Periglacial Geomorphology
Periglacial Geomorphology

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For Rebecca

Till a' the seas gang dry, my dear,
And the rocks melt wi' the sun:
And I will love thee still, my dear,
While the sands o' life shall run.

Robert Burns (1759–1796)
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Periglacial geomorphology is the study of the landscapes, landforms, sediments and soil structures that have developed in cold nonglacial environments. It differs from other branches of geomorphology in that landscape development in periglacial environments is dominated or significantly influenced by the presence of perennially frozen ground (permafrost) and/or cyclic ground freezing and thawing over timescales ranging from diurnal to millennial. The periglacial realm encompasses at least 25% of the present surface area of the Earth, including 13–18% presently underlain by permafrost, and during the cold stages of the past 2.6 million years it extended over an additional 20%, encompassing vast swaths of mid-latitude regions that lay outside the maximum reach of successive Pleistocene ice sheets. The present periglacial domain includes high-latitude regions in both hemispheres, together with the higher parts of mountains and plateaus in middle and low latitudes.

Appreciation of the nature of periglacial processes and their geomorphological consequences underpins our understanding of the evolution not only of landscapes in present-day cold environments, but also of temperate mid-latitudes affected by periglacial activity in the recent geological past. Recognition of periglacial landforms and structures in former periglacial environments can also inform reconstruction of the nature and severity of past climate through comparison with the climatic controls on their present-day counterparts. Conversely, appreciation of the way in which mid-latitude periglacial environments adapted to rapid warming at the termination of the last glacial stage provides insights into the possible evolution of periglacial environments in response to future climate change. Predictions of future atmospheric warming in high latitudes and high mountain areas imply that the next few decades will witness radical changes in ground thermal regime, potentially leading to widespread degradation of permafrost and a cascade of landscape changes that have both local and global consequences. The study of periglacial processes and landforms is therefore not simply a component of our understanding of the landscapes of the Earth; we now understand the fragility of these vast silent areas of tundra, polar desert, mountains and boreal forest, and how climatic perturbation of periglacial landscapes may have consequences that affect the entire planet.

This book presents a comprehensive introduction to the processes that operate in present periglacial environments and how they contribute to our understanding of former periglacial environments. It includes accounts not only of the nature of frozen ground and frost-action processes, but also of the operation of slope, fluvial, aeolian and coastal processes in cold environments. It is organized in six parts. Part I (Chapters 1–2) introduces the historical and scientific context of periglacial geomorphology and the nature of periglacial environments. Part II (Chapters 3–5) addresses the physics of ground freezing and thawing, the characteristics of permafrost and the nature and origin of underground ice. Part III (Chapters 6–9) considers the characteristics, formation and significance of landforms, sediments and structures associated with permafrost, permafrost degradation and seasonal freezing and thawing of the ground. Part IV (Chapters 10–12) discusses rock weathering in periglacial environments, the periglacial processes operating on hillslopes and the distinctive landforms produced by rock breakdown and slope processes in cold environments. Part V (Chapters 13–15) is devoted to the operation of fluvial, aeolian and coastal processes in present and past periglacial environments. Finally, Part VI considers the employment of relict periglacial features to reconstruct past cold environments in mid-latitude regions (Chapter 16) and evaluates the response of periglacial environments to recent and predicted climate change (Chapter 17).

Most of the central chapters (6–15) follow a common format: a brief introduction defining terminology is followed by an account of relevant processes, a description of resulting landforms, deposits and/or sediment structures, and finally an outline of equivalent relict (Pleistocene) phenomena and their significance. This format allows consideration of relict periglacial features in association with their active counterparts.

The book is designed to be used by both undergraduate and graduate students studying geomorphology or
Quaternary science in the context of geography and geology degree programmes. It will be of use to all scientists whose research involves understanding of cold environments, whether from a geographical, geological, ecological, climatological, pedological, hydrological or engineering perspective. Its aim is to stimulate interest in and understanding of some of the most fascinating landforms and landscapes on Earth, the processes responsible for their formation, the part these processes played in mid-latitudes in the recent geological past and how these processes might be affected on a future warmer planet.

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As the book grew, so did my children, Hamish and Kate, who have become accustomed to having a father who spends many hours working in a cabin at the bottom of the garden. I am deeply grateful to both for tolerating this eccentric behaviour and reminding me daily that the important things in life lie outside the cabin walls. My wife Rebecca has been a constant source of support in every possible way; without her love, encouragement, patience and sacrifice, this book would never have reached completion.

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1.1 The Periglacial Concept: Definitions and Scope

The term *periglacial* is used to describe the climatic conditions, processes, landforms, landscapes, sediments and soil structures associated with cold, nonglacial environments. *Periglacial geomorphology* is the study of the landforms developed under periglacial conditions, the processes responsible for their formation, modification and decay, and associated sediments and sedimentary structures. *Periglacial environments* are those in which cold-climate nonglacial processes have resulted in the development of distinctive landforms and deposits, usually related in some way to freezing of the ground. The term *periglaciation* describes the collective effects of periglacial processes in modifying the landscape, much as ‘glaciation’ describes the geomorphological effects of glacier ice.

