkney-Shetland Platform. Shetland (Chap. 7) differs from Orkney (Chap. 8) not only in terms of its greater geological complexity, but also because during the last glaciation it formed an independent centre of ice dispersal. Orkney shares its geology and glacial history with neighbouring Caithness (Fig. 1.3), so both have been included in Chap. 8. Both Orkney and Shetland are exposed to extreme storm and wave conditions on the Atlantic margin, and host spectacular coastal landforms.

The Outer Hebrides (Chap. 9) also represent the exposed parts of a major submarine platform but are almost entirely composed of the resistant Archaean basement rocks (Lewisian gneiss) of the Hebridean terrane, which form wide expanses of low-lying, glacially scoured knock-and-lochan terrain, surmounted by rounded ice-moulded hills and inselbergs, and with a western fringe of calcareous sandy beaches and coastal plains. By contrast, those islands that form part of the Palaeogene Hebridean Igneous Province (Skye, Rùm, Mull and Arran; Chap. 10) are unique in Scotland in illustrating the effects of successive Pleistocene glaciations on terrain underlain by complex igneous geology and the aftermath of glaciation in terms of postglacial landscape evolution on such terrain. Our geomorphological journey to the Hebrides concludes with visits to the islands of Islay, Jura, Colonsay, Tiree and Coll, which collectively host internationally renowned raised shorelines that include

