# Geomorphological Landscapes of the World

Piotr Migoń
Editor

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Springer

*Editor*
Piotr Migoń
Department of Geography and Regional Development
University of Wrocław
Poland
migon@geogr.uni.wroc.pl

ISBN 978-90-481-3054-2 e-ISBN 978-90-481-3055-9
DOI 10.1007/978-90-481-3055-9
Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2009941466

*Cover images*: background image, Durdle Door in the Purbeck, photo R. Edmonds; images from left to right: Nærøyfjorden, photo A. Nesje; Uluru (Ayers Rock), Central Australia, photo C. R. Twidale; the Pokhara valley, Nepal, photo M. Fort; the Dead Sea area in the Middle East, photo D. Bowman.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

# Contents

# Introduction

Geomorphology, a part of Earth Sciences, is the scientific study of landforms, their assemblages, and processes that molded them in the past and that change them today. Geomorphologists study shapes of landforms and regularities of their spatial distribution, decipher their origin and evolution, and try to establish their ages. 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.

But geomorphology has also been named "the Science of Scenery." And the natural scenery, which is essentially a combination of landforms of different sizes, shapes, origins, and ages, can be captivating. You do not need to be a geomorphologist to marvel at the Grand Canyon of Colorado, the fjords of Norway, or the lofty peaks of the Himalayas, to name just a few great landscapes on Earth. However, where an untrained eye sees mainly the beauty of a physical landscape, geomorphologists go a step further, trying to answer how and why such a natural beauty has come into being. Many of the great landscapes are unique by global standards and a question inevitably arises what is the reason for this uniqueness. What are the fundamental controls on the evolution of landscape? Tectonics, rocks, changing climates, or humans? In short, each geomorphological landscape tells a story and unravels pages from the history of the Earth. Yet, deciphering a complete story is not always easy and many striking landscapes still remain somewhat mysterious.

This book aims to tell some of these stories, hidden behind the marvelous sceneries. It does so in the hope that better scientific understanding will not deprive the world's iconic landscapes of their magic, but may help us to appreciate their beauty even more than before. It is a joint endeavor of nearly 50 geomorphologists from more than 20 countries, who for many years have researched some of the most fascinating sceneries on Earth and are willing to share their knowledge. The scientific patronage for the book is provided by the International Association of Geomorphologists. Among its statutory aims are promotion of geomorphology and fostering international cooperation, and this is precisely the idea of the presented volume. The International Association of Geomorphologists, which now has more than 60 member states, was founded 20 years ago, in 1989, and so with this book we also salute its 20th anniversary and its overall success.

Altogether, there are 36 individual stories told. Selecting the landscapes to write about was an arduous task and I am fully aware of themes which some readers may miss. However, each continent is present, and the most splendid sceneries have their chapters. It was intended to present landscapes of different origin, so that the reader can learn about the complexity of processes behind the sceneries and discover that the sadly too often used phrase "the action of water and wind" does not do justice to the geomorphological wonders of our Planet.

The primary control on the evolution of landscapes is tectonics – the movement of the Earth's crust – but in some places its influence is clearer than in others. Landforms offer unparalleled insights into the nature of tectonic processes, and plate boundaries in particular host spectacular tectonic landscapes, however, constantly modified by erosion. A few such stories, from different tectonic and climatic settings, can be found in this volume. T. Waltham tells a geomorphic story from diverging plates in *Afar* in northeast Africa, D. Bowman presents the great strike-slip structure of the *Dead Sea Graben*, whereas a story of uplift and erosion can be read from the landscape of *Wellington* in New Zealand (M. Crozier and N. Preston). Finally, M. Fort, using the *Pokhara Valley* in the Nepal Himalaya as an example, introduces processes shaping the highest mountains on Earth, situated at a convergent plate boundary. Among the most intriguing gross geomorphic features of the world are Great Escarpments, which border ancient landmasses, particularly in the southern hemisphere. Their complex evolution is presented through the examples of the *Drakensberg* in South Africa (S. Grab) and the *Western Ghats* of India (V. Kale). In many places tectonics goes side by side with volcanism, which is one of the great sculptors of the Earth surface. Two famous volcanoes are presented in detail, the archetypal stratovolcano of *Mt. Fuji* (T. Oguchi and C. Oguchi) and the 1943-born *Parícutin* in Mexico (I. Alcántara-Ayala). However, on a larger scale, the magnificent scenery of *Iceland* is very much a product of volcanism, in addition to glacial and fluvial processes (B. Whalley).

Many great landscapes of the world are those of karst and these feature extensively in this volume. Examples of limestone scenery include the cold-climate karst of *South Nahanni* in Canada (D. Ford), the cockpit karst of *Jamaica* (P. Lyew-Ayee), the famous tower karst of *Guangxi* in south China (T. Waltham), and the big cave-riddled tropical karst of *Mulu* in Borneo (D. Gillieson and B. Clark). However, karst is not necessarily confined to carbonate rocks and this volume contains two fascinating stories of karst on quartzite and sandstone, of *Gran Sabana* in Venezuela (R. Wray) and *Bungle Bungle* in Australia (R. Young), respectively. Another rock which supports distinctive morphology is granite and no volume about the greatest world's landscapes would go without stories from granite terrains. Yet these can be strikingly different as can be seen comparing ones from the wider surroundings of *Rio de Janeiro* (N. Fernandes et al.), *Sanqing Mountains* of east China (M. Thomas), and the *Spitzkoppe massif* in the Namib Desert (P. Migoń). Sandstones have a decisive influence on landforms too, as explored by R. Twidale who reads the story behind one of the truly iconic landforms worldwide, *Uluru* in Australia. No less impressive are the sandstone "rock cities" of the *Saxon-Bohemian Switzerland* in Central Europe (V. Cílek) and the multitude of arches and deep canyons in the *Canyonland – Arches* area of Utah, USA (J. Dixon). Finally, the *Dolomites* of Italy (M. Soldati) tell a complex story of how rocks, glaciers, and landslides created one of the most attractive and unique mountain sceneries.

Deserts have long conquered the minds of many geomorphologists, attracted by their unusual scenery and the power of wind in shaping the surface. One of greatest sand seas on Earth, the *Namib Sand Sea*, is presented by A. Goudie, whereas D. Busche unravels the complex story behind the Saharan landscape of *northeast Niger*, which can be traced back to much wetter periods of the distant past. Wherever it is more humid, rivers assume the role of a key modeler of any scenery. However, before rainwater reaches large permanent rivers, it can do marvels on unconsolidated deposits, creating some of the most striking erosional landscapes on the world, among which the *badlands of the Great Plains* of North America are the most famous (M. Gonzalez). The great efficiency of erosion can also be admired in the *Loess Plateau* of China, as presented by X. Yang et al. Riverine landscapes can be subtle and subdued, but can also be awe-inspiring. Such are the great waterfalls and associated canyons, including two featuring in this volume, the *Iguazu Falls* in South America (J. Stevaux and E. Latrubesse) and the *Victoria Falls* in Africa (A. Moore and F. Cotterill). A very different type of landscape is associated with great deltas, and the *Mackenzie Delta*, introduced by C. Burn, is of particular interest because much of the ground there is frozen. But perhaps *the* most famous geomorphological landscape of the world is one created by the Colorado River where it cuts through the Colorado Plateau and forms the *Grand Canyon*. Surprisingly, or maybe not, its history is still open to debate as reviewed by L. Dexter.