The term ‘periglacial’ (literally ‘bordering glaciers’) is an etymological oddity. It was coined by Łozinski (1909, 1912) to designate a climatic zone of rock weathering by frost that occurs immediately outside the limits of present and former ice sheets, and to describe frost-weathered rubble (‘periglacial facies’) characteristic of this zone (French, 2000). Present usage of the term, however, contains no implication of present or former proximity to glacier ice, and some of the most extensive periglacial environments on Earth – in Canada, Alaska and northern Eurasia – are hundreds of kilometres distant from the nearest glacier. It has become, effectively, an elegant synonym for ‘cold, nonglacial,’ whether applied geographically, climatically or geomorphologically.

Periglacial geomorphology is concerned primarily with developing our understanding of the physical and chemical processes that operate at the surface and near-surface of the Earth, and the nature, composition, evolution and distribution of landforms, sediments and sedimentary structures produced by such processes. It differs from other branches of geomorphology not only in that it focuses on cold, unglaciated environments, but also because landform development in such areas is dominated by freezing of the ground. This is manifest over wide areas in the presence of *permafrost* (ground in which the temperature remains below 0°C for two years or more) and the associated existence of subsurface *ground ice*, together with a wide range of landforms and soil structures that reflect cyclic freezing and thawing of the uppermost layers of the ground over timescales ranging from diurnal to annual. However, a wide range of *azonal processes* that are common to most or all climates also affect periglacial environments: erosion and deposition by rivers, wind action, coastal processes and slope failure also shape the periglacial landscape, though often in particular ways that are conditioned by frozen ground, prolonged subzero winter temperatures or snow cover (Berthling and Etzelmüller, 2011; Vandenberghe, 2011; Figure 1.1). The mechanisms by which these azonal processes occur are common to all environments, but the conditions under which they operate and their geomorphological effects are subtly to substantially different in cold climates.

In addition to its central focus on present-day processes and landforms, periglacial geomorphology is an integral component of *Quaternary science*, the study of how the environments and landscapes of the Earth have changed during the *Quaternary period*, an era of radical climatic shifts that encompasses the past 2.58 million years. Within the past million years, periods of pronounced global cooling triggered the growth of ice sheets that covered up to a third of the present land surface. During these *glacial stages*, periglacial conditions affected extensive tracts of mid-latitude landscapes ahead of the advancing ice, beyond the limits of ice-sheet advance, and during periods of ice-sheet retreat. As a result, periglacial landforms, sediment accumulations and soil structures developed in mid-latitude areas that now experience a temperate climate, and in favourable circumstances these are preserved as *relict periglacial features* (Figure 1.2). The distribution of relict periglacial landforms, deposits and sediment structures therefore provides evidence of former cold climatic conditions, often in the form of features indicative of former permafrost. Moreover, as some present-day periglacial landforms and soil structures presently occupy a fairly
well-defined climatic niche, identification of their relict counterparts can provide information on the nature of the climate at the time they were formed.

A further tenet of periglacial geomorphology is a concern for reconstructing long-term landscape evolution. This is a challenging area of research, particularly as many periglacial landscapes have been covered (and sometimes radically altered) by glacier ice for much of the past million years. However, periglacial landscapes that remained unglacierized throughout the Quaternary exist in a few locations, such as northern Yukon Territory in Canada (Figure 1.3) and the Dry Valleys of Victoria Land in Antarctica, and these provide tantalizing glimpses of how landscapes have evolved under prolonged periglacial conditions (e.g. French and Harry, 1992). The introduction of new techniques for establishing long-term rates of rock breakdown (e.g. Small et al., 1999), coupled with numerical modelling of slope evolution (e.g. Anderson, 2002; Anderson et al., 2013), promises to revolutionize our understanding of the rates at which periglacial landscapes evolve, and the forms they adopt as they do so.

Many periglacial landscapes, moreover, are highly sensitive to disturbance. This is particularly true of terrain underlain by ice-rich permafrost, which is prone to subsidence or slope failure if the ground temperature regime is altered (Figure 1.4). Applied periglacial geomorphology is that branch of the subject devoted to identification of sensitive terrain, the effects of human activity on such terrain and the geotechnical approaches to minimizing terrain disturbance. A major area of current concern is the effects of projected climate warming on permafrost environments, which has led to urgent research devoted to monitoring and modelling the thermal, geomorphological and geotechnical response of permafrost to recent and projected climate change (e.g. Nelson et al., 2008; Harris et al., 2009; Romanovsky et al., 2010a; Callaghan et al., 2011; Slater and Lawrence, 2013). A particular area of concern is that thaw of permafrost underlying arctic tundra environments and subarctic boreal forests will release greenhouse gases (carbon dioxide and methane) into the atmosphere, thus potentially accelerating global warming (Schuur et al., 2015).

Finally, it is notable that periglacial phenomena are not confined to planet Earth. High-resolution imaging data obtained for Mars show landforms strikingly similar to some in terrestrial permafrost environments, suggesting that in the relatively recent geological past the Martian
Figure 1.2 Wedge-shaped structure in sand and gravel deposits near Lincoln, eastern England. This structure represents infill of the void left by thaw of an ice wedge that formed in permafrost during the last glacial period. Source: Courtesy of Julian Murton.

