World Geomorphological Landscapes

Olav Slaymaker *Editor*

Landscapes and Landforms of Western Canada

Springer

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This book is dedicated to the memory of Robert Gilbert (1945–2015), Professor Emeritus, Geography, Queen's University.
Bob was engaged in co-authoring Chap. 22 *of this volume when he was stricken with cancer. He died on 27 April 2015 and we have all lost an extraordinary scientist and friend. He was one of my most outstanding Ph.D. students who taught me more than I was able to teach him. During his time at UBC, Alberta and Queen's he led his colleagues and students by example through his passion for research and a deep commitment to teaching at all levels. The sediment cascade and the physical mechanisms by which sediments are delivered to, distributed through, and deposited in water bodies in the Great Lakes region, western Canada, the Canadian Arctic, Greenland, Antarctica, Nepal and the southern USA were the foci of his research. Bob was a highly respected physical limnologist of arctic and periglacial environments whose work will stand the test of time.*

Olav Slaymaker

Preface

The inspiration for this volume is a "love of landscape" (Goudie and Viles 2010), specifically the geomorphological landscapes of western Canada. Although the word landscape has many rich and varied meanings, I am here referring to "the total character of a region of the Earth's surface which includes landforms, vegetation (ecosystems), and fields and buildings (anthropogenically modified land)" (von Humboldt 1845). Landscape is the dynamic backdrop to people's lives. Landscapes inspire awe, aesthetic pleasure and scientific curiosity. In my experience, coastal landscapes have been most influential: the island archipelago (skerry guard) and fjords of Norway; the raised beaches, limestone headlands and ria coastline of Wales; and the dramatic fjords and paraglacial coastline of British Columbia have all excited my imagination. These coastal landscapes compel the observer to look beyond immediate surroundings and towards the neighbouring landscapes of Denmark, England, Ireland, Vancouver Island and Asia. All the landscapes in which I have lived have been significantly influenced by glaciation in the geologically recent past, and contemporary processes of coastal and anthropogenic change are self-evident. Geomorphological landscapes are a natural heritage of great aesthetic appeal and are intrinsically valuable (Gray 2003). The threat of degradation from unwise economic development is everywhere real.

The terrestrial surface of Canada is the subject of this two volume series on western and eastern Canada. This first volume deals exclusively with western Canada, an area of approximately 4.65 million km^2. Western Canada is herein defined as British Columbia, Alberta, Saskatchewan, almost all of Manitoba, Northwest Territories, Yukon and a few enclaves of Nunavut. This vast area contains a splendid variety of landscapes and landforms almost all of which have been profoundly influenced by one or more of three continental ice sheets during the Quaternary Period: the Laurentide, the Cordilleran and the Innuitian ice sheets.

The Northwest Territories contain some of the oldest rocks at the Earth's surface. Some 300 km north of Yellowknife and to the east of Great Bear Lake is found the Acasta gneiss with an estimated age of 4 billion years, which is close to the absolute age of the Earth. However, only a tiny fraction of the landscape that is visible today provides clues to the interpretation of palaeolandscapes older than a few hundred million years. Rocks which underlie the Northwest Territories have undergone numerous mountain building episodes, have been sutured along former plate collision zones and have experienced a series of erosion cycles. Today, these landscapes are topographically subdued and some have suggested that they are the most genuine peneplains, or end points of erosion cycles, that exist on the planet (Ambrose 1964).

This book is about landscapes that are larger than individual landforms and smaller than continental scale (Slaymaker et al. 2009). Landform assemblages of western Canada that form uniquely distinctive landscapes are the essence of the volume. These distinctive landscapes include the presence of ice caps and glaciers (almost 30,000 km^2); permafrost underlying 50 % of the region; glacivolcanism and volcanic landscapes; spectacular karst landscapes; structurally controlled landscapes in sedimentary rock sequences; unparalleled variety of mass movement phenomena in paraglacial and periglacial landscapes; fossil sand dune fields and some of the world's finest pingos and patterned ground landscapes; arctic and temperate coastal landscapes adjoining the Arctic and Pacific oceans and magnificent fluvial landscapes,

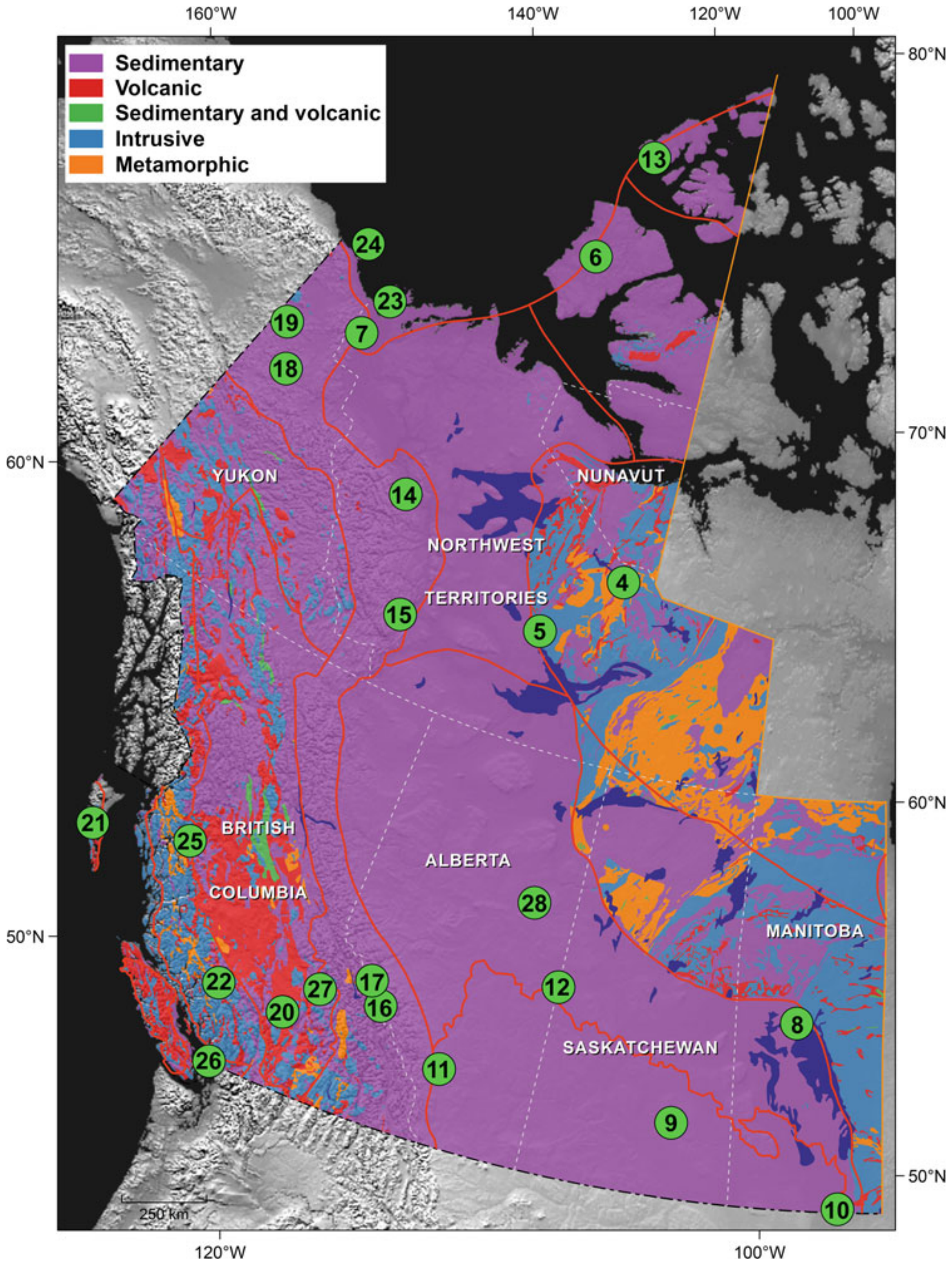

Fig. 1 Distribution of major rock types in western Canada (after Wheeler et al. 1997) and approximate locations of case studies in Chaps. 4–28. Numbers at the sites correspond to the chapter number in this book. Chapter numbers: *4* Slave Geological Province; *5* Great Slave Lowland; *6* Banks Island; *7* Peel Plateau; *8* Little Limestone Lake; *9* Assiniboine River watershed; *10* Red River valley; *11* Foothills Erratics Train; *12* Prairie Dune archipelago; *13* Prince Patrick Island; *14* Canol Road corridor, Mackenzie Mountains; *15* South Nahanni National Park; *16* Castleguard Cave, Banff National Park; *17* Glaciers in Canadian Rockies; *18* Northern Interior, Yukon, *19* Old Crow Flats; *20* Southern Fraser Plateau; *21* Haida Gwaii; *22* Lillooet–Harrison river basin; *23* Mackenzie Delta; *24* Herschel Island; *25* Terrace-Kitimat area; *26* Fraser Lowland; *27* Fraser River; *28* Alberta Oil Sands. Not shown are Chaps. 1–3 and 29. Chapters 1 through 3 are introductory and Chap. 29 deals with the intrinsic value of geomorphological landscapes and the evolution of western Canada's parks and natural heritage sites. The *red lines* represent geomorphological landscape regions and the *orange line* is the boundary between western and eastern Canada (see Chap. 1)

highlighted by the Mackenzie River basin, the fourth largest polar river basin in the world. Anthropogenic change in a thinly populated region such as western Canada (fewer than 2 people per km^2) is nevertheless significant and rapidly intensifying (Slaymaker et al. 2009).