Rivers have great power, but even greater landscape effects are associated with megafloods, which typified the period of decay of huge Pleistocene ice sheets. The *Channeled Scablands* of the northwest USA, presented by V. Baker, is the area where this sheer power was appreciated for the first time. Megafloods occurred in Antarctica too, forming a page in the complex story of inheritance and glacial erosion deciphered in the *Dry Valleys of Antarctica* (D. Sugden). Glaciers have been of fundamental importance in morphological evolution of the *Southern Patagonian Andes* (E. Mazzoni et al.), whereas in a different location they remodeled the preexisting fluvial landscape to create another wonder of the world – the *fjords of Norway* (A. Nesje). The fjords are not the only landscape where the meeting of land and sea produces spectacular scenery. Two other coastal sceneries are explained in the volume. The *Dorset and East Devon Coast* of southern England (D. Brunsden and R. Edmonds) is a natural laboratory for coastal geomorphology, whereas the remote *atolls of the Pacific* (P. Nunn) show how living organisms, adapting to changing conditions at the sea floor, contribute to the evolution of the Earth's surface.

The beauty of many geomorphological landscapes has long been recognized, starting from travelogues of ancient travelers and scientists. Today, many such landscapes, if easily accessible, are top tourist destinations, accommodating millions of visitors annually. They come to see the scenery, which in their eyes has outstanding universal value. However, this phrase has also a more formal meaning. Places, whose outstanding universal value can be demonstrated beyond doubt, fulfill one of the criteria to be inscribed on the prestigious list of UNESCO World Heritage properties. Among 36 landscapes presented in this volume, nearly half have already received this distinction, whereas others are protected and cherished at a national level, as national parks, reserves, and areas of outstanding beauty. The closing chapter in this volume, written by T. Badman, reviews the position of geomorphological landscapes in the World Heritage initiative and indicates the way forward.

The volume could not have been completed without the help and assistance of various individuals. First and foremost, I would like to thank the contributors themselves who enthusiastically responded to the invitation, added this one more task to their busy agendas, and came up with texts which required very limited further work. Particular thanks go to Professor Andrew Goudie, who came with the original idea of this volume, helped to select chapters and authors, and then kindly reviewed many individual chapters and corrected English of non-native authors. At the early stage of preparation I also enjoyed the assistance of Professor Denys Brunsden, Professor Michael Crozier, and Professor Carol Harden. Dr Wolfgang Eder, the former Director of Earth Science Division of UNESCO, provided a vital link to the Springer Verlag, for which I am immensely grateful. My very special words of thanks are to Ms Joanna Remisz who expertly drew most of the figures for this volume. Ms Monika Krawczyńska helped with editorial work in the closing stages, when it was all too easy to get lost. Finally, I thank my wife Edyta for the constant encouragement and the brave decision to accept living with yet another book.

Wrocław, June 2009 Piotr Migoń

# Chapter 1
# The Mackenzie Delta: An Archetypal Permafrost Landscape

Christopher R. Burn

**Abstract** The Mackenzie Delta, in Canada's western Arctic, is North America's largest arctic delta. For over half the year the rivers and lakes of this vast alluvial plain are ice covered. Permafrost is ubiquitous in the delta and the surrounding landscape. Treeline traverses the delta, separating closed-canopy white spruce forests in southern parts from low shrub tundra and sedge wetlands at the Beaufort Sea coast. The extension of the delta northwards into the ocean is the net result of 128 Mt of sediment brought annually to the delta by Mackenzie and Peel Rivers, of which about two thirds are deposited offshore. The permafrost of the uplands adjacent to the delta is ice-rich, with numerous tabular bodies of almost pure ice that formed when the ground originally froze. Throughout the region the terrain surface is criss-crossed by networks of ice-wedge polygons, formed by water freezing in cracks opened by ground contraction during winter cooling. The world's largest population of pingos – ice-cored, conical hills up to 50 m high – has developed in the sandy sediments of drained lakes in the area. These features form as permafrost aggrades in saturated lake sediments, and continual uplift of these little hills demonstrates the enormous forces that can be generated by ground freezing.

**Keywords** Ground ice • ice-wedge polygons • Mackenzie Delta • permafrost • pingos

## 1.1 Introduction

Mackenzie River's delta is North America's largest arctic delta, and, with an area of 13,000 km$^2$, the world's second largest arctic delta, smaller than only the delta of the Lena River in Russia. The Mackenzie Delta is a maze of lakes and sinuous channels, carrying the discharge of Mackenzie and Peel Rivers to the Beaufort Sea (Fig. 1.1). For over half the year the rivers and lakes are ice covered, and in this period roads and trails can be constructed to connect points accessible in summer only by boat or aircraft (Fig. 1.2). Treeline crosses the delta, with spruce forest covering the southern portions, and willow bushes and sedge wetlands and marshes to the north. The Delta is an alluvial plain with lakes occupying up to half of the total area (Mackay 1963). It is 210 km long and on average 62 km wide. The elevation at Point Separation, at its apex (Fig. 1.1), is only about 15 m above mean sea level (Mackay 1963). A few bedrock "islands" are exposed in the southeast portion of the Delta, the highest being about 30 m above the delta plain.

The northern portion of the delta, adjacent to the Beaufort Sea, and the area to the east form the Tuktoyaktuk Coastlands, a rolling, lake-rich plain, only a few tens of meters above sea level. The area is a treasure trove of landforms created by the ubiquitous presence of permafrost, ground that remains at or below 0°C for 2 or more years. The world's largest population of pingos – small, conical, ice-cored hills – is found here (Fig. 1.3), and over vast swaths of the terrain the ground surface is dissected by networks of ice-wedge polygons (Fig. 1.4). Landforms caused by the melting of permafrost are also abundantly distributed over the landscape, especially where wave erosion along lake shores or at the coast has exposed ice-rich ground (Fig. 1.5).