Figure 1.3 Landscape of northern Yukon, Canada, an area that escaped glaciation during the Pleistocene epoch and has evolved under periglacial conditions since the beginning of the Quaternary period. Source: Courtesy of Matthias Siewert.
surface was not only underlain by ice-rich permafrost, but may also have experienced surface or nearsurface freeze–thaw cycles that imply the existence, albeit transient, of liquid water (Balme et al., 2013).

As this brief survey indicates, periglacial geomorphology is strongly integrated with several scientific disciplines. At the process-landform core of the subject lies the interaction of geomorphology and geocryology, the science of frozen ground, but there are also strong interactions with Quaternary science, climatology, hydrology and engineering geology, and weaker but important links with a range of other disciplines (Figure 1.5).
1.2 The Periglacial Realm

There are many different views regarding the geographical dimensions of what climatic geomorphologists have termed ‘the periglacial zone’ (Thorn, 1992; Berthling and Etzelmüller, 2011). This has variously been interpreted as constrained by the distribution of permafrost and/or deep seasonal ground freezing, or by climatic parameters such as the 0 °C mean annual air temperature isotherm. Such criteria are unrealistically restrictive from a geomorphological perspective. In this book, the present periglacial realm is considered to encompass all unglacierized parts of the Earth’s land surface where frozen ground or freezing and thawing of the ground significantly influences landform development, so that the present operation of periglacial processes and the distribution of resultant landforms effectively defines the extent of the periglacial domain. Similarly, the extent of former periglacial environments that existed in temperate mid-latitudes during Quaternary cold stages can be defined by the distribution of relict periglacial landforms, deposits and soil structures.

Using similar criteria, French (2007) estimated that the present periglacial realm occupies at least 25% of the Earth’s land surface, and that an additional 20–25% experienced periglacial conditions during Quaternary cold periods. Moreover, because air temperatures decline with increasing altitude as well as increasing latitude, active periglacial processes and the extent of the periglacial domain. Similarly, the extent of former periglacial environments that existed in temperate mid-latitudes during Quaternary cold stages can be defined by the distribution of relict periglacial landforms, deposits and soil structures.

Several broad zones can nevertheless be distinguished on the basis of characteristic terrain types and landform assemblages. Polar deserts are areas of extreme cold and aridity, very limited vegetation cover and continuous permafrost at shallow depth, conditions typical of the northernmost circumpolar lands and some unglacierized parts of Antarctica. Arctic tundra landscapes are characterized by partial or complete tundra vegetation cover, and are usually underlain by continuous permafrost at shallow to moderate depths, typified by the landscapes of northern Alaska, northern Siberia, northernmost mainland Canada and much of the Canadian Arctic Archipelago. Arctic and subarctic boreal forest landscapes, often interrupted by wetlands, are underlain by continuous or discontinuous permafrost and extend in a huge belt across Eurasia and North America south of the tundra zone. Maritime periglacial landscapes, exemplified by Iceland, high plateaus in Scotland and subantarctic islands, are characterized by high winds, high precipitation, variable vegetation cover and patchy (or no) permafrost. Distinctive alpine periglacial environments occur on mid-latitude mountains above the treeline, where permafrost-free ground merges upwards into areas underlain by permafrost; they are typified by the European Alps, the Carpathians, the Canadian Rocky Mountains and the Southern Alps of New Zealand. A mid-latitude high-altitude periglacial landscape is represented by the Tibetan (Qinghai-Tibet) Plateau (28–40 °N), much of which lies over 4000 m above sea level, incorporates several major mountain ranges and is extensively underlain by permafrost. Additional periglacial environments are represented by the Canadian Arctic, but as a result of its maritime location experiences much less severe winters. Equally, the Jotunheimen Massif in Norway is difficult to classify: an area of alpine relief at subarctic latitude, but facing relatively mild, moist westerly airstreams from the North Atlantic. The climatic and terrain characteristics of the periglacial realm are considered further in Chapter 2.

1.3 The Development of Periglacial Geomorphology

Though the roots of periglacial geomorphology lie in the nineteenth century, the subject did not flourish as an independent discipline until midway through the twentieth. The development of periglacial research up to 1965 has been charted by French (2003), who described the various early accounts of permafrost and ground ice recorded by arctic explorers, gold miners and mining engineers, and Shiklomanov (2005), who summarized the early development of periglacial geomorphology as a scientific subdiscipline in the work of late 19th century geologists seeking to explain the origin of Pleistocene deposits and landforms in areas outside the limits of the Quaternary ice sheets (Ballantyne and Harris, 1994). Interest in frost action as a geomorphological agent appears to have been ignited at the beginning of the 20th century by several developments. One was the appearance of an influential account by Andersson (1906) of the rubble deposits of the Falkland Islands and of Łozinski’s (1909, 1912) papers on...
the periglacial zone and ‘periglacial facies’. Another was a scientific expedition to Svalbard following the International Geological Congress of 1910, which produced remarkably prescient work on various aspects of frost action (Meinardus, 1912; Högbom, 1914). A third was the appearance of reports by geologists working in Alaska and Yukon of a wide range of hitherto undocumented periglacial phenomena, such as frost polygons, ice wedges, rock glaciers and cryoplanation terraces (e.g. Capps, 1910; Cairns, 1912; Leffingwell, 1915; Eakin, 1916). Russian research of the era tended to focus on permafrost and ground ice phenomena (Shiklomanov, 2005).