The complexity of geology at the scale of western Canada precludes a discussion of detailed lithological variations. We map the broadest categories of rock types (sedimentary, volcanics, metamorphic and intrusives), thereby giving the reader only a first-order statement about western Canada's geological complexity that must be complemented with details of historical and structural geology at individual sites (Wheeler et al. 1997) (Fig. 1).

Part I (Chaps. 1–3) provides a general overview of the range of outstanding western Canadian landscapes arranged by scale, by tectonic structure and by dominant processes of change. Part II (Chaps. 4–28) consists of case studies of outstanding representative landscapes from which original, field-based research is reported. The locations of these case studies are shown in Fig. 1. Part III (Chap. 29) addresses the question "Wherein lies the intrinsic value of landscape?"

This book could not have been completed without the assistance and technical skills of Dori Kovanen, Research Associate in the Department of Geography at the University of British Columbia. She spent countless hours processing data and designing effective ways of illustrating the landscapes and landforms of western Canada. The Book Series editor, Piotr Migoń, provided valuable advice at all times during the process of book preparation, and Robert Doe and Marielle Klijn of Springer Verlag were consistently supportive. The following expert reviewers gave freely of their time to ensure the scientific quality of the text: Chris Burn (Ottawa), Norm Catto (St. John's), Mike Church (Vancouver), John Clague (Burnaby), Bob Gilbert (Kingston), Vic Levson (Victoria), Piotr Migoń (Wroclaw), Pascale Roy-Léveillée (Sudbury), Jim Teller (Winnipeg), Harvey Thorleifson (St. Paul), Paul Williams (Auckland), Mike Wilson (Vancouver), and Ming-ko (Hok) Woo (Hamilton). To all I express my personal thanks. Whatever errors of interpretation and fact remain are solely the responsibility of the author.

Vancouver, Canada
2016

Olav Slaymaker

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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 creating shapes which look improbable. Many physical 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 tens of million years and include unique events. In addition, many landscapes owe their appearance and harmony not solely to the natural forces. Since 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, 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 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 the first among two planned to show the geomorphology of the second largest country in the world—Canada. It focuses on the western part of this enormous territory, presenting highly diverse geomorphology, with the legacy of tectonics, volcanism, glaciation, periglaciation, karst and river action. Western Canadian landscapes range from extremely rugged mountain terrains in the west through permafrost-dominated lowlands in the north to nearly featureless plains in the east. But even the latter record a fascinating story of geomorphic change which this book will undoubtedly help to understand.

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 the Editor, Prof. Olav Slaymaker, past President of the IAG, who enthusiastically responded to the invitation to coordinate the volume (and eastern Canada at a later date) and produced it remarkably quickly. I am also grateful to all individual contributors who agreed to add the task of writing chapters to their busy agendas and delivered high-quality final products.

Piotr Migoń

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Part III The Intrinsic Value of Our Geomorphological Heritage

Editor and Contributors

About the Editor

Olav Slaymaker Member of the Order of Canada, is a professor emeritus of geography in the Department of Geography at the University of British Columbia, Vancouver, BC. His 20+ co-authored and edited monographs and 160+ refereed papers reflect three distinct styles of work. First, he has pursued original field research for 40 years on sediment systems in the Canadian Cordillera and the European Alps, strongly supported and enhanced by his stellar doctoral and postdoctoral students and international colleagues. Second, he has produced papers and books summarising trends in land use and environmental change in mountain regions. Third, he has edited monographs with invited international contributions on major environmental and geomorphological themes. He is a former President of the Canadian Association of Geographers and a former President of the International Association of Geomorphologists.

Contributors

Nigel Atkinson is a Quaternary scientist and section leader of the Quaternary geology section of the Alberta Geological Survey, Alberta Energy Regulator, in Edmonton, Alberta.

Alexandre Bevington is a research earth scientist with the BC Ministry of Forests, Lands and Natural Resource Operations Prince George, British Columbia, Canada. He is a guest lecturer at the University of Northern British Columbia. His main research interest is the application of thermal models and satellite remote sensing to better understand natural hazards in mountain environments.

Tracy A. Brennand is a professor and chair of geography at Simon Fraser University, Burnaby BC, and a former President of the Canadian Geomorphological Research Group. A geomorphologist and sedimentologist by training, her field-intensive research programme probes the palaeoenvironmental record contained within glacigenic sediments and landforms. Her main interest is in understanding how ice sheets operated in the past, with a view to better understanding how present-day ice sheets may behave in the future. Her research programme integrates geomorphology, digital terrain modelling, topographic surveying, remote sensing, sedimentology, shallow geophysical techniques and geochronology.

Greg Brooks is a research scientist with the Geological Survey of Canada, Earth Sciences Sector, Natural Resources Canada, Ottawa, ON. A geomorphologist by training, his research interests have focused on natural hazard topics, including the effects of high-magnitude flooding, the chronology of prehistoric sensitive clay landslides and palaeoseismicity. He has conducted research in many regions of Canada.

Chris Burn is a professor of geography at Carleton University in Ottawa, Canada. His research concerns relations between climate and permafrost in northwestern Canada, where he is committed to long-term investigations on frozen ground, especially in central Yukon and the Mackenzie Delta area.

Norm Catto is a professor of geography at Memorial University of Newfoundland, St. John's, Newfoundland and Labrador. His research and teaching interests include natural hazards and risk assessment; coastal landforms, erosion, and sea level change; and the impacts of climate and weather events on marine communities, transportation, infrastructure, fisheries, agriculture, and tourism. He has written two textbooks, one on natural hazards in Canada, and another focused on Canadian landforms and associated hazards.

Michael Church Fellow of the Royal Society of Canada, is a professor emeritus in the Department of Geography at the University of British Columbia in Vancouver, BC. His research interests focus on the morphodynamics of rivers at all scales from steepland streams to large rivers. He is engaged in long-term studies of sediment transport and stability in Fraser and Peace rivers. Sediment transport is also studied in an experimental programme conducted in UBC's environmental hydraulics laboratory. In addition, he is interested in fluvial landscape evolution over intermediate timescales (order 10,000 years) and in the history and methodology of geomorphology.

John J. Clague Fellow of the Royal Society of Canada, is a professor of earth science and holds the Shrum Chair in Science at Simon Fraser University, Burnaby, BC; he is also an emeritus scientist, Geological Survey of Canada, and has 40 years experience in surficial/terrain mapping, Quaternary stratigraphic investigations, engineering and environmental interpretations of surficial geological information and natural hazard studies. Clague has published more than 300 papers, reports and monographs on a wide range of earth science topics of regional and national importance. He has had numerous television and radio interviews and has been featured in newspaper and magazine articles. He is a past President of the Association of Professional Engineers and Geoscientists of British Columbia (APEGBA) and a former President of Geological Association of Canada (GAC) and the International Association for Quaternary Research (INQUA).

David M. Cruden Fellow of the Engineering Institute of Canada, is a professor emeritus of the Department of Civil and Environmental Engineering and the School of Mining and Petroleum Engineering at the University of Alberta in Edmonton, AB. His research interests include landslides, slope stability, engineering geology, rock mechanics, geological hazards, geomorphological mapping and geotechnical materials. He has won numerous awards, including the Stermac Award, Canadian Geotechnical Society, and was Legget Medallist of Canadian Geotechnical Society and Varnes Medalist of the International Consortium on landslides.

Derek Ford Fellow of the Royal Society of Canada, is a professor emeritus of geography and earth sciences at McMaster University in Hamilton, ON. His chief interests are in karst processes and landforms, cave genesis and karst aquifers, and palaeoclimate studies of speleothems. These days he is most interested in applied consulting, advising on conservation and UNESCO World Heritage applications. He is author/co-author of ~200 journal papers, many reports to Canadian and foreign government agencies, co-author or co-editor of twelve scientific books, one coffee table book, and producer of a movie for the National Film Board of Canada. He is a former President of the Canadian Association of Geographers and of the International Union of Speleology, and Gold Medallist of the Royal Canadian Geographical Society.

Hugh M. French is a professor emeritus, University of Ottawa, and currently an adjunct professor, Department of Geography, University of Victoria. He is an earth scientist with a special interest in the terrain conditions and landscapes of the cold non-glacial regions of the world. Between 1968 and 1998, he undertook geomorphic research in the western Canadian

Arctic. He has received the Roger Brown Award of the Canadian Geotechnical Society for outstanding contributions to permafrost science and engineering (1989), the Canadian Association of Geographers award for scholarly distinction (1995) and the Lifetime Achievement Award of the International Permafrost Association (2016). He was the founding editor-in-chief of the Wiley journal, *Permafrost and Periglacial Processes,* 1990–2005, and President of the International Permafrost Association, 1998–2003. He is the author of *The Periglacial Environment*, first published in 1976 and now in its 3rd edition (2007), and is co-author with Olav Slaymaker of *Canada's Cold Environments*, published in 1993, and *Changing Cold Environments*, published in 2012.