Mackenzie Delta is a post-glacial feature, building out into the southeastern Beaufort Sea (Fig. 1.1). Most of the ground in the delta is underlain by permafrost, but there are patches, or taliks, of unfrozen ground due to the influence of shifting river channels on ground temperatures (Smith 1976). The Beaufort Delta region

P. Migoń (ed.), *Geomorphological Landscapes of the World*,
DOI 10.1007/978-90-481-3055-9_1, © Springer Science+Business Media B.V. 2010

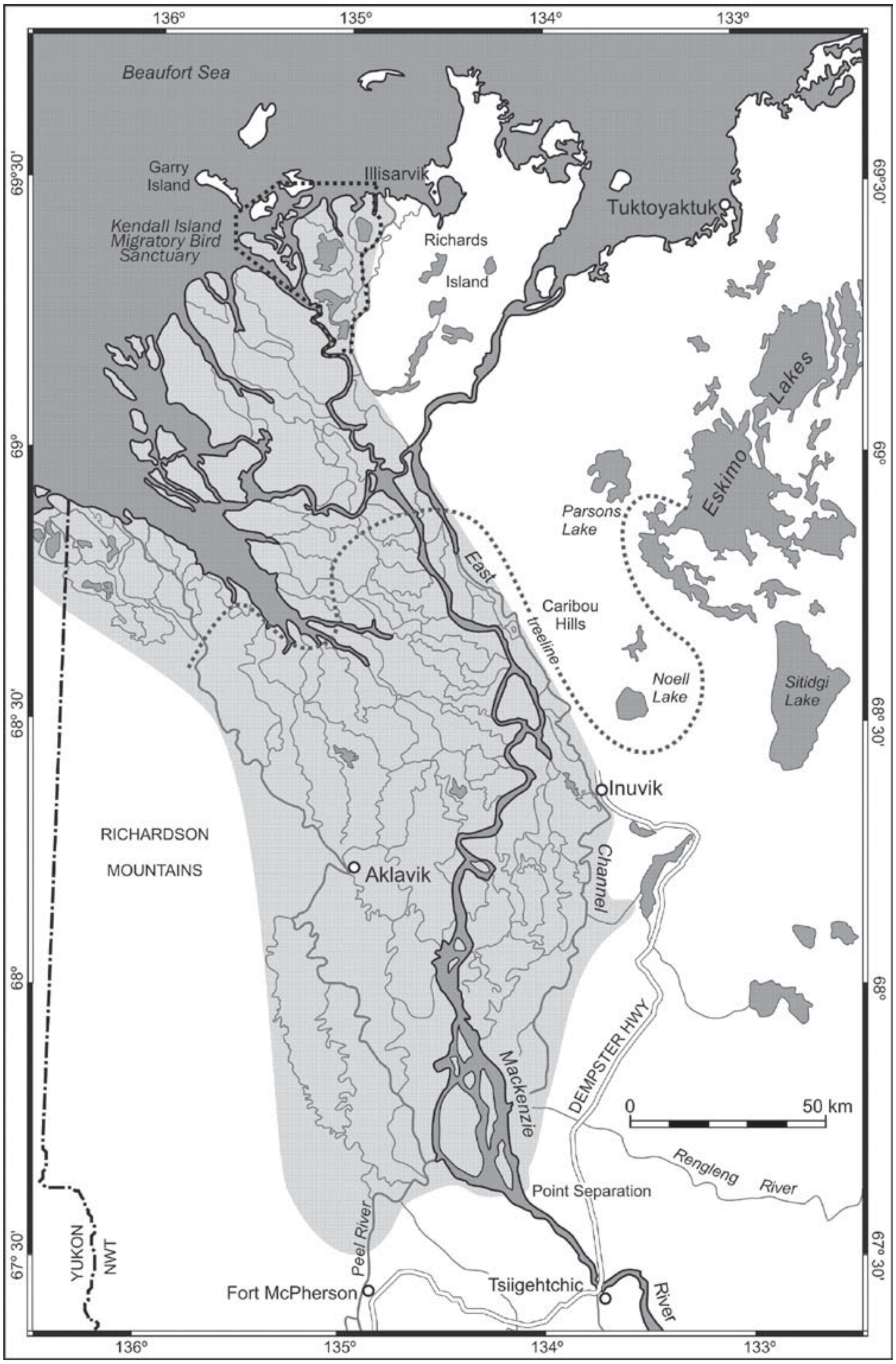

**Fig. 1.1** Location map of the Mackenzie Delta area. Treeline is from Mackay (1963; Fig. 70)

**Fig. 1.2** The Mackenzie Delta in winter, showing an ice road built on a river channel (Photo C.R. Burn)

is the northernmost extent of the Western Canada Sedimentary Basin, and contains considerable discovered and anticipated reserves of oil and gas (Dixon et al. 1994). The delta is an arctic wetland of international significance, providing critical habitat for numerous fish and mammals, and for thousands of migratory birds, as recognized through establishment of the Kendall Island Bird Sanctuary in 1960 (Fig. 1.1). Each summer, hundreds of beluga whales use the warm water in the near offshore for calving. Inuvik is the principal settlement in the region, established in 1958 as an alternative to Aklavik, which is flooded about once in every 10 years.

## 1.2 Geographical Setting

The Mackenzie Delta lies at the northern margin of North America. The land to the east and south of the Delta is the northwest corner of the Interior Plains of Canada, a sedimentary basin between the Western Cordillera and the Canadian Shield. The hilly uplands east of the delta are generally less than 60 m above sea level. The western side of the delta is bounded by Richardson Mountains, which rise to over 1,500 m and are part of the northernmost ranges in the Western Cordillera. At the foot of Richardson Mountains, the Delta fills part of Mackenzie Trough, which trends northwest into the Beaufort Sea (Rampton 1988). The most northern portion of the delta, around the Kendall Island Bird Sanctuary, lies north of Mackenzie Trough. In this area, the hilly uplands have been partially eroded by sea-level rise and degradation of the ice-rich permafrost that underlies the upland terrain. In the last 1,500 years the area between the remaining hills has become incorporated into the distributary system of the delta.

The climate of the region is bounded by conditions at Fort McPherson and Tuktoyaktuk, where the mean annual air temperatures and total precipitation are −7.3 and −9.8°C and 310 and 151 mm, respectively. The ecological gradient evident across the treeline is associated with the climatic gradient through the region,

**Fig. 1.3** Ibyuk Pingo near Tuktoyaktuk. Ibyuk at 50 m height is the tallest pingo in Canada, and is currently growing higher at about 2 cm/year. Ice-wedge polygons are visible in drained-lake basins in the lower right of the photograph (Photo C.R. Burn)

controlled by latitude and proximity to the Beaufort Sea (Burn 1997). A snow cover is established throughout the region by early October, but while it melts at Fort McPherson before the end of May, it remains into June at Tuktoyaktuk, where the presence of sea-ice offshore in early summer lowers coastal temperatures during on-shore winds. Mean annual air temperatures have increased recently throughout northwest Canada, and the rate of change is relatively high in the Delta area. The regional temperature was relatively stationary between 1926 and 1969, but subsequently the annual mean temperature at Inuvik has increased at a rate of 0.77°C per decade, with the warming primarily in winter. These observations are consistent with projections for climate warming in northern Canada being greatest in winter and least in summer.

## 1.3 Glaciation and Sedimentation

Most of the bedrock beneath the delta is sandstone and shale, and in the middle of the Delta lies approximately 80 m below the ground surface (Johnston and Brown 1965). The area was entirely covered by the northwest corner of the Laurentide ice sheet for several thousand years during the last glaciation, with the maximum extent perhaps reached about 30,000 years ago (Duk-Rodkin and Lemmen 2000). Portions of the outer delta area and Richards Island were ice-free for much of the glaciation, but the Inuvik area was not deglaciated until about 14,500 years ago (Ritchie 1985). The delta has been building seaward for about the last 14,000 years. It is a result of drainage diversion, for before glaciation, most of Mackenzie River basin

**Fig. 1.4** Ice-wedge polygons in the outer Mackenzie Delta. The growth of ice wedges deforms the adjacent ground, raising the soil on either side of the wedge. The vegetation on these ridges is modified from the plant community that grows in the saturated ground in the middle of the polygons (Photo C.R. Burn)

drained eastwards and emptied into the Atlantic Ocean (Duk-Rodkin and Lemmen 2000). At present, the Mackenzie Delta receives about 128 Mt of sediment each year, with 83% supplied by Mackenzie River and the remainder by Peel River (Carson et al. 1998). About two thirds of the sediment load are deposited in the ocean and the balance is added to the delta, mostly in the outer margins. The sediment is dominantly silt.