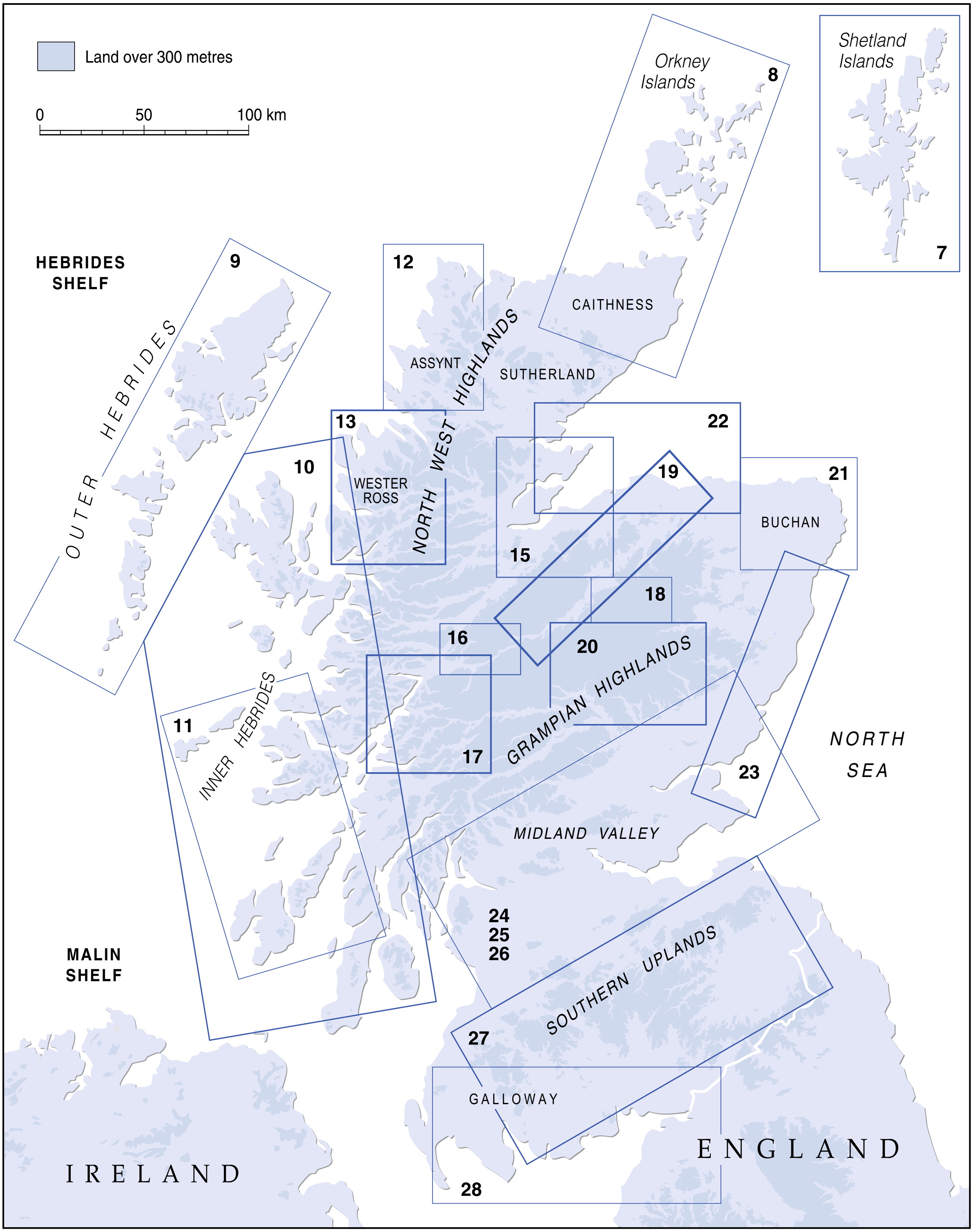

Fig. 1.3 Approximate areas covered by the regional and thematic chapters in this book (numbered boxes). Chapter 6 (Offshore geomorphology) covers the offshore shelf and Chap. 14 (not shown) covers the entire North West Highlands

both raised rock platforms and sequences of raised gravel beaches (Chap. 11).

Chapters 12 (Assynt and Sutherland) and 13 (Wester Ross) cover the spectacular mountainous terrain that straddles the Moine Thrust Zone in the NW Highlands. West of the thrust zone, mountains and inselbergs of Neoproterozoic sandstones and Cambrian quartzite rise above an undulating basement of Archaean gneiss; east of the thrust zone are the glaciated mountains of Moine metasedimentary rocks. All have been transformed by successive glaciations into a landscape of intersecting troughs and glacial breaches that extend westward into some of the finest fjords in Scotland. Chapters 17 (Western Grampian Highlands) and 20 (Central and Eastern Grampian Highlands) illustrate the contrast between the landscapes of intensive glacial dissection that characterize the western Highlands and the landscapes of selective linear glacial erosion that typify more easterly locations, where pre-glacial palaeosurfaces are widely preserved, mainly on Dalradian metasedimentary rocks. The preservation of granite palaeosurfaces and tors is spectacularly illustrated by the Cairngorm Mountains (Chap. 18), a landscape of striking contrasts where cirques and deep glacial troughs are incised into a plateau of essentially pre-glacial origin.

The Midland Valley terrane of central Scotland represents an archetypal landscape of differential erosion. Here, drift-covered undulating lowlands on sedimentary rocks are interrupted by high ground underlain by stacked lava flows, sills and volcanic plugs that have proved resistant to the passage of successive Quaternary ice sheets. The geomorphological diversity of this region is explored in Chaps. 24, 25 and 26 that cover, respectively, the glacial geomorphology of the Highland boundary zone, the legacy of glacial meltwater rivers on the landscape and the effects of ice-moulding in creating a glacial landscape of drumlins, ribbed moraine and crag-and-tail landforms. The Southern Uplands terrane to the south is mainly composed of a Caledonian forearc accretionary complex and forms a rolling tableland, dissected by fluvial valleys and glacial troughs. The upland landscapes of this distinctive region are explored in Chap. 27, and the glacial and coastal characteristics of the adjacent Solway coast and lowlands are described in Chap. 28.