Pierre A. Friele is a self-employed professional geoscientist in Squamish, BC, and specialises in engineering geology. Pierre's work assignments typically include terrain and slope stability mapping, hazard and risk assessment, flood and erosion protection, and palaeoenvironmental reconstruction. His research has focused on the Quaternary geology and volcanic hazards of the Sea-to-Sky Corridor.

Adrian J. Gaanderse is an agricultural soil science researcher at Cainthus Corporation in Ottawa, with a background in permafrost science. His research focused on lithalsa morphology in the Great Slave Lowland, Northwest Territories, and he currently investigates crop analytics based on aerial imagery.

Marten Geertsema is a research geomorphologist with the BC Ministry of Forests, Lands and Natural Resource Operations in Prince George, BC, and is an adjunct professor at the University of Northern BC in Prince George, BC. His primary focus is on natural hazards and terrain analysis. He is interested in the influence of landslides on biophysical diversity. He is also interested in the effects of climate change on natural hazards, and studies past and present hazard regimes.

Robert Gilbert (deceased) was a professor emeritus of geography at Queen's University in Kingston, ON. He was a highly productive, dedicated and creative scientist. His research focused on sedimentology, limnology and marine systems in the Great Lakes region, western Canada, the Canadian Arctic, Greenland and Antarctica. This book is dedicated to his memory with profound respect.

James P. Hamilton is an associate professor in the Department of Geography at Wilfrid Laurier University, Waterloo, ON. His research interests include climate change and palaeoclimatology; hydrology and geomorphology of karst terrains in cold regions.

Lionel E. Jackson, **Jr.,** is an emeritus scientist, Geological Survey of Canada (GSC) in Vancouver, BC, and is an adjunct professor at Simon Fraser University in Burnaby, BC. He is an authority on the surficial geology of the Rocky Mountain Foothills and southern Yukon. He is a continuing authority in the recognition and evaluation of debris flow hazards in the Canadian Cordillera and he has investigated debris flow and rock avalanche hazards in California, Venezuela, Ecuador, Peru, Bolivia and Argentina. He led an expedition on behalf of the United Nations and GSC to the Republic of Seychelles in 2005 to investigate the effects of the 2004 Indian Ocean tsunami on that island nation. He is currently investigating the glacial and postglacial geology of the Greater Vancouver area of British Columbia.

Peter Jordan is an emeritus scientist with the British Columbia Ministry of Forests, Lands and Natural Resource Operations, based in Nelson, BC. His primary research interests are slope stability, erosion and sedimentation, and watershed sediment budgets. Recent research has focused on large landslides in south-eastern BC, and post-wildfire erosion and mass movement processes.

Daniel E. Kerr is a research scientist with the Geological Survey of Canada in Ottawa, ON. His research focuses on surficial geology mapping and drift exploration techniques for gold, diamonds and other commodities, within the Northwest Territories and Nunavut.

Steven V. Kokelj is a permafrost scientist with the Northwest Territories Geological Survey in Yellowknife, Northwest Territories. He has conducted numerous studies on the physical and thermal conditions of permafrost, thermokarst processes, and the influence of anthropogenic disturbance on permafrost. His research interests include understanding the patterns and processes of permafrost landscape change and improving the compilation, management and synthesis of permafrost information to support northern decision-making.

Dori J. Kovanen is a professional engineering geologist and research associate in the Department of Geography at the University of British Columbia, Vancouver, BC. She is a specialist in Quaternary geomorphology and has written extensively on Late Glacial and Holocene history of the Pacific Northwest as well as contemporary environmental changes in the region.

Denis Lacelle is an associate professor of geography at the University of Ottawa, Ottawa, ON. His research interests include investigation on near-surface permafrost disturbances on water quality under changing climate; origin, stability and habitability of ancient ground ice and permafrost; ice dynamics; and polar environments as planetary analogues.

Brian Henry Luckman is a professor emeritus of geography at the University of Western Ontario in London, ON. He was one of Canada's pioneers in the field of dendro-palaeoclimatology and was seconded as Global Change Coordinator, Terrain Sciences Division, Geological Survey of Canada. He established some of the longest, and regionally extensive, proxy dendroclimatic records in the world. He was the President of the Canadian Geomorphological Research Group and was awarded the CAG Award for Scholarly Distinction in Geography.

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Bill Rannie is a retired professor of geography and senior scholar at the University of Winnipeg in Winnipeg, MB. His research has focused on the historical hydrometeorology of the Red and Assiniboine Rivers, the nineteenth-century environment of the Red River Settlement and the evolution of the lower Assiniboine River.

Pascale Roy-Léveillée is an assistant professor of geography at the Laurentian University School of Northern and Community Studies in Sudbury, ON. Her research focuses on permafrost conditions and thermokarst processes in central and northern Yukon.

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Chris Smart is a professor of geography at the University of Western Ontario, London, ON. Following a doctorate under Derek Ford's supervision on Castleguard, he has continued work in alpine regions including the Rockies, the Swiss Alps and Southern Alps of New Zealand. His academic focus is on environmental monitoring and instrumentation, coupled with work on glacier hydrology and hydraulics, karst groundwater contamination and landscape evolution.

Jon F. Tunnicliffe is a lecturer in the School of Environment at University of Auckland in Auckland, New Zealand. His research focuses on fluvial and glacial processes and the roles they have played in shaping the Canadian and New Zealand landscapes over timescales of decades to millennia. Jon is presently working on questions relating to climate change impacts in the western Canadian Arctic, including hillslope stability, river sedimentation and permafrost hydrology.

Ian J. Walker is a professor of geography in the Department of Geography at the University of Victoria, Victoria, BC. He is a geomorphologist with expertise in beach and dune systems, sedimentary processes, environmental fluid dynamics, wind (aeolian) processes, coastal erosion, climate change impacts and Holocene landscape interpretation. His research focuses on the British Columbia coast from Haida Gwaii to Pacific Rim National Park and the southern Gulf Islands.

Stephen A. Wolfe is a research scientist with the Geological Survey of Canada, Ottawa, ON, and is an adjunct professor at Carleton University in Ottawa, ON. His research focuses on cold climate processes in Canada, including permafrost and aeolian geomorphology.

Part I

Introduction to the Geomorphological Landscapes of Western Canada

Long-Term Geomorphic History of Western Canada

1

Olav Slaymaker and Dori J. Kovanen

Abstract

Geological timescales and large spatial landscape units of Canada are introduced. The tectonic framework of western Canada is sketched with specific attention to the north–northwest to south–southeast orientation of western Canadian mountain landscapes and the east–west grain of much of the western arctic islands. Structural, physiographic, and geomorphological landscape units of western Canada are defined, and the distinctive landscape impact of volcanic and carbonate lithologies is discussed. A descriptive account of each of the geomorphological landscape units of western Canada provides a general background for the individual case studies reported in Chaps. 4–28.

Keywords

Western Canada • Structural units • Physiographic regions • Geomorphological landscapes • Landforms

1.1 Scale Typology

The terrestrial surface can be considered within four time and space scales as follows. Plate tectonics has been the dominant driver of change over geological time and at the largest and oldest landscape scales (up to 10^8 year and 10^5 km^2); glaciation has superimposed its effects on tectonics at intermediate landscape scales (up to 10^6 year and 10^3 km^2); paraglaciation, defined as non-glacial processes conditioned by glaciation, has modified glaciated land systems at scales of up to 10^4 year and 10^1 km^2; and finally, at up to 10^2 year and 10^{-1} km^2 scales, the effects of local relief, hydroclimate, and human activity are superimposed on older morphologies. The timescales involved correspond closely to the Late Cretaceous–Quaternary periods (this chapter), the Pleistocene Epoch (Chap. 2), and the Holocene and Anthropocene epochs (Chap. 3).

The cumulative effect of all drivers (tectonics, climate, lithology, glaciation, paraglaciation, local relief, hydroclimate, and human activity) has produced the polygenetic landscape we see today. This chapter emphasizes the effects of tectonics, climate, and lithology over millions of years and over thousands of square kilometers.

1.2 Terrestrial Structural Units, Physiographic Regions, and Geomorphological Landscapes of Canada

1.2.1 Terrestrial Structural Units

The largest elements of the surface morphology of Canada are determined by long-term tectonic history. These elements are here referenced as the main terrestrial structural units of Canada (Stearn 1975). They have evolved around the core area known as the Canadian Shield and form a concentric pattern of highly folded and faulted mountain systems as well as relatively flat-lying sedimentary platforms. The eight terrestrial

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structural units are as follows: Canadian Shield, surrounded by the Arctic, Interior, Hudson, and St. Lawrence platforms; and these platforms are in turn surrounded by the Innuitian, Cordilleran, and Appalachian mountain systems (Fig. 1.1).

1.2.2 Physiographic Regions

Physiography is the land surface morphology, in so far as it summarizes the effects of lithology and available relief superimposed on the tectonic history. The eleven physiographic regions of Canada are the Canadian Shield, the lowlands identified as Arctic Lowlands, Interior Plains, Hudson Bay Lowlands, and St. Lawrence Lowlands, the mountains of Innuitian, Cordillera, and Appalachia, and the coastal areas of the Arctic Coastal Plain, the Pacific Coastal Lowlands, and the Maritime Plain. These regions, with the exception of the last three, are recognizably associated with the eight largest structural units of Canada (Bostock 2014; Fig. 1.2).