Sea level has risen since glaciation (Hill et al. 1985), and there has been considerable inundation of low-lying areas, erosion of ice-rich ground, and, in total, coastal retreat of about 100 km. As a result, there are four depositional histories for terrestrial sites in the area. First, there is upland terrain that has remained above water level since glaciation. In these areas the ground is characteristically covered by sand or glacial till. Several hills in the Kendall Island Bird Sanctuary represent such terrain. Second, parts of the outer delta have been submerged by sea-level rise, but have emerged as a result of sedimentation (Taylor et al. 1996). Third, in most of the delta the surface has built up over time, emerged from the ocean, and ground level has kept pace with sea level. Finally, in some parts of the hilly terrain, peat deposits have accumulated in low-lying ground.

## 1.4 Hydrology

The flooding hydrology of the Mackenzie Delta creates the stark contrast between the wetlands of the delta plain and the dry terrain of the surrounding uplands. Peak water levels occur in late May or early June, as snow melt from the Mackenzie basin, which extends southwards to Alberta and British Columbia, reaches the coast. There is relatively modest precipitation

**Fig. 1.5** Two retrogressive thaw slumps on the coast of Kendall Island. Ice wedges are exposed in the thaw slumps, and their polygons are visible in the adjacent ground (Photo C.R. Burn)

locally during summer, and discharge into the delta responds to frontal precipitation in Mackenzie River valley and the Peel River basin. Great Slave and Great Bear lakes are permanent reservoirs for Mackenzie River, so there is a constant discharge into the delta in winter, and the water level in the Delta rises as distal channels freeze through.

In late summer, when water levels in the delta are low, storm surges may advance upstream to Point Separation and beyond (Marsh and Schmidt 1993). These surges may inundate the outer delta, but they are rarely sufficient to flood areas south of treeline. Instead, the principal flood hazard occurs in late May and early June when ice jamming may raise water levels to flood much of the delta. The frequency and duration of flooding has systematic effects on vegetation development, so that specific forest communities in the delta are associated with flooding regimes, in addition to the vegetation succession that may be anticipated on aggrading point bars (Pearce et al. 1988). The hydrology of lakes in the delta is closely associated with the hydrograph, for the annual water balance of the area is negative, and over time water bodies will dry up, unless refilled by flooding (Marsh and Hey 1989).

## 1.5 Channel Migration

Mackenzie Delta is a maze of shifting channels and lakes (Fig. 1.2). Channel migration can be inferred from the vegetation succession on the edges of channels, especially at point bars, which are commonly opposite cut banks. The vegetation succession in the forested areas of the delta follows a path from horsetail (*Equisetum* spp.) in newly emerged river bars, through willow and alder associations (*Salix* spp., *Alnus crispa*), to white spruce forest (*Picea glauca*) (Pearce et al. 1988). Channel migration undercuts the surface vegetation, which then floats away. Flooding commonly leads to sediment deposition on the forest floor, and over time adventitious roots may extend out from tree trunks. However, the aggradation of the delta is primarily by infilling of channels, because forest vegetation, particularly logs, are rarely encountered while drilling.

## 1.6 Permafrost and Ground Ice

Perennially frozen ground is ubiquitous north of treeline and beneath forested surfaces in the middle and upper delta. Permafrost is absent beneath lakes and river channels that do not freeze to the bottom, where the water maintains a mean annual temperature above 0°C (Smith 1976). Along the edges of channels permafrost may not be formed where willows capture snow blown off river or lake ice in winter to create deep snow banks that keep summer heat in the ground. In forested terrain the mean annual ground temperature is about −2°C. This is considerably higher than the mean annual air temperature, due to the proximity of "warm" water bodies, and because snow in the forest does not drift, but accumulates steadily through the winter. In contrast, in the tundra of the outer delta, where the snow depth is reduced by wind scour, the mean annual ground temperature is about −6°C (Kokelj et al. 2007).

Permafrost thicknesses in the Delta may be divided into three categories. First, in places that were unglaciated for much of the last 100,000 years, the thickness is on the order of 500 m or more. These environments include parts of the outer delta that were submerged relatively recently, and have now emerged due to sedimentation (Taylor et al. 1996). Second, in much of the delta itself, the thickness is less than 100 m, as a result of relatively warm ground at depth, due to the abundance of water bodies (Smith 1976). Third, permafrost is thin in the emerging sedimentary environments of Mackenzie Trough, where it is beginning to develop.

Although the permafrost in the delta contains ice throughout its depth, most of the sediments, having been laid down in river channels, were not exposed at the ground surface. As a result, the majority of the permafrost contains ice in the sediment pore spaces only. However, high ice contents develop beneath exposed surfaces, as water is drawn into permafrost from thawed, saturated soil near the ground surface at the end of summer. Characteristically, the uppermost 2–3 m of permafrost are ice-rich and release water upon thawing, but below this the soil ice content is close to the pore volume only (Williams 1968).

In the glacial outwash sediments of the outer delta area and Tuktoyaktuk Coastlands, there are extensive bodies of massive ground ice (Fig. 1.6) that formed after glaciation as permafrost grew in the exposed ground. In some places glacier ice may lie buried under a veneer of till. Retrogressive thaw slumps, up to 200 m wide, commonly form where such ground ice is exposed by erosion (Fig. 1.5), and the warmth of summer conditions begins to thaw the permafrost.

Ice wedges develop under contemporary conditions in the outer delta, where the winter cold is sufficient to lead to ground contraction and cracking. These linear cracks are filled with snow melt water, leading to veins of ice in the ground. After many years of repeated cracking, the veins develop into wedge-shaped bodies of almost pure ice (Fig. 1.7). Characteristically, these wedges form polygonal networks, with a distance across each polygon of about 10 m. Ice-wedge polygons are visible in much of the outer delta, but there are also similar features in the forest. In tundra lowlands, these networks are readily visible (Fig. 1.4), but in uplands the appearance is less common, because slope movement obscures their surface expression on hillsides. Ice-wedge polygons are best developed in drained-lake basins, which may cover several square kilometers (Fig. 1.3). Ice wedges in the forests of the delta do not crack under the present ground climate, although they were active until early in the twentieth century (Kokelj et al. 2007).

## 1.7 Pingos

The landforms of the Mackenzie Delta area have stimulated a considerable amount of the geocryological research in the region, because they are natural indicators of the geotechnical behavior of permafrost. The most well known are the closed-system pingos of the Tuktoyaktuk Coastlands (Fig. 1.3), which demonstrate the efficacy of pore-water expulsion during ground freezing to deform permafrost (Mackay 1998).