Between 1920 and 1950, research in arctic and alpine environments produced several further seminal accounts of permafrost and periglacial processes and landforms (e.g. Shostakovitch, 1927; Elton, 1928; Poser, 1933; Sørensen, 1935; Paterson, 1940), and in both Europe and North America there was widening recognition of the importance of Pleistocene periglacial conditions in the development of mid-latitude landscapes, landforms and deposits. Particularly important developments during this era were the introduction of laboratory experimentation as a means of understanding freezing effects in soils (Taber, 1929, 1930; Beskow, 1935), the appearance of a monograph by Troll (1944) on alpine periglacial landscapes, and the publication of the first English-language treatise on permafrost (Muller, 1947), which drew substantially on earlier Russian research.

French (2003) identified three strands in the rapid evolution of periglacial geomorphology in the years after the Second World War. In Europe, energetic leadership was provided in France by André Cailleux and Jean Tricart, in Germany by Han Poser and Julius Büdel, and in Poland by Jan Dylık and Alfred Jahn. Much of these authors’ research focused on Pleistocene periglacial features or, in the case of Tricart and Büdel, on climatic geomorphology, but collectively they forged periglacial research as a distinct entity, as evidenced by the publication of the first textbooks on the topic (Cailleux and Taylor, 1954; Tricart, 1963; Jahn, 1975), syntheses of Pleistocene periglacialization in Europe (e.g. Büdel, 1953; Poser, 1953–54), and the founding in 1954 of Biuletyn Peryglacjalny, the first journal devoted to periglacial research. In Great Britain, advances in periglacial research were sluggish by comparison, though research by Williams (1965, 1969) on the distribution of permafrost in England during the last glacial period bears comparison with similar work in continental Europe. A British textbook entitled Glacial and Periglacial Geomorphology (Embleton and King, 1968) proved excellent on the first topic but disappointingly pedestrian on the second.

North American research in the decades following 1945 looked north to the permafrost zone, where expansion of roads and settlements required a fuller understanding of permafrost terrain: permafrost distribution and thermal regime, the consequences of permafrost disturbance and the origins of permafrost phenomena such as thermal contraction cracking and ground ice formation (e.g. Muller, 1947; Hopkins, 1949; Lachenbruch, 1962). J.B. Bird’s book The Physiography of Arctic Canada (1967) placed the periglacial geomorphology of the Canadian north in a broader landscape perspective, and R.J.E. Brown’s monograph Permafrost in Canada (1970) summarized the findings of two decades of research on the topic. During the same period, permafrost scientists in the former Soviet Union made enormous advances in geocryological research, but much of this was inaccessible to researchers outside the Soviet Union until improved international relations allowed for the publication of key reports in English translations (e.g. Baranov, 1964; Kachurin, 1964; Shumskii, 1964; Tsytovitch, 1964; Kudryavstev, 1965).

The third strand in postwar periglacial research was the beginning of detailed field and laboratory investigations of periglacial processes. An outstanding early proponent of such research was the Canadian geomorphologist Ross Mackay, who developed a masterful synthesis of physical theory and field testing to investigate a wide range of frozen-ground phenomena, most notably ice-cored hills (pingos) and thermal contraction cracking of permafrost; much of his work remains unsurpassed, and is described in later chapters. At roughly the same time, A.L. Washburn (1967, 1969) was carrying out long-term field investigation in NE Greenland of slope processes and frost action that forms the foundation of much current understanding of these topics (Hallet, 2008), and various geomorphologists were carrying out groundbreaking research on the processes operating in alpine periglacial environments (e.g. Rapp, 1960; Caine, 1974). Such work represents the beginning of the present era of periglacial research, with its central focus on process–landform relationships. Washburn’s Periglacial Processes and Environments (1973) and its successor Geocryology: A Survey of Periglacial Processes and Environments (1979) are magnificent syntheses of the subject built on an encyclopaedic knowledge of the literature up to that time. Geocryology cites over 2100 references, and might justifiably be considered the Old Testament of periglacial research.

During the past three decades, there has been a shift in the focus of periglacial geomorphology, away from field mapping, classification and spatial differentiation of periglacial phenomena and towards a critical and technologically sophisticated re-evaluation of periglacial processes (André, 2009). Process-oriented field research has been transformed by the advent of instrumentation for simultaneous monitoring of such variables as snowcover, surface and subsurface ground temperature, soil moisture content, pore-water pressure and associated volume change and shear strain in rock and soil (e.g. Matsuoka, 2006; Harris et al., 2007). Allied to these advances has been the development of geophysical techniques for the detection
of permafrost and ground ice, and the delimitation of subsurface structures within periglacial landforms and deposits (e.g. Hauck and Kneisel, 2008; Kneisel et al., 2008). Upscaling of data on landforms, processes and terrain characteristics to landscape scale has been accomplished using remote-sensing techniques and digital terrain modelling (e.g. Etzelmüller et al., 2001; Hjort et al., 2007), and major advances have been made in numerical modelling of ground thermal regime and certain geomorphological processes (e.g. Riseborough et al., 2008). Laboratory simulation experiments, conducted both at full scale (e.g. Murton et al., 2006; Harris et al., 2008a) and at reduced scale in a geotechnical centrifuge (e.g. Harris et al., 2005, 2008c), have transformed our understanding of the processes involved in thaw of ground ice, weathering of intact bedrock and particularly downslope movement of soils under cyclic freezing and thawing. New dating techniques, coupled with numerical modelling (e.g. Anderson, 2002; Anderson et al., 2013), are transforming our understanding of how periglacial landscapes have evolved over long timescales. Overshadowing all these developments is an awareness that predictions of rapid warming in present-day arctic and alpine environments may bring about geomorphological changes at a rate and scale not seen on Earth since the end of the last glacial stage (e.g. Harris et al., 2009; Callaghan et al., 2011).