The thematic chapters of this book have been chosen to represent particular facets of Scotland's geomorphology. The legacy of pre-glacial landscape evolution is explored in Chap. 21, which describes the palaeolandscape of the Buchan region of NE Scotland, where the effects of glaciation are muted and evidence for pre-glacial landscape evolution, such as basins and saprolite covers, is exceptionally well-preserved. Chapter 15 focuses on the rich legacy of glacial and glacifluvial geomorphology of the Inverness and Moray Firth area. Chapter 16 is set in the Lochaber area of the Western Grampians, where shorelines and lake deposits in Glen Roy and neighbouring valleys record the history of glacier-dammed lakes during the Loch Lomond Stade; this is one of the most-visited and most intensively researched geomorphological locations in Scotland. Finally, five thematic chapters explore aspects of the postglacial evolution of the Scottish landscape. Chapter 14 records over 400 rock-slope failures in the NW Highlands and considers their causes, timing and influence on long-term landscape evolution, whilst Chap. 19 is devoted to the fluvial geomorphology of the catchment of the River Spey and its much-studied tributary, the River Feshie. The origins, development and present status of the spectacular beaches, spits and barrier islands of the Moray Firth coast and eastern Scotland are explored in Chaps. 22 and 23. The volume concludes with Chap. 29 on geoconservation, which outlines the approach and measures adopted to protect Scotland's exceptional geoheritage and key geomorphological sites.

1.4 Conclusion

The outstanding diversity of Scotland's landscapes and landforms has captured the imagination of geologists and geomorphologists for over two centuries, leading to groundbreaking insights of international significance, such as the concepts of uniformitarianism, the Glacial Theory, thrust-faulting, glacio-isostatic uplift, the significance of meltwater channels and the formation of raised shorelines. The Late Pleistocene glacial history of Scotland between ~35 and 11 ka has been established in greater detail than probably for any other part of the globe. Yet despite the contribution of geologists and geomorphologists working in Scotland to our understanding of geomorphological processes and landscape evolution, there remain gaps that became evident during the compilation of this book. The nature of pre-glacial landscape evolution during the Cenozoic Era remains to be unravelled for large parts of the country, and only a limited number of studies provide insights into Quaternary landscape changes prior to the last ice-sheet glaciation. Within Scotland, much recent research has been focused on particular topics (such as the last glaciation and glacial-interglacial transition, and sea-level change) and particular locations, such as the Isle of Skye, the Cairngorms and Glen Roy. Some parts of the Scottish landscape, such as parts of the NW Highlands and the Southern Uplands, have received little attention during the present century. There remains much to be discovered about (and from) the landscapes and landforms of Scotland that, as James Hutton presciently suggested, 'may afford the human mind both information and entertainment' (Hutton 1785, p. 30). This applies not only from a research perspective, but through enhancement of wider public awareness and appreciation of the origins of Scotland's scenery and its significance both for geoscience and as an asset for its aesthetic and cultural values, enjoyment and inspiration.

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Part I

Physical Environment

Scotland: Geological Foundations and Landscape Evolution

2

John E. Gordon and Philip Stone

Abstract

Scotland displays remarkable geological diversity, comprising igneous, sedimentary and metamorphic rocks that date back to the Archaean and span all the major periods of the geological timescale. This geodiversity reflects global plate tectonics, the position of Scotland near convergent and divergent plate margins at different times during its history, the drift of the Scottish landmass as a small part of larger continental entities across the surface of the globe through different morphoclimatic zones and depositional environments, and long-term changes in global climate and sea level. The Scottish landmass was essentially assembled ~425 Ma, from the amalgamation of the Laurentia and Baltica–Avalonia plates during the Caledonian Orogeny as the Iapetus Ocean closed. This brought together different crustal fragments comprising Archaean igneous and metamorphic rocks, and Proterozoic and Early Palaeozoic sedimentary and metasedimentary rocks. Orogenesis was accompanied by the emplacement of igneous intrusions, and uplift and erosion of the Caledonian mountain chain. Deposition of thick accumulations of terrestrial sediments during the Devonian was followed later by Palaeozoic and Mesozoic marine, deltaic and continental sedimentation and Palaeozoic igneous activity. During the Palaeogene, central igneous complexes and extensive lava fields formed in the Hebridean Igneous Province due to the presence of an underlying mantle plume that also initiated the opening of the North Atlantic Ocean to the west. The influence of this geodiversity is widely expressed in the geomorphology of the present landscape as a consequence of differential weathering and erosion, modulated by variable tectonic uplift, tilting and downwarping, mainly during post-Caledonian times and particularly during the Cenozoic.