Pingos – the name is derived from the Inuvialuktun word for a hill – are generally conical, ice-cored hills, which reach up to the heights of 50 m, and are up to >100 m in basal diameter. In the Mackenzie Delta area,

**Fig. 1.6** Massive ground ice exposed near Tuktoyaktuk. This ice was formed after melting of glacial ice from the landscape, as permafrost developed in the exposed sediments. The ice grew from water injected under pressure toward the growing permafrost. Sand below the ice was the conduit through which a water supply was maintained to feed the ice body as it grew (Photo C.R. Burn)

most of the pingos occur in drained lake basins (Fig. 1.3). There are about 1,350 pingos in the region, with the largest being Ibyuk Pingo, a few kilometers south of Tuktoyaktuk. These landforms grow because of the ubiquitous permafrost, the sandy sediments, and the presence of about 5,000 lakes in the Tuktoyaktuk Coastlands.

Each year one or two of the lakes drain as the permafrost retaining the water is eroded (Fig. 1.8a). Usually drainage occurs in a matter of hours, and commonly small ponds are left in depressions on the drained-lake bottom. Prior to drainage, permafrost is absent beneath the lake if the water depth is sufficient to prevent freezing of the lake-bottom sediments. But after drainage, permafrost invades the talik and the saturated lake-bottom sediments freeze. During freezing, water expands as it turns to ice, leading to a greater volume of pore contents than pore space in the unfrozen, saturated sediments. The excess volume is accommodated by expelling water from the location of freezing, and this builds up a pressure inside the talik, because the excess water is confined by the surrounding permafrost. In some cases, pore water has been ejected from the ground along fractures, but in others sufficient pressure develops to deform the aggrading permafrost, leading to heave of the ground surface (Fig. 1.8b). The ground is domed up by a lens of water, which freezes over time to form the pingo's core of ice (Fig. 1.9). Pingos may keep growing while the talik continues to freeze, and Ibyuk Pingo (Fig. 1.3), which is over 1,200 years old, is still growing. In some cases more than one pingo may form in a drained-lake basin (Fig. 1.9). The pressures involved in lifting a pingo the size of Ibyuk are remarkable, for the weight of this 50 m high hill is equivalent to that of a 50-story building, and demonstrates the forces generated by permafrost aggradation.

The first scientific reports on pingos were provided by Sir John Franklin and Sir John Richardson during their journeys to the Mackenzie Delta area in 1825–1826 and in 1848, but the vast majority of our knowledge of these features and of permafrost in the Mackenzie Delta area

**Fig. 1.7** An ice wedge exposed near Tuktoyaktuk. The wedge is about 3 m tall. A thermal contraction crack penetrates the wedge. The growth of the wedge, by repeated thermal contraction cracking and infilling with snow melt water, has deformed the sediments on each side of the wedge (Photo C.R. Burn)

comes from the pioneering field research of Professor J.R. Mackay, which began in 1951 and continues to this day (2009) (e.g., Mackay 1963, 1997; Mackay and Burn 2002).

## 1.8 Conclusion

The Mackenzie Delta is ecologically the most productive landscape in arctic Canada, fundamentally nourished by the annual flood of the Mackenzie River. For millennia it has provided nesting and staging grounds for thousands of migratory birds and calving grounds for beluga whales. It has sustained a population of indigenous people, hunting and trapping for food and clothing. Analysis of the development of landforms in the region has contributed a large portion of our knowledge concerning the behavior of freezing ground and permafrost. For the last 50 years, there has been considerable interest in the energy resources of the region, especially the significant reservoirs of natural gas, held both in conventional reservoirs and as hydrates. Exploitation of these resources poses substantial engineering challenges, principally due to the presence of permafrost and ground ice in a deltaic setting. These issues are perhaps matched in difficulty by the


a
b

**Fig. 1.9** A collapsing pingo on Richards Island in the outer Mackenzie Delta area, showing the interior core of ice in the pingo. A second pingo in the same drained-lake basin is to the right (Photo C.R. Burn)

challenges of managing industrial development in a remote but ecologically critical environment.

## The Author

**Chris Burn** is Professor of Geography and NSERC Northern Research Chair at Carleton University in Ottawa, Canada. His research concerns the permafrost environments of northwest Canada, especially central Yukon and the Mackenzie Delta area. He has published over 30 chapters in books and more than 50 peer-reviewed papers, all concerning northern Canada, and recently concentrating on the impact of climate change on permafrost conditions. He is Vice President of the Royal Canadian Geographical Society.

**Fig. 1.8** (**a**) The Illisarvik drained-lake experiment, Richards Island. Illisarvik – an Inuvialuktun word meaning "a place of learning" – is a full-scale field experiment initiated by Professor J. Ross Mackay of the University of British Columbia, when he drained this lake in 1978 by digging a small trench between the lake and the coast (Mackay 1997). The trench was eroded by the flowing water to form the ditch visible on the left foreground of the photograph, as the water flow accelerated from a trickle to a torrent. A residual pond remains in the center of the lake, and a small pingo has grown in the middle of the lake bed. This photograph was taken in July 2008, almost 30 years after drainage, and shows the considerable development of vegetation in the lake basin. Illisarvik is the location of continuing research into the geomorphological effects of permafrost aggradation. (**b**) A profile of the small pingo that has developed in the center of Illisarvik since winter 1994–1995. The people in the photograph are approximately of the same height. The pingo is about 1 m tall and 50 m in diameter (Photos C.R. Burn)

**Acknowledgments** Our research on permafrost in the Mackenzie Delta area is supported by the Natural Sciences and Engineering Research Council of Canada, Indian Affairs and Northern Development Canada, the Polar Continental Shelf Project, Natural Resources Canada, and the Aurora Research Institute.

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# Chapter 2
# The South Nahanni: High-Latitude Limestone Landscapes

Derek Ford

**Abstract** South Nahanni River drains a basin of ~34,000 km$^2$ at 61°N in the remote Mackenzie Mountains of the Northwest Territories, Canada. In its central sector it flows through a never-glaciated zone where resistant limestones, dolomites, and sandstones are folded into regular anticline and overthrust topography rising to 2,000 m a.s.l. Permafrost is widespread below 1,200 m, technically continuous above. The river has carved three magnificent antecedent meandering canyons through the anticlines. The Nahanni Formation (Devonian) is an ideal platformal karstic limestone 180 m thick, resting on 800 m of karstifiable dolomites in the First Canyon. Relict caves in the canyon contain ancient phases of speleothem growth that were investigated in some of the pioneer applications of U series dating to geomorphic questions, such as rates of canyon entrenchment. The most accentuated surface karst landforms known in any arctic or sub-arctic region extend as a belt for 40 km north of First Canyon. A natural labyrinth of solutional corridors, plus sinkholes and small poljes has developed in the limestone there, modified by scabland glacial outbursts when water was impounded by Laurentide Glacier ice from the east. Modern drainage is all underground, over distances up to 25 km and rates >3,500 m/day in both limestones and dolomites. Northwest of the main belt an ancient upland karst has been gutted by canyon recession and periglacial action. In contrast, most of a younger anticline to the northeast was not stripped of shale cover strata until the regional permafrost was well established: there are deeply entrenched canyons but little karst in either limestone or dolomite as a consequence.