1.2.3 Geomorphological Landscapes

Geomorphological landscapes are built on the physiographic foundation of tectonic history and surface morphology but also incorporate the role of permafrost, vegetation cover, and human activity in so far as they affect geomorphological processes of erosion and sedimentation (Smith et al. 2001; Environment Canada 1995; Meidinger and Pojar 1991). The Canadian Shield structural and physiographic region is divided into four geomorphological landscapes on the basis of relief, permafrost, and forest cover; the Interior Plains' structural and physiographic region is divided into three geomorphological landscapes on the basis of permafrost, forest cover, and grasslands; the Hudson Bay Lowlands' structural and physiographic region comprises two geomorphological landscapes on the basis of permafrost and forest cover; Innuitia is divided into two geomorphological landscapes on the basis of relief; and the Cordillera is divided into five geomorophological landscapes based on relief,

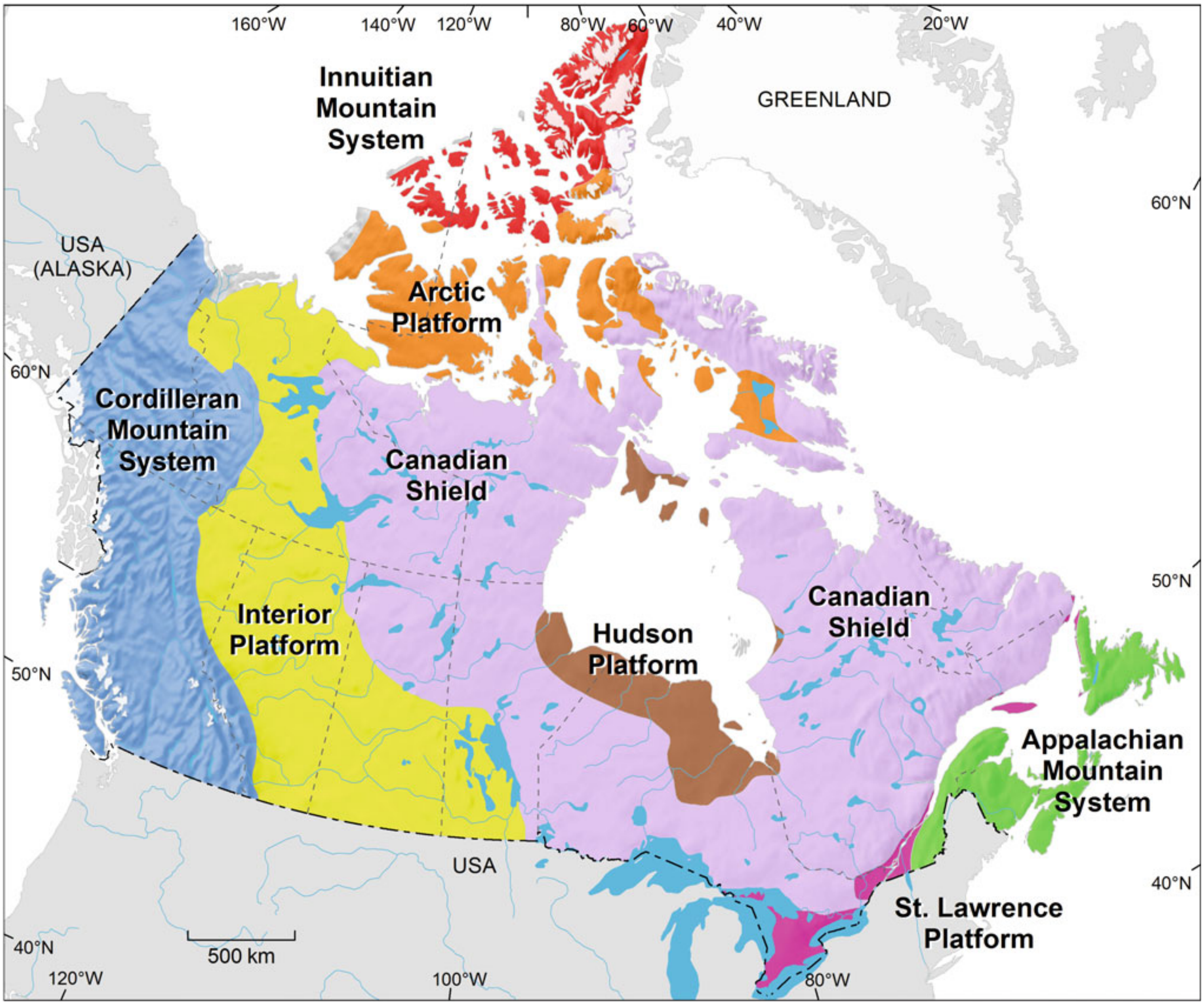


Fig. 1.1 Main structural units of Canada (adapted from Bostock 2014)

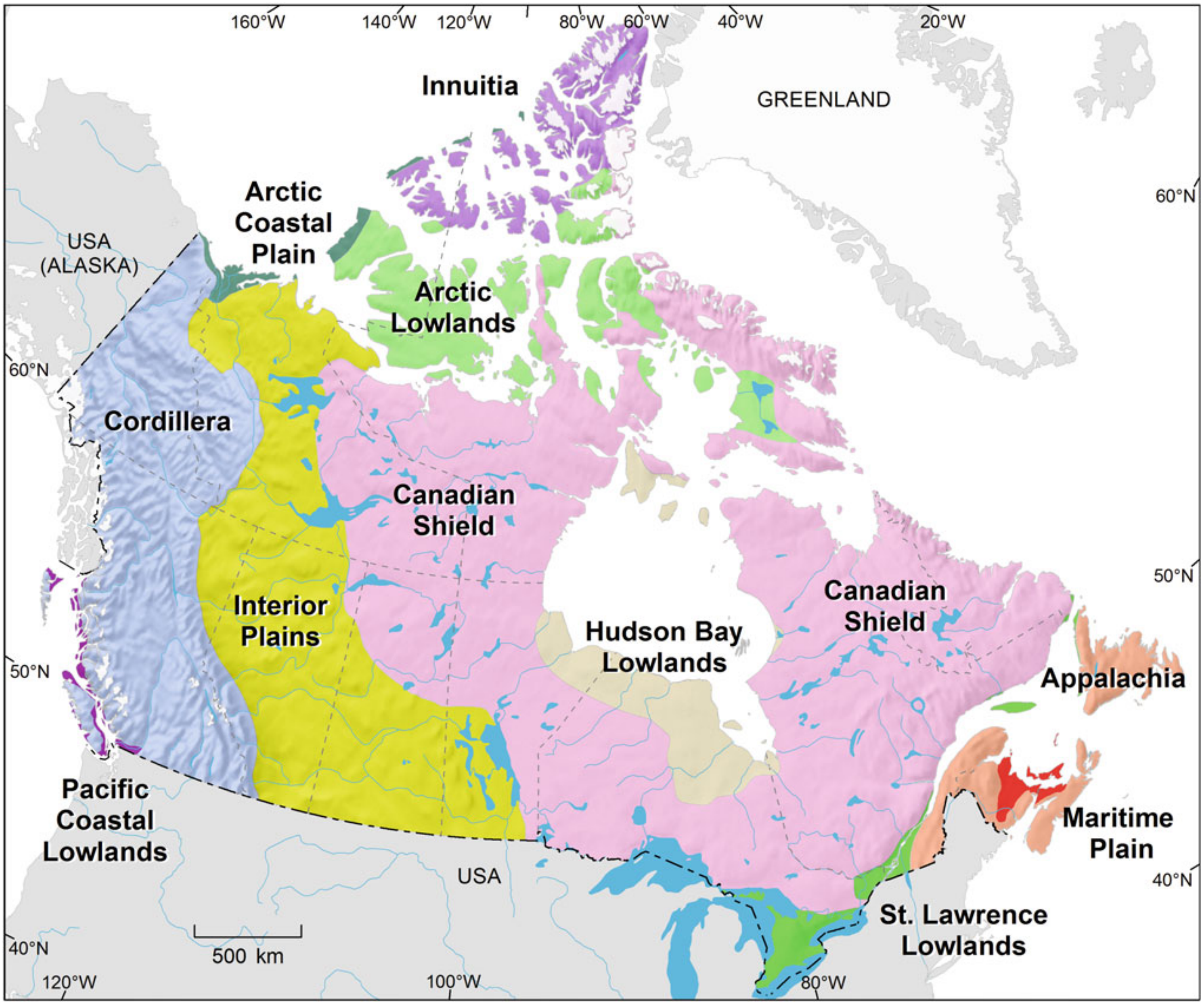


Fig. 1.2 Physiographic regions of Canada (derived from Bostock 2014)

permafrost, forest cover, and grasslands. This brings the total number of geomorphological landscape regions of Canada to twenty-two (Fig. 1.3).