Keywords

Geological history • Plate tectonics • Caledonian Orogeny • Palaeogene volcanism • Differential weathering and erosion • Geology and landscape

2.1 Introduction

This chapter outlines the development of the geological framework that provides the foundation for the geomorphology of Scotland, and the processes and events that have shaped the present landscape (Fig. 2.1). In recent decades, new dating methods, geophysical models, and studies of Mesozoic and Cenozoic deposits in offshore sedimentary basins have provided fresh insights into the links between geology, tectonics, surface processes, climate and long-term landscape evolution, highlighting the antiquity of many features in the present landscape (Hall 1991; Hall and Bishop 2002; Fame et al. 2018; Chap. 3).

Although located today on the passive continental margin of NW Europe, the geological development of Scotland has given rise to remarkable geodiversity for a country of its size, with the presence onshore and in offshore sedimentary basins of rocks spanning all the major geological time periods since the Archaean (Trewin 2002; McKirdy et al. 2007; Stone 2008; Gillen 2013). Several factors account for this geodiversity, which reflects the combined influence of geological and geomorphological processes operating over a wide range of timescales.

First, the broad geological and topographic framework of Scotland is the result of major global tectonic events. These

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Fig. 2.1 Scotland: topography and main locations mentioned in the text. (Map base by Eric Gaba, NordNordWest, Uwe Dedering from Wikimedia Commons CC BY-SA 3.0)

include the repeated formation and break-up of supercontinents, the closure of the Early Palaeozoic Iapetus Ocean and the associated crustal shortening and uplift during the Caledonian Orogeny, Mesozoic rifting and subsidence in the North Sea Basin and the Minches, and finally the opening of the North Atlantic Ocean in the Palaeogene (Table 2.1). The effects of these global-scale events have also imparted more local geological influences on the landscape and landforms through the formation of faults, shatter zones and structural grain, and the juxtaposition of resistant and weaker rocks, all subsequently exploited by surface processes of differential weathering and erosion, particularly during the Cenozoic.

Second, the position of Scotland near an active plate margin at various times during its history has resulted in episodes of mountain building, volcanism, large-scale crustal deformation, uplift and erosion, all of which have left a legacy both in the rock record and in the present landscape.

Third, as a result of plate tectonics, the Scottish landmass has drifted across the surface of the globe and through different climatic zones and morphogenetic and sedimentary

Table 2.1 Summary of the geological history of Scotland (Main sources: Trewin 2002; Woodcock and Strachan 2012; Gillen 2013)