**Keywords** Antecedent river canyons • aquifers • caves • karst • neotectonics • permafrost • periglacial processes

## 2.1 Introduction

The Mackenzie Mountains are a chain of ranges extending between latitudes 60° and 67°N, dividing Pacific drainage (Yukon Territory) from that to the Mackenzie River and Arctic Ocean (Northwest Territories; Fig. 2.1). They are scarcely peopled. Along the spine, batholithic rocks of Cretaceous age are carved into typical alpine topography – the "Ragged Ranges." They supported extensive Cordilleran valley glaciers during the ice ages and preserve a few extant glaciers and ice caps today. To the east, thick sequences of Paleozoic sedimentary rocks were deformed by the plutonic injections into fold and overthrust topographies, with rivers flowing eastwards across them – the "Canyon Ranges." Their western parts were invaded by the Cordilleran valley glaciers, while the Laurentide Continental Ice Sheet was able to override the most easterly sectors: in between there is a never-glaciated corridor in which magnificent river canyon landscapes are preserved. Limestone, dolomite, and gypsum are prominent amongst the sedimentary rocks and there is salt at depth. As a result, karst landforms are frequent, exhibiting many different morphologic styles as consequences of their differing composition, lithology, geologic structure, and glacial or periglacial history. This account focuses on the most spectacular of the limestone landscapes, which are found in the eastern sector of the South Nahanni River basin and the smaller Ram River basin to the north of it, as shown in Fig. 2.1.

P. Migoń (ed.), *Geomorphological Landscapes of the World*,
DOI 10.1007/978-90-481-3055-9_2,

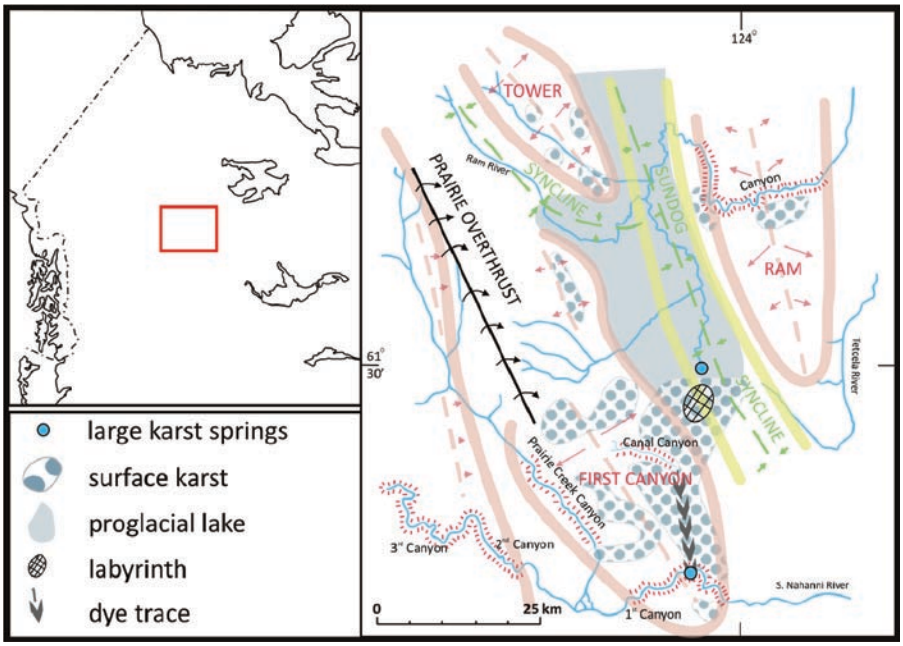

**Fig. 2.1** The location and principal topographic and geologic structural features of the South Nahanni karst lands, Northwest Territories, Canada; see the text for details

## 2.2 The Geologic and Physiographic Settings

The principal karst stratum is the Nahanni Formation of Devonian age, 180–220 m of thick to massive, regularly bedded, platformal limestones. They are chemically pure and mechanically resistant, very like such well-known karstic limestones as those of the Yorkshire Dales in England or the Burren in Ireland. They are overlain by mechanically weak shales that are readily stripped off. The underlying facies are more complex. Broadly, underneath the First Canyon and Ram Plateau anticlines (Fig. 2.1) there are medium-to-thick bedded, mechanically strong, dolomites >800 m in total thickness. They display a few scattered dolines and other karst forms at the surface and may channel groundwater flow in solution conduits. Underneath the Tower anticline, the dolomites are replaced by much weaker shales, calcareous shales and thin dolomites that together function as an aquitard in which groundwater flow is greatly inhibited.

The structural features (Fig. 2.1) are bold and simple. The three anticlines are each broad, symmetrical domal forms with gentle stratal dips. Ram Plateau (the Ram anticline) retains a nearly complete cover of Nahanni Limestone, and even of the overlying shales around its southern margins and north of the river canyon. The limestone is removed from the crest of the First Canyon anticline, exposing the dolomites there. The Tower anticline has been gutted by dozens of canyons entrenched in the underlying shales; the limestone is preserved only on its eastern flank and at scattered localities along ridge crests.

It is most important to appreciate that these structures have been active during neotectonic times. The epicenter of the strongest earthquake experienced anywhere in continental Canada during the past 50 years (Richter 6.9) was at shallow depth on the Ram anticlinal trend 40 km further north; it triggered a major landslide in the limestone there. As consequences of this continuing activity, the trunk rivers have carved antecedent, meandering canyons 300–1,000 m in depth across the up-domings in their paths, and tributary Prairie Creek cut a comparably deep canyon along the strike in the flank of the First Canyon anticline (Fig. 2.1; Ford 1991).

At its greatest extent the Laurentide Ice Sheet buried Ram Plateau and the Sundog Syncline and extended up to elevations of ~1,400 m above sea level on the eastern flanks of the First Canyon and Tower anticlines (Ford 1974; Brook 1976). Land to the west was not glaciated. In the last glaciation, ice advanced up the Syncline to a terminus just south of the northern springs marked on Fig. 2.1, impounding proglacial "Lake Sundog" at ~900 m a.s.l. to the north. Deposition of ~100 m of lacustrine silts buried much preexisting karst there. The Lake drained abruptly at some time after 40,000 years ago (based on a $^{14}$C date of tree wood in the silts – A. Duk-Rodkin, personal communication, 2006): it cut a broad spillway through the silts and into the top of the karst beneath it.

Today, karst features extend from 240 m a.s.l. (the springs in First Canyon, Fig. 2.1) to ~1,900 m a.s.l. on the crest of the First Canyon dome. The climate is sub-arctic to arctic. Mean annual temperatures range from −3°C on the low ground to −10°C or below on the crests. Treeline marking the limit of the Northern Boreal Forest is at ~1,200 m a.s.l. Permafrost is widespread but discontinuous below that elevation, technically continuous above it. Annual precipitation ranges 400–800 mm or more across the elevations, about half of it falling as snow. Summer rains can be intensive when systems from the northeast Pacific and the Beaufort Sea (Arctic Ocean) clash (Brook and Ford 1980). There is some evidence to suggest that the frequency and intensity of these storms is increasing as a consequence of the general summer melt of sea ice over the Beaufort Sea; this is suggested by a great increase in the number of landslides over permafrost on steep shale slopes in the region.