These developments have forced a reassessment of many long-established views concerning, for example, the efficacy of frost action in rock breakdown (e.g. Hall et al., 2002), the erosional potential of late-lying or perennial snowbeds (e.g. Thorn and Hall, 2002) and the role of viscous flow in downslope movement of soil during thaw (e.g. Harris et al., 2003). Many of these changes in the understanding of periglacial processes can be traced through a comparison of the three editions of Hugh French’s book *The Periglacial Environment* (1976, 1996, 2007), the papers published in *Permafrost and Periglacial Processes* (a journal founded in 1990 and now the main vehicle for publication of periglacial research), the proceedings of successive International Permafrost Conferences, and the mainstream geomorphological and Quaternary science journals.

### 1.4 Periglacial Geomorphology: The Quaternary Context

Though there are occasional references to periglacial sediments or structures in ancient sedimentary rocks (e.g. Deynoux, 1982; Williams, 1986), almost all periglacial research is devoted to present-day periglacial processes and landforms, or to relict periglacial features that formed under cold conditions during the Quaternary period, colloquially known as ‘the Ice Age’, which spans the last 2.6 million years or so. The Quaternary period is subdivided into two geological epochs, the *Pleistocene* (~2.6 Ma to 11.7 ka) and the *Holocene* (11.7 ka to the present). Note that ‘years’ are here expressed by a (Latin *annus*), thousands of years as *ka* and millions of years as *Ma*; these abbreviations may refer to a span of time, but are usually employed here in the sense of ‘years before present’.

The Quaternary period is further subdivided into the *Early Quaternary* (= Early Pleistocene, ~2.6 to ~0.9 Ma), the *Middle Quaternary* (= Middle Pleistocene, ~0.9 Ma to ~130 ka), and the *Late Quaternary* (= Late Pleistocene plus the Holocene).

The Quaternary period has been an era of major and often rapid climatic changes, marked by the alternation of cold glacial stages and warmer interglacial stages (Figure 1.6). Shorter periods of cold conditions are termed

![Figure 1.6 Marine oxygen isotope stage (MIS) record of glacial-interglacial oscillations during the past 700 ka. Changes in the δ¹⁸O:δ¹⁶O ratio in benthic foraminifera in deep ocean cores record the expansion and contraction of global ice sheets, and thus changes in global temperatures. Dashed horizontal lines mark the main boundaries between glacial stages (even numbers) and interglacial stages (odd numbers).](image-url)
**1 Introduction**

Stades or stadials, and shorter periods of warmer climate are referred to as interstades or interstadials. The Holocene epoch represents the present interglacial, and climatically is probably representative of earlier interglacials if we exclude the effects of recent anthropogenic climate warming. Glacial stages, particularly over the last million years, were characterized by expansion of ice sheets over mid–latitude areas, and by drops in global sea level of up to about 120–130 m below present due to the huge volumes of water locked up in the ice sheets. During the last glacial maximum (LGM) of 26.5–19.0 ka (Clark et al., 2009), glacier ice occupied more than 30% of the present land area of the Earth, compared with about 10% today: the Laurentide Ice Sheet in North America covered much of Canada and extended to latitude 38°N in Ohio; roughly 70% of the present land area of the British Isles was covered by an ice sheet that terminated southwards along a line between South Wales and Yorkshire; and Scandinavia was buried by an ice sheet that extended southwards to Denmark, northern Germany and northern Poland. Climatic cooling during glacial stages was also associated with extension of periglacial conditions and permafrost into areas beyond the ice margin, such as southern England, northern France, the Netherlands, Belgium, central Germany and central Poland, northern states of the USA and extensive parts of Russia, China and Japan. In such areas, evidence for Pleistocene periglacial conditions is locally preserved in the form of relict periglacial landforms, sediments and soil structures (Figure 1.2). As very cold conditions persisted during at least the initial stages of ice-sheet retreat, permafrost and periglacial phenomena also developed in terrain vacated by the retreating ice margins, so that relict periglacial deposits sometimes overlie glaciogenic deposits, and periglacial soil structures are developed in glaciogenic sediments. Moreover, though ice sheets and permafrost have often been regarded as separate entities, there is growing evidence that permafrost influences the dynamics and erosive behaviour of overlying ice sheets and the resultant sediment–landform assemblages (Waller et al., 2012).