1.3 Plate Tectonics of Western Canada

1.3.1 Pre-100 Ma

The Alberta Plateau, the Rocky Mountains, and the Cassiar–Columbia Mountains began to develop on a zone of continental shelf-slope sedimentation on the west side of the North American craton in Precambrian time [1.6–0.5 Ga (billion years ago)] with a period of mountain building (East Kootenay orogeny) about 0.9 Ga ago. Between 500 Ma (million years) and 200 Ma ago, a complex sequence of island arc activity developed to the west as crustal subduction became more active. Successive, westerly stepping subduction zones defined the Interior Cordillera, the Coast Mountains, and the Insular Ranges. Mathews (1992) considered that the middle or late Jurassic was the starting point of the geomorphic development of the Canadian Cordillera (175–150 Ma ago). The ancestral North America collided with a previously existing intermontane superterrane along its western margin so as to form the Omineca morphogeological belt. Later in the Mesozoic Era (c. 100 Ma ago), a similar collision gave rise to the Coast morphogeological belt.

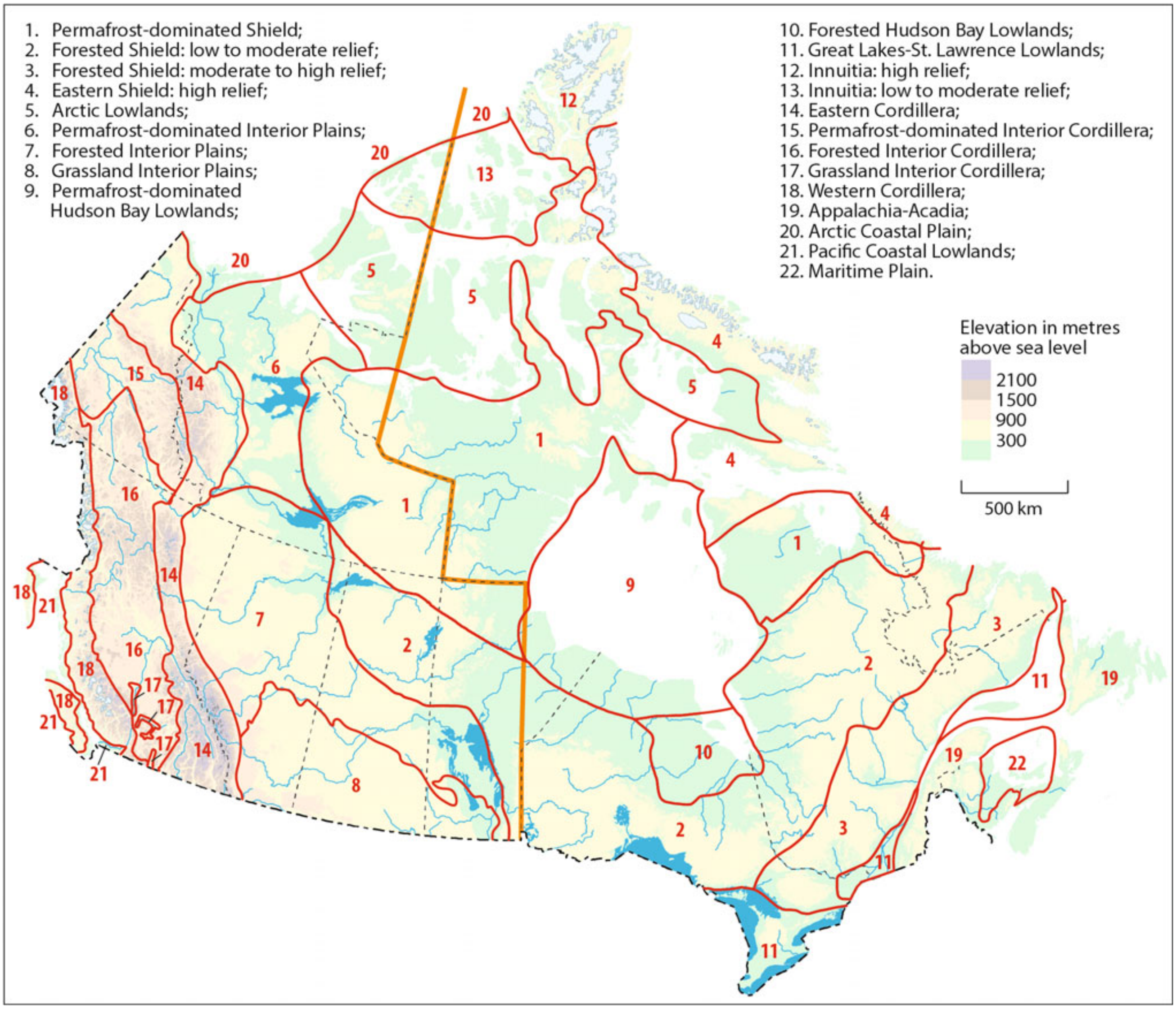


Fig. 1.3 Geomorphological landscapes of Canada. Data sources include physiographic regions of Canada (Bostock 2014), permafrost limits in Canada (Smith et al. 2001), and ecozones of Canada (Environment Canada 1995). Cartography by E. Leinberger

1.3.2 The Emergence of the Contemporary Cordilleran Landscape

Extensive mountain building in late Mesozoic and earliest Cenozoic eras (c. 75–35 Ma ago) was followed by erosion of the mountain landscapes during the bulk of the Cenozoic Era. Topography west of the Rocky Mountains was reduced to gentle slopes and broad valleys with up to 500 m of local relief. Remnants of this eroded landscape are found widely distributed as high surfaces in the Cordillera. The contemporary landscape of the Cordillera began to develop during the most recent phase of uplift and river incision commencing in the Miocene Epoch about 10 Ma ago (Parrish 1981; Mathews 1992).

Summit surfaces in the Juan de Fuca–Georgia Strait area and in the Interior Cordillera represent relict fragments of mid-Cenozoic erosion surfaces (Ryder 1981). Gravel-capped pediment fragments east of the Eastern Cordillera represent Pliocene and early Quaternary fluvial surfaces that have escaped glacial obliteration. The surface of the Beaufort Formation (Miocene) of the Queen Elizabeth Islands presents a similar denudation history.

The present-day plate tectonic regime at the tectonically active western boundary of the North American Plate consists of three contrasting segments:

(1) The southern segment is a subduction zone, along which slabs of oceanic lithosphere of the Juan de Fuca Plate and the Explorer Plate are slipping northeastward under southern British Columbia at 20–46 km Ma^{-1}.

(2) The central segment, which extends northward into the Gulf of Alaska from just south of the Queen Charlotte Islands, consists of the Queen Charlotte and Fairweather transform faults, along which the Pacific Plate and the Yakutat "block" are slipping northwestward or northward relative to the North American Plate at about 55 km Ma^{-1} (Riddihough and Hyndman 1992).

(3) The northern segment of the Cordillera consists of a tectonic "collage" of allochthonous terranes. The larger terranes (Quesnellia, Stikinia, Wrangellia, and Alexander) are laterally persistent tectonostratigraphic assemblages.

1.3.3 The Innuitian–Greenland Plate Connection

The Queen Elizabeth Islands archipelago is a subplate, bounded by major shear zones, that was broken by rifting in the late Cretaceous and Paleogene periods (75–50 Ma; Hodgson 1989). The islands are largely underlain by the deformed sediments of the Innuitian Province lying between the Arctic Ocean basin to the northwest, the stable Arctic Platform in the southeast, and Greenland in the northeast. Initial fragmentation started possibly by the late Paleozoic (c. 300 Ma), and deformation parallel to the present northeast–southwest topographic grain continued late into the Cenozoic (c. 25 Ma). Prince Patrick Island, the southwesternmost member of the Queen Elizabeth Islands, has an east–west topographic orientation.

1.4 Major Lineaments of Western Canada

The net effect of western Canada's tectonic history is that much of the landscape, with the exception of the Innuitian region, is aligned in a general north–northwest to south–southeast direction. The main orientations of the major valleys in the Coast Mountains, including the fjords, define the principal conjugate failure planes for the stresses established by onshore movement of the Juan de Fuca and Explorer plates, demonstrating their specific influence over the topography of coastal British Columbia (Church and Ryder 2010) and also, in a more general sense, their extensive influence over most western Canadian landscapes (Brew and Ford 1978).

1.4.1 Thrust Faults

One of the most dramatic expressions of western Canada's tectonic history is the surface trace of the thrust faults that separate the Rocky Mountain Foothills to the east and the Rocky Mountains proper to the west. The morphological expression of this surface trace is illustrated in Sect. 1.7.3. Older rocks have traveled more than 100 km over the top of younger rocks. For example, the McConnell Thrust, at Mount Yamnuska (65 km west of Calgary, Alberta), is a nearly horizontal thrust fault. There is a remarkably thin deformation zone of only about 1 m in thickness that separates overlying Cambrian carbonates from underlying Cretaceous sandstones and shales. It forms the easternmost surface thrust fault in a sequence that first started forming with the docking of the first superterrane (the Intermontane Belt) onto the western margin of the North American craton.

1.4.2 Trenches

A second even more dramatic landscape expression of western Canada's tectonic history is the presence of three semi-continuous linear valleys, each at least 500 km long, and oriented in a north–northwestern to south–southeastern direction. These trenches are known as the Rocky Mountain, Tintina, and Shakwak trenches. Running parallel between the peaks of the Columbia and Rocky mountains and ranging 3–16 km wide and about 1400 km long, the Rocky Mountain Trench (Fig. 1.4) extends past Mount Robson, the highest peak in the Canadian Rockies at 3954 masl. The trench likely formed due to underlying normal faults that emerged as a result of tectonic collisions that pushed up the mountains.