## 2.3 The Relict Caves of First Canyon

More than 200 relict karst solution caves (i.e., caves drained of their formative waters) have been found in the region but most are sealed off by ground ice or frozen lacustrine silts within a few meters of their entrances. The lengthiest open systems are preserved along the North (updip) wall of First Canyon, near its mouth. Their form is of dendritic drainage, from the sinkpoints of allogenic streams flowing from a shale cover that is now largely or entirely removed. Flow was downdip into the river at and just below the contemporary water tables. A first example, Grotte Valerie, has 2 km of passages now stranded in cliffs 450 m above the river. It has partial fillings of lacustrine silts, and winnowings of an older till cemented by calcite (Fig. 2.2). Its modern entrances (former downstream galleries now truncated by cliff recession) are south-facing. In the summer cold air drains from a low exit, drawing warm air to replace it through an entry that is 40 m higher. This creates (1) a "warm entrance cave" (+6 to +1°C) where there is active deposition of small speleothems today, supplying moist air to (2) a "cool exit cave" (0 to −1.5°C) that is covered with ice and hoar frost: behind and below both is (3) a "permafrost cave" receiving only the cold air of winter, dry and dusty, without speleothems or ice and preserving the remains of 80 or more wild sheep. It is a spectacular example of cave climate zonation (see Ford and Williams 2007: 294–298 for details).

Nearby, Grotte Mickey has more than 3 km of galleries at several different levels between 250 m and 400 m above the river. This multilevel, multiphase pattern points to extended development that kept pace with the entrenchment of First Canyon for a while (Schroeder 1977, 1979).

An important feature of these caves and some in the Labyrinth (discussed below) is the occurrence of large, highly ornamented, stalagmites, columns, and flowstones of calcite. They are no longer growing (modern growth is limited to very small deposits) and most are weathered, partly eroded by invading streams or shattered by freezing (Fig. 2.2). They are indicative of much warmer conditions in the past which (allowing for truncation of the caves by cliff recession since) extended much further into cave interiors than today. There is an abundance of uranium in the cover shales which, re-precipitated in the calcite, has made the speleothems particularly suitable for U series dating. This region saw much of the pioneer speleothem dating work as a consequence (e.g., Harmon et al. 1977). The large majority of samples proved to be >350,000 years in age (the limit of the dating method using 1970s α spectrometric technology), although they were younger than 1.25 million years. The first application of U series speleothem dating to a geomorphic problem was by the author, who showed that the mean rate of South Nahanni River entrenchment below Grotte Valerie could not be more than 0.8 m/ka and that there had been possibly as much as 350 m of uplift on the First Canyon anticlinal axis since 1.5 million years ago (Ford 1973).

**Fig. 2.2** Scenes from Grotte Mickey and Grotte Valerie in the First Canyon, South Nahanni River, Northwest Territories. These are relict stream caves now raised high above the River in the canyon walls. *Upper center*: glaciolacustrine silts on the floor of a large stream cave passage. *Upper right*: modern speleothem deposition in the warm sector of Grotte Valerie. The stalactites and stalagmites are typically small. Their bright red coloration is due to contained organics. *Lower left*: above the figure is a typical relict stalagmite and flowstone of the warm period >400 ka BP; only stalagmites of ice grow in this gallery today. *Lower center and right*: ice stalagmites and hoarfrost in the cool sector, Grotte Valerie. The base of the hoarfrost in the center frame marks the surface of a lake of very cold air that is trapped behind the ice dam; it is renewed only by winter inflow (Photos D.C. Ford and J. Schroeder)

## 2.4 Springs

The main belt of karst terrain between First Canyon and the Sundog Syncline (Fig. 2.1) drains to just two sets of springs. At the north end, "Bubbling Springs" (700 m a.s.l.) rise where the stratigraphic top of the limestone dips under impermeable cover shales in the Syncline. They drain perhaps the northern one-third of the belt, with discharges >10 $m^3/s$ during wet summer spells. In contrast, "White Spray," the southern spring, discharges at 240 m a.s.l. in First Canyon from dolomites that are stratigraphically ~580 m below the base of the Nahanni Limestone. Most of their discharge is into the river bed and is strong enough to keep this stretch of the river free of ice throughout the winter, a unique feature; "White Spray" itself is the summer overflow spring. These springs must drain much of the First Canyon dome, including Canal Canyon (30 km in length, up to 1,000 m in depth) which drains underground where it is blocked by a Last Glacial terminal moraine at its mouth. Dye traces from there (Fig. 2.1) and a lake further north proved the existence of underground flow of 21+ km at mean rates >3,500 m/day on hydraulic gradients of 0.03 or lower. Although no enterable caves have been found in them yet, the dolomites thus can rapidly develop efficient, well-integrated systems of underground solutional conduits.

## 2.5 The Nahanni Labyrinth

Between Canal Canyon and Bubbling Springs the Nahanni Labyrinth is developed in the limestone. It is the largest example of karstic labyrinth morphology reported in the Northern Hemisphere. The outstanding landforms are dissolutional corridors ("streets") that follow major vertical fractures created by the doming (Brook 1976; Brook and Ford 1978). Individual corridors are 10–100 m wide and deep, and up to 6 km in length. For a distance of 13 km they intersect one another to form a natural labyrinth. The walls recede from frost shattering, causing some parallel corridors to amalgamate into broader closed depressions, like squares in a pattern of city streets; the greatest of these measures 800 × 400 m. Towers isolated by cliff recession are preserved within them. The floor profiles of the corridors and squares are highly irregular, with local streams sinking into depressions between talus accumulations or into bedrock shafts. In the labyrinth and elsewhere on the limestone are large, vertical-walled sinkholes and smaller, elliptical solutional shafts (Fig. 2.3). Many can trap water for a succession of melt seasons: its depth increases slowly until pressure bursts an ice plug below and the feature drains with catastrophic rapidity. Raven Lake, an unusually large doline within a corridor, is 300 m in length and 180 m deep; under flood conditions waters rise >75 m in it, at rates up to 3 m/day.

At the north end of the labyrinth the shale cover and glaciolacustrine silts encroach to reduce the limestone outcrop to a narrow spillway with three small (<2.5 km$^2$) but elegant poljes developed in it. There are many collapse and suffosion dolines in the flanking shale and silt terraces, pointing to the existence of mature karst drainage in the past that is now largely clogged by the proglacial injecta.