The great majority of relict Pleistocene periglacial features that have been described relate to the last glacial stage, which lasted from ~130 ka until 11.7 ka. This period is known in North America as the Wisconsinan stage, and elsewhere as the Devensian (Britain), Weichselian (NW Europe), Würmian (the Alps), Vistulian (Poland) and Valdaian (European Russia). This was not a period of uniformly cold conditions, but comprised a complex sequence of alternating cold stadials and cool temperate interstades. The last global ice-sheet maximum (26.5–19.0 ka) occurred during the Late Wisconsinan (Late Weichselian) substage of ~31.0–11.7 ka, itself a climatically complex period. Of particular note is the final stadial episode of the Late Weichselian in Europe, the Younger Dryas Stade of ~12.9–11.7 ka. This occurred after an interval of cool temperate climate (14.7–12.9 ka), in response to disturbance of oceanic circulation in the North Atlantic Ocean. It involved a brief return to severe cold in NW Europe, with readvance of glaciers in Scandinavia and Scotland, and return of permafrost conditions to unglacierized parts of northern Europe (Isarin, 1997a).

The Holocene epoch (~11.7 ka to the present) has also witnessed systematic climate shifts, albeit of lesser magnitude than those associated with glacial–interglacial transitions. The Holocene thermal maximum, sometimes referred to as the Holocene climatic optimum or hypsithermal, marks the period of highest Holocene global temperatures prior to recent anthropogenic global warming. The Holocene thermal maximum occurred within the period 11.0–7.0 ka, but peaked at different times in different regions, and was most pronounced at high latitudes; Renssen et al. (2012) have suggested that the maximum air temperature anomaly relative to pre-industrial levels typically exceeded +2.5 °C north of latitude 60°N. A more recent period of relative cooling, the Little Ice Age, occurred during the last millennium. Conventionally, this has been attributed to the period ~1550–1850 AD, but in some areas there is evidence for cooling as early as 1250–1300 AD, and the thermal minimum of the Little Ice Age was reached at different times in different regions. In middle and high latitudes, the associated negative thermal anomaly was of the order of 0.5–2.0 °C, and resulted in widespread advance of glaciers and aggradation of permafrost.

Evidence of periglacial conditions prior to the last glacial stage is sometimes preserved in older Pleistocene stratigraphic sequences that have survived subsequent erosion. These demonstrate that permafrost was present outside ice margins during both the Middle Pleistocene (e.g. Murton et al., 2001a) and the Early Pleistocene (e.g. Kasse, 1993). The oldest record of Pleistocene periglacial conditions is a soil buried under till in northern Missouri. This exhibits soil structures indicative of formation under periglacial conditions and probably former permafrost, and has been dated to ~2.5 Ma (Rovey and Balco, 2010), suggesting that periglacial conditions have intermittently affected mid–latitude environments throughout the entire span of the Pleistocene. Similarly, evidence for former permafrost formation and degradation in central Alaska has been dated to ~2.1 Ma (Beget et al., 2008), suggesting that cold climate conditions have persisted (though not uniformly) in high latitudes throughout much of the Pleistocene.

An important component of our understanding of how periglacial landscapes have evolved in formerly glaciated areas is the concept of paraglacial landscape modification. The term paraglacial refers to ‘non-glacial earth-surface processes, sediment accumulations, landforms,
landsystems and landscapes that are directly conditioned by glaciation and deglaciation (Ballantyne, 2002), and paraglacial geomorphology is the study of the way in which glaciated landscapes have adjusted to nonglacial conditions (Ballantyne, 2003, 2013a). The retreat of glacier ice, especially in upland areas, exposes landscapes in an unstable or metastable state. Rock masses stressed by the weight of glacier ice experience decompression, opening of fractures and resultant adjustment in the form of rockfalls, rockslides, rock avalanches and slope deformation. Glacigenic sediments on hillslopes may be reworked by landslides, debris flows, snow avalanches and running water. Valley-floor glacigenic sediments are eroded, transported and redeposited by rivers, forming alluvial fans, alluvial valley-fills, or deltas and bottom deposits in lakes or fjords. In general, paraglacial landscape adjustment and sediment reworking is most rapid during and immediately after deglaciation and declines in importance as rock masses stabilize and glacigenic sediment sources become exhausted. However, enhanced sediment flux within deglaciated catchments may persist for thousands of years, and today still occurs in large catchments that were deglaciated in the Late Pleistocene or Early Holocene. Many depositional landforms in formerly glaciated periglacial environments (such as talus accumulations, debris cones, alluvial fans, floodplain deposits and deltas) are essentially of paraglacial origin, and reflect an unusually rapid period of landscape change in the centuries or millennia following deglaciation, rather than the operation of processes at present-day rates.

To employ relict periglacial features to reconstruct past environments, we need to establish the age of such features. Numerous techniques have been used to date Pleistocene sediments (Walker, 2005; Lowe and Walker, 2015), but three are particularly important in periglacial geomorphology. The first is radiocarbon dating. Plant and animal tissues in living organisms contain the same concentration of the unstable isotope $^{14}$C (carbon-14) as the atmosphere, and atmospheric concentrations remain roughly constant through time. When a plant or animal dies, the concentration of $^{14}$C in the dead tissue reduces at the rate of 1% every 83 years. The rate of decay therefore describes a negative exponential function: 50% of $^{14}$C is lost after 5730 years, 75% after 11460 years, 87.5% after 17190 years and so on. By measuring the concentration of $^{14}$C present in dead organic matter, we can estimate the time of death or burial. Because the concentration of $^{14}$C becomes very small with increasing age, radiocarbon dating is usually accurate only for ages up to about 45ka, though with isotope-enrichment techniques ages of up to 60ka may be detected. In a periglacial context, radiocarbon dating is usually employed to date organic matter buried under or within sediments such as slope deposits or wind-blown sand.