Characteristically, these trenches are straight, flat-bottomed, and several kilometers wide and have steep, nearly vertical sides that are often 700–1000 m high. They contain Cretaceous and Cenozoic non-marine sediments and glacifluvial and glacilacustrine deposits. (Leech 1966; Clague 1975).Within these large trenches, the upper reaches of many of western Canada's largest rivers flow as misfit streams, such as the Columbia (Fig. 1.5a), Fraser, Finlay, Kechika, and Pelly rivers. The Rocky Mountain Trench is drained by six major rivers, including the Kootenay, Columbia, Upper Fraser (Fig. 1.5b), and Finlay–Parsnip (Peace).

Three hundred and fifty km northwest of the Liard River, the Tintina Trench extends for 700 km past Dawson City into Alaska. The Shakwak Trench, the shortest of the three

Fig. 1.4 **a** The Rocky Mountain Trench, a tectonic graben in western Canada. Running parallel between the peaks of the Columbia and Rocky mountains and ranging 3–16 km wide and about 1400 km long, the trench extends past Mount Robson, the highest peak in the Canadian Rockies at 3954 masl. The trench likely formed due to underlying normal faults that emerged as a result of tectonic collisions that pushed up the mountains. In this image, snow and ice appear *turquoise*; vegetation is *green,* exposed rock in *grays*, *browns,* and *tans*; and liquid water is *dark blue*. The area has been shaped by a combination of rivers and glaciers. *Source* MDA Federal (2004). **b** Aerial oblique view of the southern Rocky Mountain Trench. *Source* © Province of British Columbia. All rights reserved. BC767:18. The inset image here and elsewhere in this chapter is extracted from NASA, Visible Earth (Stöckli et al. 2005)

trenches, parallels the Tintina Trench in the southwestern Yukon and contains Kluane Lake.

1.4.3 Major Mountain Divides

Another striking expression of the landscape impact of western Canada's tectonic history is the approximate parallelism of the major mountain divides. The Coast Mountains parallel the Rocky Mountains as do, for example, the Cassiar, Skeena, Omineca, and Mackenzie mountains. Individual mountain ranges, such as the St. Elias Mountains and the Alsek and Boundary ranges of the Coast Mountains, have the same orientation and form the international boundary between British Columbia and Alaska (Fig. 1.6).

1.4.4 Significant Tertiary Drainage Reversals

In spite of the clear control exerted by the geological structure on major lineaments of the landscape, there were numerous drainage reversals before those associated with glacial effects during the Pleistocene. Eisbacher et al. (1974) described the early Cretaceous rivers forming an alluvial

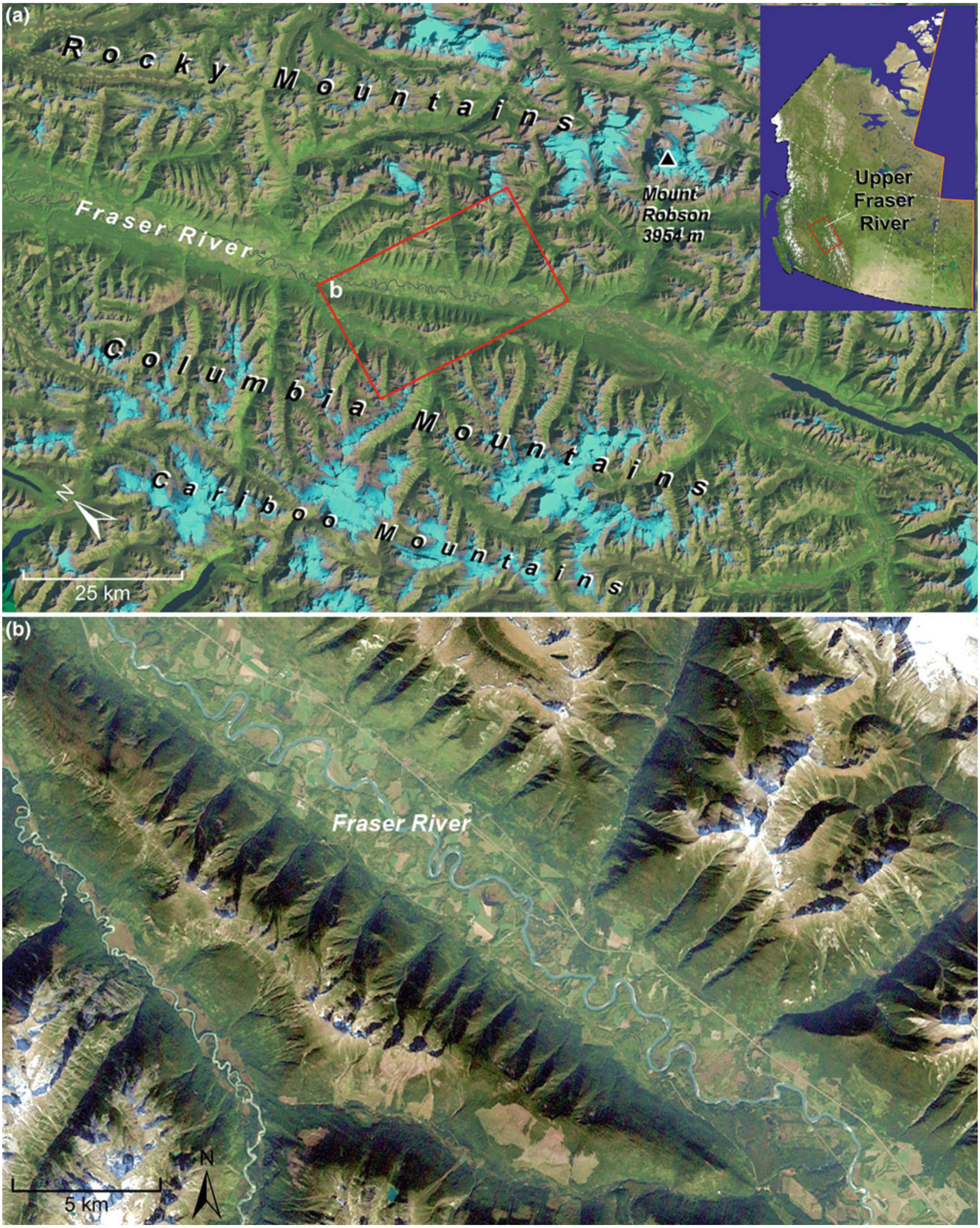


Fig. 1.5 **a** Upper Fraser River. *Source* NASA Landsat Program (2003). **b** The misfit Fraser River in the southern Rocky Mountain Trench. *Source* © Department of Natural Resources Canada. All rights reserved. Government of Canada, Centre for Topographic Information, CanImage—Landsat 7 Orthoimage, 083e04