Although all of the labyrinth is drained by mature karst groundwater systems that existed before the last glacial invasion and formation of glacial Lake Sundog,

**Fig. 2.3** In the heart of the Nahanni Labyrinth. Helicopter view of large solutional corridors to left, right, and in rear. In center, "Cenote Col" is a cluster of cenote-form shafts 40 m or more in depth; some are filled with water ponded above ground ice plugs, others are dry (Photo P. Sanborn)

**Fig. 2.4** Three scenes on the Tower Anticline. *Upper*: looking down into the Sundog Syncline across glaciated pavement with dolines on the well-preserved southeast end of the structure. *Lower left*: relict limestone pavement at the gutted center of the anticline; *lower right*: final remnants at the western end (Photos D.C. Ford)

the extent to which the surface karst landforms were modified by scablands melt flood processes during their reexcavation remains undetermined.

## 2.6 Tower Anticline Contrasted with Tower Syncline and Ram Plateau

To conclude this review of a great limestone karst that has experienced vigorous neotectonism, Quaternary cold with the ingrowth of permafrost, and partial, sporadic glacial invasions, it is interesting to compare the limestone morphology on the northern structures shown in Fig. 2.1. Tower Anticline was upraised and stripped of its shale cover at broadly the same time as the First Canyon anticline, probably late Miocene-Pliocene. But it did not have the strong, karstifiable dolomites of First Canyon beneath the limestone. Instead there were weak, shaley strata. In both the sector that was glaciated and further west in the never-glaciated zone, Tower Anticline first developed an extensive plateau epikarst with limestone pavement and dolines (Fig. 2.4) but this has since been almost entirely destroyed by

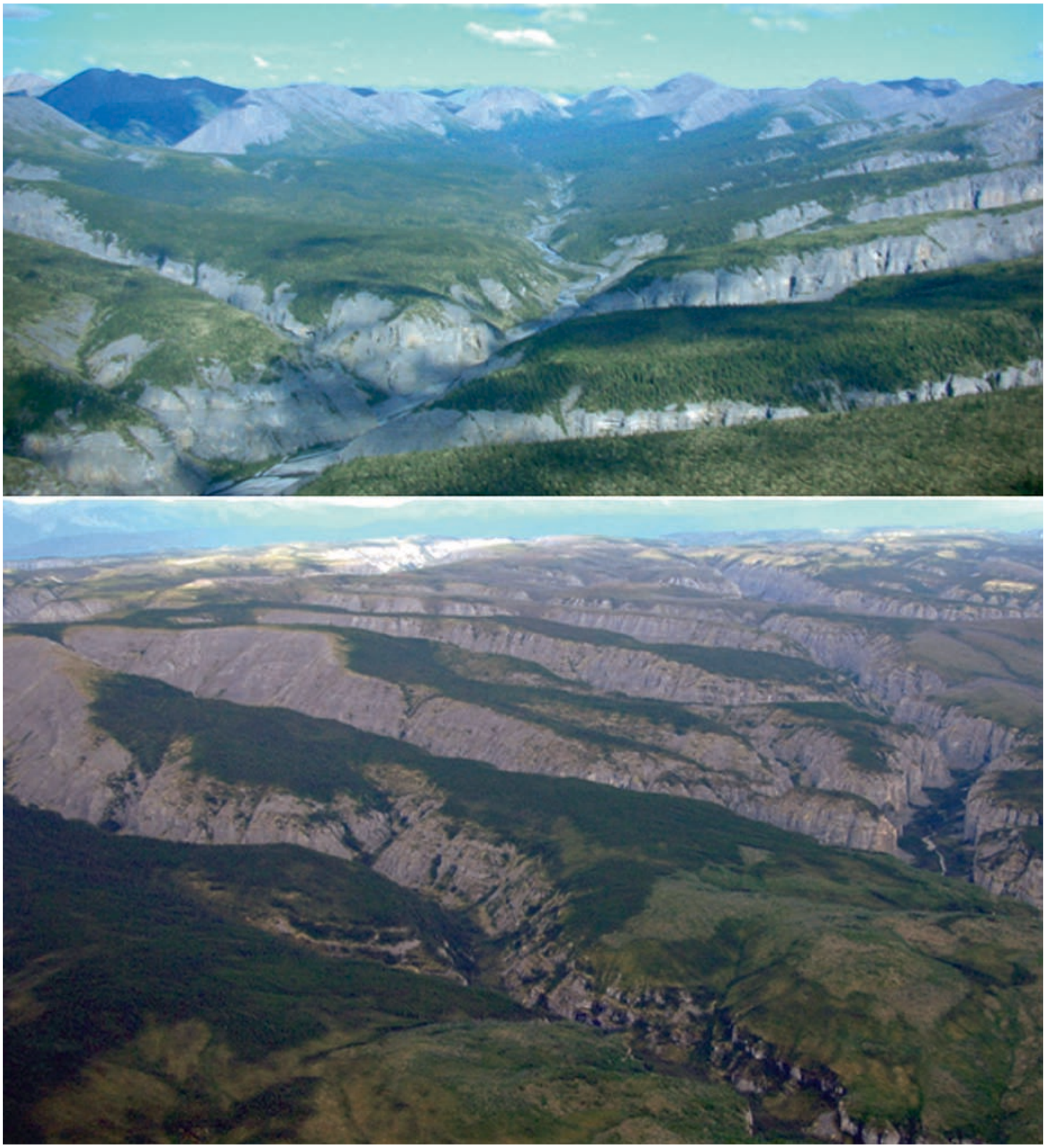

**Fig. 2.5** *Upper*: the Nahanni Limestone formation, stripped of its shale cover and dissected by consequent canyons at the head of the Tower syncline. *Lower*: the same situation is seen in the southern half of the Ram Plateau anticline; some last vestiges of the shale cover are seen in the foreground (Photos S. Worthington and P. Sanborn)

growth of permafrost that impeded the groundwater circulation which, as a consequence, has been replaced by the headward and lateral enlargement of flashflood canyons in the shales.

In contrast, stripping of the shales overlying the limestone was later in the adjoining Tower Syncline because of its lower elevation, and on Ram Plateau because (renewed?) tectonic uplift there came later due to its more easterly location. The consequences were that exposure of the limestone largely occurred after the permafrost had arrived. Except in few places of early stripping, karst groundwater circulation systems could not be established before the rock froze. Instead of karst, classical consequent river drainage patterns with canyons were carved into the limestone, as shown in Fig. 2.5.

### The Author

**Derek Ford** is Professor Emeritus of Geography and Earth Sciences, McMaster University, Canada. His main interests are in karst processes and landforms, cave genesis and karst aquifers, and paleoclimate studies of speloethems. These days he is most interested in applied consulting, and advising on UNESCO World Heritage site applications. He is author/co-author of ~200 journal papers, many reports, co-author or -editor of ten scientific books, one coffee table book, and the producer of one 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, a Fellow of the Royal Society of Canada, and Gold Medalist of the Royal Canadian Geographical Society.

**Acknowledgments** Field research in the magnificent but remote Nahanni country has relied upon the vigorous support of geomorphology students and cave enthusiasts for many years. Particular thanks to Steve Catto, Marcel Cholo, and Dana Haggarty of Parks Canada for their company and logistic support in 2006 and 2007. Paul Sanborn, Jacques Schroeder, and Steve Worthington have freely made their photographs available. The Natural Sciences and Engineering Research Council of Canada and Parks Canada are thanked for financial aid.

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