Luminescence dating works on the principle that buried sediments are subject to very low levels of natural radiation. This causes release of electrons that become trapped in structural defects within the crystal lattices of minerals. These electrons can be released under controlled laboratory conditions, either by heating (thermoluminescence (TL) dating) or by shining a beam of light on to the sample (optically stimulated luminescence (OSL) dating). Both procedures result in an emission of light (luminescence) that is proportional in intensity to the concentration of trapped electrons and thus the age of sediment deposition, provided that the luminescence signal was zeroed by exposure to sunlight prior to sediment emplacement. OSL dating has largely replaced TL dating in establishing the age of sediments, as much less prior exposure to sunlight (‘bleaching’) is required (Aitken, 1998). OSL dating of quartz and feldspar grains has an upper age limit of about 150–200ka and is primarily employed in a periglacial context to date the deposition of windblown or fluvial sediments (Bateman, 2008).

Finally, cosmogenic isotope dating, sometimes termed cosmogenic radionuclide dating, measures the concentration of isotopes produced within the lattices of certain minerals as a result of neutron spallation (nucleus fragmentation) due to exposure to secondary cosmic radiation at the Earth’s surface (Gosse and Phillips, 2001). The main isotopes used are $^{10}$Be (beryllium-10), $^{26}$Al (aluminium-26) and $^{36}$Cl (chlorine-36). All are radioactive isotopes, with half-lives of ~1360, ~301 and ~705ka respectively. The concentration of cosmogenic isotopes present within the upper part of an exposed bedrock or boulder surface can be used to determine how long that surface has been exposed to the atmosphere (surface exposure dating) and is often used to determine the timing of deglaciation or stripping of overlying sediment cover. Cosmogenic radionuclides have also been used to establish the age of alluvial deposits and landslides, the timing of emergence of tors or bedrock protrusions and the age of weathered rock material (regolith), as well as to calculate rates of land-surface lowering (e.g. Small et al., 1997, 1999; Anderson, 2002; Phillips et al., 2006; Darmody et al., 2008; Ballantyne et al., 2014).

1.5 The Aims and Organization of this Book

The aim of this book is to provide a comprehensive introduction to periglacial geomorphology, one that incorporates not only the geomorphological and sedimentological processes that operate in present-day periglacial environments, and the landforms, deposits, and sediment structures produced by such processes, but also the identification of relict periglacial features and interpretation
of their palaeoenvironmental significance. This poses several challenges. The first is the breadth and diversity of the subject, which necessitates considerable economy of treatment. The second is spatial variation: though the physics of periglacial processes are universal, the conditions under which these operate vary enormously in different periglacial environments. The processes operating arctic tundra lowlands, for example, produce an entirely different assemblage of landforms from those operating in high-relief alpine environments. The third is the need to address both present processes and landforms, and the origins and significance of relict periglacial features.

The book is divided into six parts. The remainder of this introductory section (Chapter 2) provides further background on the contrasting nature of periglacial environments. Part II (Chapters 3–5) is devoted to the characteristics of frozen ground: ground freezing and thawing, permafrost and seasonally frozen ground, and ground ice. This forms the foundation for Part III (Chapters 6–9), which considers the characteristics, origin, and formation of landforms and structures associated with frozen ground, such as thermal contraction cracking of permafrost, ice-cored mounds, thermokarst landforms produced by the thaw of ice-rich permafrost, and a range of smaller landforms produced by seasonal freezing and thawing of the ground. Part IV (Chapters 10–12) addresses the weathering or breakdown of rock in periglacial environments, the processes operating on hillslopes, and the wide range of landforms that result from cold-climate slope processes. Part V (Chapters 13–15) considers the operation of fluvial activity, wind action, and coastal processes in periglacial environments, and how these are conditioned by cold climate conditions and frozen ground. Finally, Part VI (Chapters 16 and 17) draws the book to a close by considering how relict periglacial features can inform our understanding of past environmental conditions and the responses of periglacial environments to climate change.

Most of the central chapters (6–15) follow a common format: a brief introduction defining relevant terminology is followed by an account of relevant processes, a description of resulting landforms, deposits, and/or sediment structures, and finally an outline of equivalent relict (Pleistocene) phenomena and their significance. This format allows consideration of relict periglacial features in association with their active counterparts.