Era	Period	Age (Ma)	Latitude of Scotland[a]	Main events and palaeoenvironments
Cenozoic	Quaternary	2.6–0	57°N	Repeated growth and decay of mountain glaciers and ice sheets; glacial stripping of saprolites and cumulative development of landforms of glacial erosion; formation of deglacial and postglacial landforms
	Neogene	23–2.6	50–57°N	Phases of uplift and erosion; weathering continued under warm-temperate, humid climate; climate cooling intensified after ~3 Ma
	Palaeogene	66–23	45–50°N	Opening of the northern North Atlantic Ocean (~56 Ma); extensive intrusive and extrusive igneous activity in the Hebridean Igneous Province (~61–55 Ma); differential uplift, tilting and erosion of the Scottish landmass; deep chemical weathering initially under humid, subtropical climate; stripping of saprolites and formation of etchplains
Mesozoic	Cretaceous	145–66	40–45°N	Warm, shallow seas covered much of Scotland, apart from the Highlands and Southern Uplands
	Jurassic	201–145	35–40°N	The Highlands formed an upland area of reduced relief, with rivers draining to deltas in the North Sea Basin; deposition of sediments in shallow seas around the margins of the uplands
	Triassic	252–201	25–35°N	Hot, semi-arid environment with deserts present around the margins of the Highlands; deposition of the New Red Sandstone
Palaeozoic	Permian	299–252	15–25°N	Hot, arid environment with deserts present around the margins of the Highlands; deposition of the New Red Sandstone; crustal extension and rifting initiated the North Sea Basin
	Carboniferous	359–299	5°S–15°N	Scotland drifted north into equatorial latitudes; tropical forests, intermittent shallow shelf seas and deltas were present in the subsiding Midland Valley; formation of coal measures in low-lying coastal swamps; eruption of central volcanoes and lavas in the Midland Valley; erosion of the Caledonian mountains continued
	Devonian	419–359	10–5°S	Erosion of the Caledonian mountains accompanied by the formation of large alluvial fans in hot, semi-arid conditions; large inland lake basins formed in NE Scotland and Orkney (Orcadian Basin); volcanic activity in the Midland Valley and Lochaber; Acadian orogenic event

(continued)

Table 2.1 (continued)

Era	Period	Age (Ma)	Latitude of Scotland[a]	Main events and palaeoenvironments
	Silurian	444–419	15–10°S	Closure of the Iapetus Ocean as Baltica, then Avalonia, collided with Laurentia, joining the crustal units of Scotland with those of England and Wales along the Iapetus Suture; Scandian orogenic event; uplift and erosion of the Caledonian mountains; Moine sediments folded and metamorphosed; major crustal dislocations along the Moine Thrust Zone; turbidite sediments deposited in the Iapetus Ocean with ensuing accretionary deformation (Southern Uplands terrane); volcanic activity and granite intrusions in the Highlands and volcanic activity in the Midland Valley
	Ordovician	485–444	30–15°S	The Iapetus Ocean was closing rapidly; limestones formed on the shelf of a warm shallow sea in NW Scotland; turbidite sediments deposited in the Iapetus Ocean with ensuing accretionary deformation (Southern Uplands terrane); Grampian orogenic event as the Midland Valley Arc collided with Laurentia; uplift of the Caledonian mountains accompanied by metamorphism and folding of Dalradian sediments and intrusion of gabbros and granites in the Grampian Highlands
	Cambrian	541–485	30°S	Sandstones, then limestones formed in warm, shallow shelf seas in NW Scotland; the Iapetus Ocean reached its maximum extent
Neoproterozoic		1000–541	Close to South Pole	~800–500 Ma: Dalradian sediments deposited in marine basins, mainly on the continental margin; glaciations occurred on a global scale; the Iapetus Ocean opened
			South of Equator	~1000–875 Ma: Moine sediments deposited mainly in shallow seas
Mesoproterozoic		1600–1000	10–30°N to 15–20° S	~1200–950 Ma: Torridonian sandstones mainly formed from sediments eroded from the mountains of the Grenville Orogeny (~1100–1000 Ma) on the Laurentian plate and deposited in alluvial, fluvial and lacustrine environments on its continental margin ~1200–1000 Ma: Lewisian rocks exposed at the surface following uplift and erosion
Palaeoproterozoic Neoarchaean Mesoarchaean		3200–1600	Unknown	~2300–1700 Ma: Laxfordian event ~2400–2000 Ma: formation of Scourie Dykes ~2900–2300 Ma: Badcallian event ~3200–2800 Ma: formation of the Lewisian Gneiss Complex by metamorphism of older igneous and subsidiary sedimentary rocks

[a]All latitudes are generalisations; there is a range within individual time periods and not all schemes agree. The overall pattern is one of northward drift of Scotland during the last ~1000 Ma