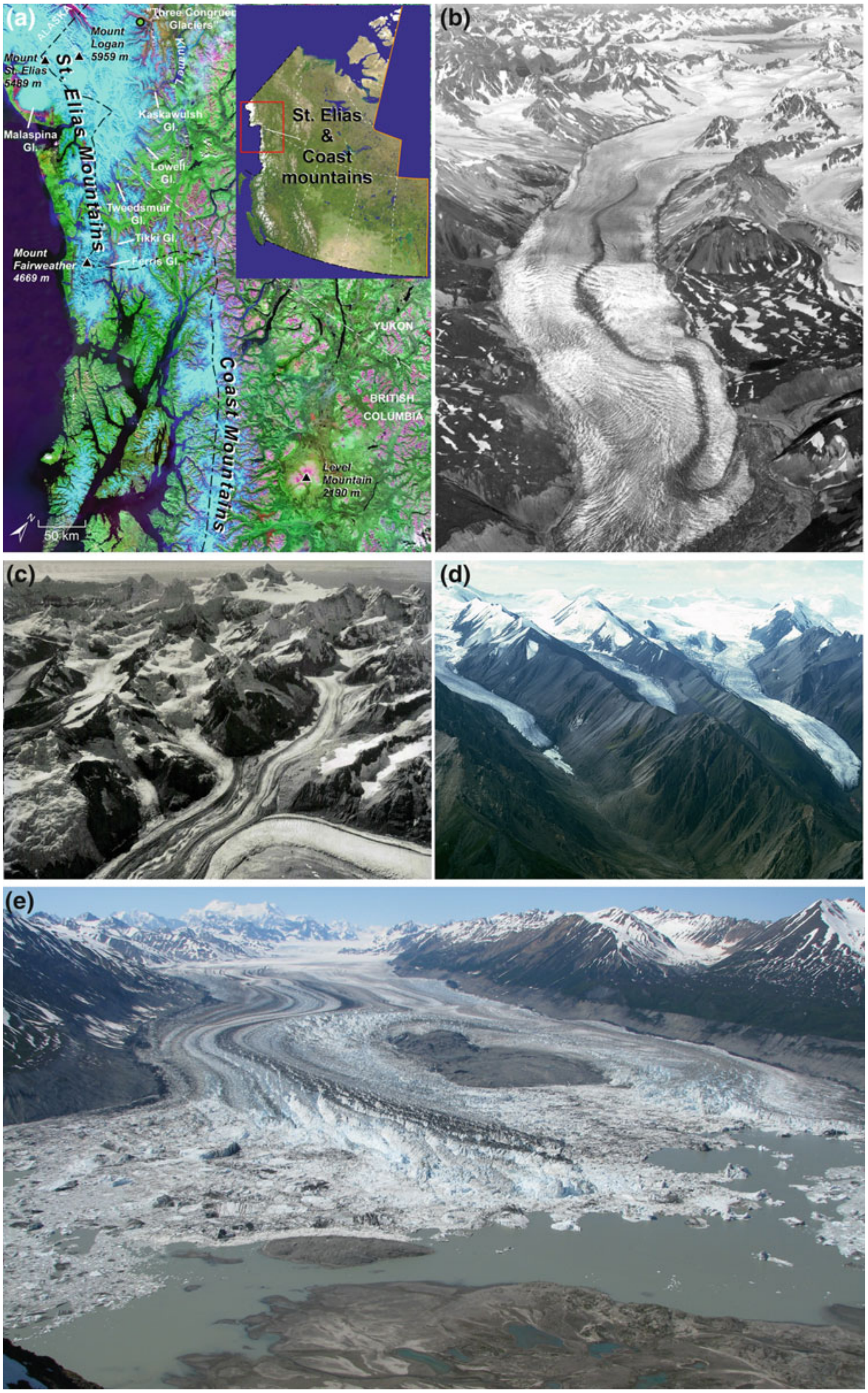


Fig. 1.6 **a** Saint Elias Mountains hold the world's most extensive ice fields outside the polar ice caps. Many peaks exceed 5200 masl, including Mount Logan (5959 masl, the highest in Canada) and Mount St Elias. *Source* MDA Federal (2004). **b** Aerial oblique view of the Tikki Glacier in the Boundary Ranges of the Coast Mountains in British Columbia. Tikki Glacier is one of many glaciers in Canada which can be expected to form hazardous lakes periodically (*Source* US Geological Survey, Department of the Interior; photograph by Austin Post 1966). **c** Aerial oblique view of the Ferris Glacier. Medial moraines are clearly formed at the juncture of the glacier's adjacent tributaries. In the background is Mount Fairweather (4669 masl). *Source* © Province of British Columbia. All rights reserved. BC 688:16. **d** "Three Congruent Glaciers" in the St. Elias Mountains in Yukon. These glaciers originate from similar firn basins and flow along nearly identical parallel valleys. Their history has shown that their lengths have markedly different responses to changes in mass balance. Reproduced with the permission of Natural Resources Canada, 2015 (photograph: NRCan 2002-678 by Robert Bélanger). **e** Panoramic view of the terminus of Lowell Glacier from Goatherd Mountain in Kluane National Park and UNESCO World Heritage Site (June 14, 2010; © Government of Yukon, Panya Lipovsky. Image reproduced with permission). Mount Kennedy (4238 masl) is part of the white massif in the background

apron on the western and westward flowing side of the Omineca Belt, whereas Yorath and Cook (1981) focused on the tributaries of the Mackenzie in the northern Interior Plains and Duk-Rodkin and Hughes (1994) discussed the evolution of the gravel-capped pediplains of the late Tertiary landscape of the eastern Rocky, Mackenzie, and Richardson mountains. During the uplift of the mountains during the Laramide Orogeny, two major drainage systems developed:

one to the Atlantic Ocean and another to the Arctic Ocean. The Atlantic drainage is composed of the northwestern tributaries of an integrated drainage system that flowed toward Hudson Bay. Traces of this drainage are found in the Canyon Ranges of the Mackenzie Mountains, Iroquois upland, and in the Norman Range of the Franklin Mountains (see Chap. 14). The arctic drainage included two main basins—the Porcupine basin that drained from west to east across the Richardson Mountains (see Chap. 19) and the Anderson basin that included the Peel (see Chap. 7) and Snake rivers as its tributaries (Duk-Rodkin and Hughes 1994). Tempelman-Kluit (1980) and Jackson et al. (2012) have differing views on the evolution of the Miocene drainage pattern of the Yukon. Mathews (1992) showed the effects of volcanic diversion of the upper Stikine. Lay (1940/41) made an early study of the reversal of the Fraser River flow based on placer gold evidence (see Chap. 27), and Tribe (2005) has made an exhaustive analysis of drainage evolution on the central Interior Plateau.

1.5 Volcanic Landscapes of Western Canada

Within the Cordilleran structural and physiographic region, there has been and continues to be much volcanism. Active volcanism extends across BC and Yukon from the Cascade Mountains (Hickson 2000) to Wells Gray Provincial Park (Neuffer et al. 2006), the Anahim Plateau (Cassidy et al. 2011), northern BC (Edwards and Russell 2000), and north to Fort Selkirk in central Yukon (Jackson et al. 2012). More than 200 potentially active volcanoes exist in western Canada, and 49 have erupted in the last 10,000 years (Stasiuk et al. 2003). Not only all standard volcanic landforms are represented, but also, more unusually, volcanic landforms created beneath the Cordilleran Ice Sheet are present (Fig. 1.7).

1.5.1 The Northern Cordilleran Volcanic Province

Possibly the oldest volcanic events in the Northern Cordilleran Volcanic Province (NCVP) are represented by Miocene age volcanics of 27–16 Ma around Atlin Lake. More than 100 eruptions have occurred in the past 20 Ma with a broad range of eruptive styles. These volcanic processes have created a range of different volcanic landforms, including stratovolcanoes, shield volcanoes, lava domes, and cinder cones along with a few isolated examples of rarer volcanic forms such as tuyas. Tuyas are flat-topped subglacially formed volcanoes (Mathews 1947). Four large volcanoes have formed: Hoodoo Mountain (Fig. 1.8), the Mt. Edziza volcanic complex, the Level Mountain Range, and Heart Peaks.

At least three types of volcanic zones are present in the NCVP, including large persistent lava plateaus like those found at the Mount Edziza volcanic complex, polygenetic volcanoes such as Hoodoo Mountain, and monogenetic volcanoes such as the basaltic cinder cones found throughout the volcanic province.

Basaltic shield volcanoes throughout the central NCVP form lava plateaus and are the largest volcanoes of the volcanic zone. The massive Level Mountain Range shield volcano, occupying an area of 1800 km^2, forms a broad cliff-bounded lava plateau. The Mount Edziza volcanic complex covers an area of 1000 km^2. Just west of the Level Mountain Range lies Heart Peaks, the third largest volcano of the NCVP with an area of 275 km^2. Glacial ice and streams have since dissected the >2000 masl volcanoes into a series of valleys with intervening ridges that constitute the Level Mountain Range proper.

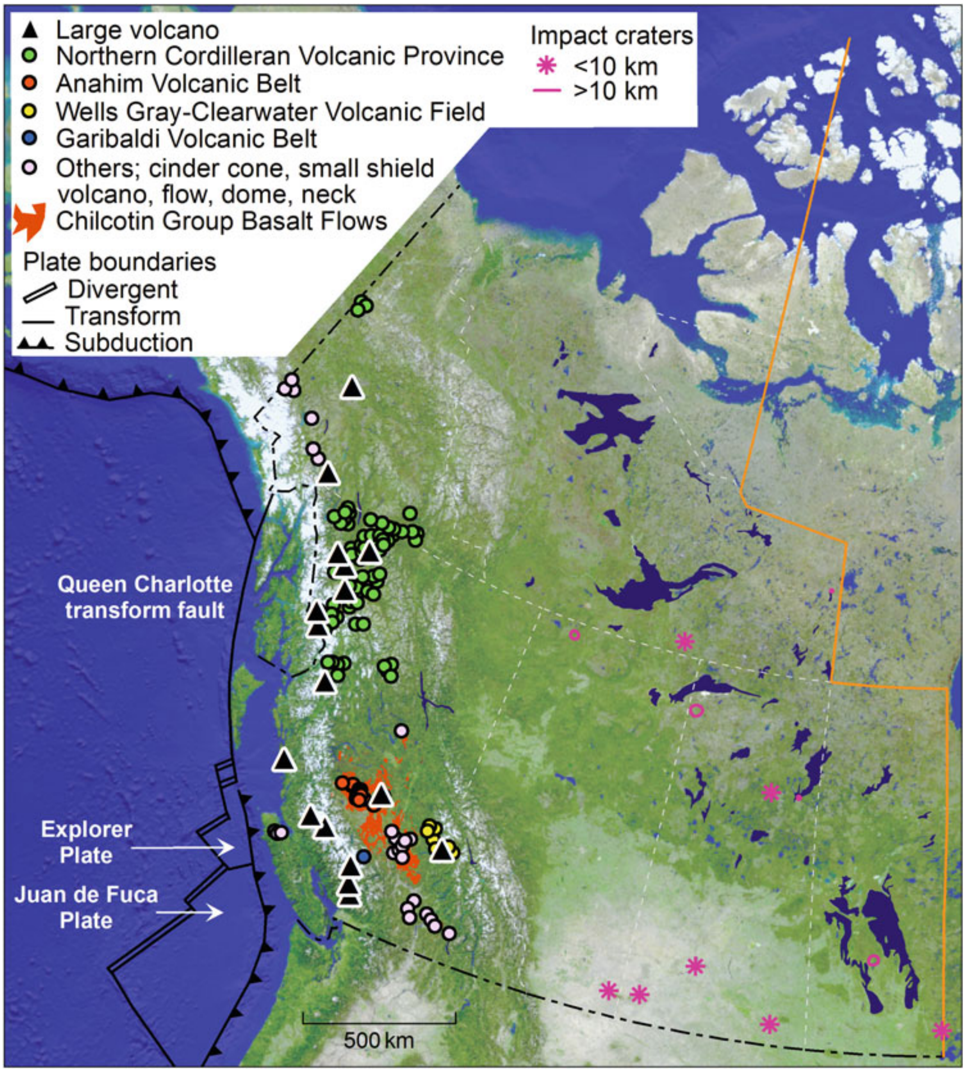
In northern British Columbia, remnants of a shield volcano are found throughout the western Cassiar Mountains. This prehistoric shield volcano, known as Maitland Volcano, erupted from 5–4 Ma ago on a mature eroded surface. Remnants of this prehistoric shield volcano include a cluster of 14 volcanic plugs and scattered cliff-bounded basaltic lava flows. A series of lava domes was constructed in the Level Mountain Range alpine valley system 4.5–2.5 Ma ago. Headward erosion has modified the Level Mountain Range shield by incising youthful V-shaped stream canyons into the lava plateau margin.

1.5.2 The Garibaldi Volcanic Belt

To the northwest of Mt. Garibaldi, the Mount Cayley massif constitutes the largest and most persistent volcano in the central Garibaldi Volcanic Belt. It is a highly eroded stratovolcano composed of lava that was deposited during three phases of volcanic activity. The first eruptive phase started about 4 Ma ago with the eruption of lava flows and pyroclastic rock. This resulted in the creation of Mount Cayley proper. Subsequent volcanism during this volcanic phase constructed a significant lava dome.

To the northwest, the Franklin Glacier complex is volcanic bedrock that encompasses an area 20 km long and 6 km wide. Volcanics include breccia and lava flows associated with tuffs that reach 450 m thick. Potassium–argon dates obtained from some of the subvolcanic intrusions

Fig. 1.7 Distribution of selected volcanic landforms and impact structures in western Canada. Data sources include Volcanoes of the World dataset (Siebert and Simkin 2002), regional volcanic centers (modified from Edwards and Russell 2000), Chilcotin Group basalts (Massey et al. 2005), and Earth Impact Database (2015). *Background image*: NASA, Visible Earth



indicate that Franklin formed during two volcanic events, each separated by about 5 Ma of dormancy. The first event occurred between 6 and 8 Ma ago. When the Garibaldi Volcanic Belt moved to its current location 5 Ma ago, another volcanic event occurred at the Franklin complex. This final and most recent volcanic event occurred between 2 and 3 Ma ago, about a million years after Mount Cayley to the south began its formation.

Silverthrone Caldera is the larger and better preserved of the two caldera complexes in the northern Garibaldi chain, the other being the Franklin Glacier complex 55 km to the east–southeast. The caldera has a diameter of 20 km and contains breccia, lava flows, and lava domes. Near-vertical flanks extend from near sea level to more than 3000 m in elevation.

1.5.3 Anahim Volcanic Belt

The Anahim Volcanic Belt is a 600-km-long volcanic belt, stretching from Vancouver Island to near Quesnel. It has had three main magmatic episodes, dated at around: 15–13, 9–6, and 3–1 Ma. The volcanoes generally become younger eastward at a rate of 2–3.3 cm a year. The Nazko Cone, which last erupted only 7200 years ago, is the youngest Anahim volcano. These volcanoes are thought to have formed as a result of the North American Plate sliding westward over a long-lived center of upwelling magma called the Anahim Hotspot.

The volcanic belt is defined by 37 Quaternary basalt centers and three large shield volcanoes called the Rainbow,

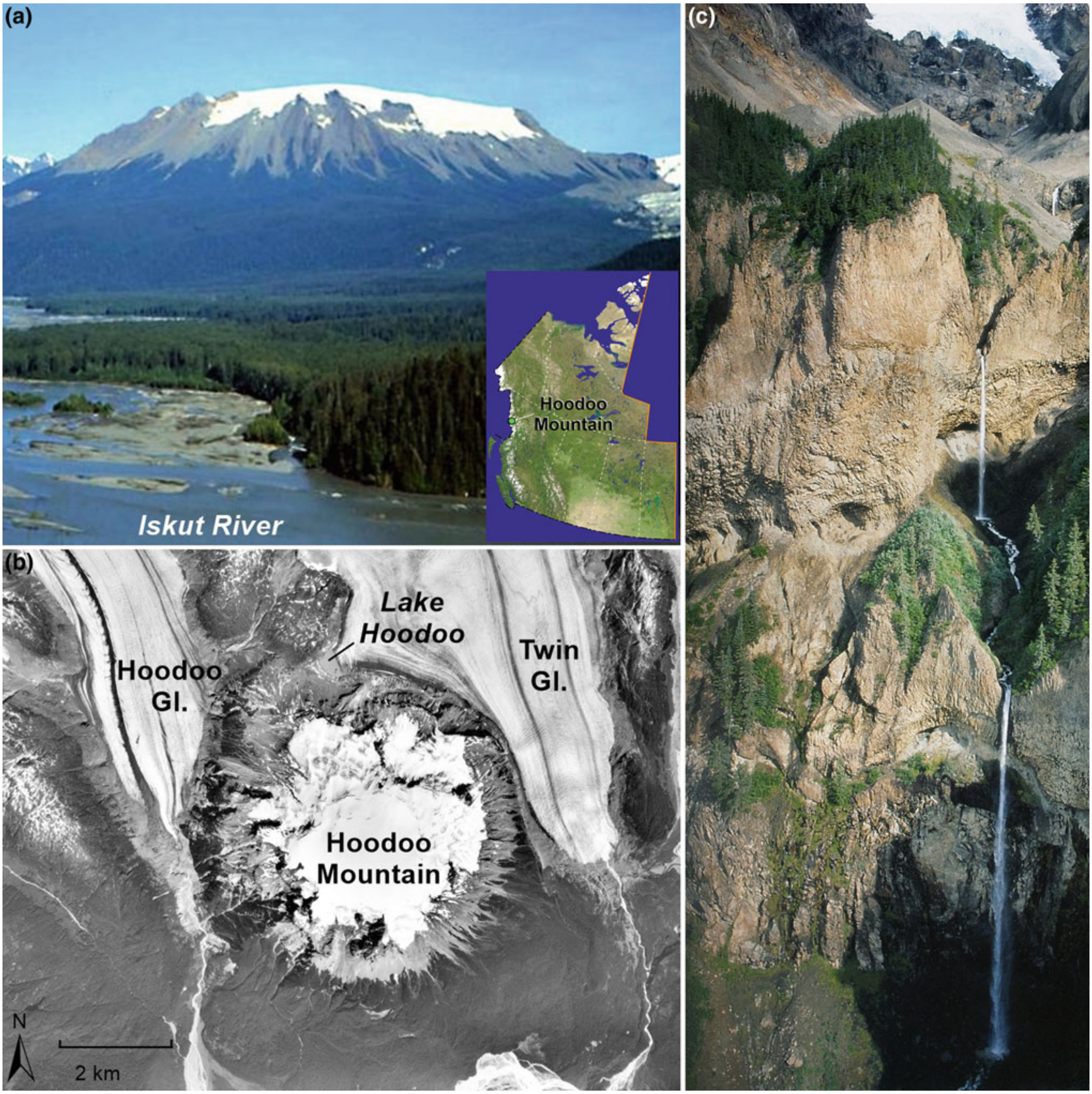


Fig. 1.8 **a** Hoodoo Mountain is a classic flat-topped glacivolcanic edifice (tuya) that rises to 1850 masl on the north side of the Iskut River, in the Coast Mountains of northwestern British Columbia. The volcano formed under glacial ice within the Cordilleran Ice Sheet during the Quaternary. *Photograph* by Ben Edwards, 1994. **b** Aerial photograph of Hoodoo Mountain volcano, the Hoodoo and Twin valley glaciers, and Lake Hoodoo. At present, the summit region is covered by a 3–4 km diameter ice cap above 1700 masl. *Source* © Province of British Columbia. All rights reserved. BC82022:206. **c** On Hoodoo's south face, meltwater cascades from the ice-filled crater and drops over vertical volcanic cliffs. The stratigraphy of the volcano is dominated by thick lava flows. *Photograph* by Gary Fiegehen

Ilgachuz, and Itcha ranges (Fig. 1.9). These three large volcanoes have built up dome-like piles of lava and fragmental rocks to a height of 2478 masl at Tsitsutl Peak in the Rainbow Range, 2400 masl at Far Mountain in the Ilgachuz Range, and 2365 masl at Mt. Downton in the Itcha Range. The Rainbow Range is a low dome-like cone about 36 km diameter, with Anahim Peak an obsidian plug on its northeast flank. The Ilgachuz Range is 24 km or more in diameter, and the Itcha Range is 16 km wide and about 64 km long.