The literature on periglacial geomorphology is vast, and any synthesis of the topic has to be highly selective. The main criteria for selection of sources has been scientific importance, innovation, or representativeness, but where possible English-language publications or translations are cited, in acknowledgement of the likelihood that many readers of this book will be monoglot anglophones, or students who have mastered English as the lingua franca of scientific research. For those who have not, van Everdingen (1998) has compiled and edited an indispensable multi-language glossary of permafrost and related ground ice terminology, the Rosetta Stone of multilingual periglacial research. Major contributions have been made to our understanding of both periglacial geomorphology and geocryology by Russian, Chinese, Japanese, Scandinavian, French, German, and Polish scientists, with growing contributions by researchers in other European countries and South America. The focus on the English-language literature should not be interpreted as an attempt to promote anglophone hegemony on a subject to which innumerable scientists have contributed from all parts of the globe. The community of periglacial geomorphologists is international in both heritage and membership.
2

Periglacial Environments

2.1 Introduction

As outlined in Chapter 1, the geographical extent of present-day periglacial activity is not easily defined, but here we adopt the view that the present periglacial realm encompasses all unglacierized regions where frozen ground and/or freezing and thawing of the ground significantly influences landform development. The present operation of frost-action processes and the distribution of resultant landforms thus define the extent of the periglacial domain. The driving influence on frost action is climate, which represents the primary control not only on the distribution of permafrost and the depth of seasonal ground freezing and thawing, but also on the frequency of ground-level freeze-thaw events, the depth of winter snowcover, the seasonal availability of liquid water in the upper levels of the ground, and the propensity for erosion and deposition of sediment by strong winds. At a more local level, however, the effects of climate on ground temperature and geomorphological processes are modulated by vegetation cover and substrate characteristics. This chapter sets the scene for analysis of the processes operating in periglacial environments by outlining the characteristics of periglacial climates and briefly summarizing those of soils and vegetation cover in cold environments.

2.2 Periglacial Climates

No single climatic parameter adequately defines the limit of periglacial climates, though French (2007) suggested that this can be approximated by a mean annual air temperature (MAAT) of +3°C. This is a useful criterion that encompasses not only the polar, subpolar and high-altitude regions of the Earth, but also areas of shallow seasonal ground freezing. Classification of periglacial climates is inevitably rather arbitrary, as boundaries between climatic zones are gradational, and even within particular areas there may be marked climatic variation relating to such factors as altitude, slope aspect and distance from the coast. French (2007) employed a fourfold classification of periglacial climates (high arctic, continental interiors, alpine and climates with low annual temperature range) and identified two areas (the Qinghai-Tibet Plateau and Antarctica) that do not fall readily into any of his classes. A similar but modified approach is adopted here. Note that precipitation figures cited here and illustrated in Figures 2.3–2.5 are probably low estimates, particularly for winter snowfall, due to possible undercatch of snow under windy conditions.

2.2.1 Arctic Climates

Serreze and Barry (2014) have provided a comprehensive and accessible account of arctic climates. These can be understood with reference to three key factors. The first is a strongly negative annual radiation budget at the top of the atmosphere (roughly −60 to −120 W m⁻²) in arctic areas, implying that outward radiative losses exceed inputs. In part, this is due to the fact that north of the Arctic Circle (66.5° N) there is a period of winter darkness that becomes progressively longer with increasing latitude (Figure 2.1), but it also reflects the fact that in summer, solar radiation reaches high latitudes at a shallow angle (i.e. the sun remains low in the sky), so radiative inputs are relatively low despite 24-hour daylight. A second key feature is the development, particularly during autumn, winter and spring, of semipermanent atmospheric high-pressure systems over much of the Arctic. These prevent incursion of frontal systems and associated movement of relatively warm, moist air into northern polar latitudes, with the notable exception of the North Atlantic cyclone track that extends eastwards from a zone of pervasive low pressure (the Icelandic Low) centred southeast of southern Greenland around latitude 60° N, and to a lesser extent the Aleutian Low in the North Pacific. The effect on precipitation totals can be seen in Figure 2.2, in the form of zones of low (<400 mm a⁻¹) precipitation centred on the Canadian Arctic and northern Asia, and a belt of much higher (>600 mm a⁻¹) precipitation crossing from Baffin Island across southern Greenland and Iceland into the Barents and Kara Seas. Finally, heat transfer from the Arctic
Ocean tends to reduce temperature extremes in winter in surrounding landmasses, but heat loss to the Arctic Ocean also depresses summer temperatures slightly in coastal locations.

Figure 2.3 depicts climatic summaries for Eureka (79°59′ N) and Resolute Bay (74°41′ N), both in the Canadian Arctic Archipelago. In common with most of the high Arctic, winter monthly average temperatures are typically within the range −30 to −40 °C, and summers are short (2–3 months) and cool, with mean July
Figure 2.3  Mean monthly temperature and precipitation at high-arctic, low-arctic and continental interior locations near sea level. Horizontal dashes represent mean monthly temperature and vertical lines the range between maximum and minimum mean monthly temperatures. The histograms represent mean monthly precipitation. The figures in the centre of each graph are the mean annual air temperature (MAAT) and mean annual precipitation (MAP).
temperatures of +4 to +6 °C, though some summer days are remarkably mild; the author fondly remembers basking in warm (17 °C) sunshine one July afternoon at 78° N on Ellesmere Island, and according to one commentator it may be (theoretically) feasible to grow lettuce in benign parts of the Canadian high Arctic. Measured mean annual precipitation (MAP) is low (79 and 141 mm for Eureka and Resolute Bay respectively) and concentrated in the months of June to October, when there is increased cyclonic activity. By contrast, mean monthly winter air temperatures at Longyearbyen on Svalbard (78° 13'N) are warmer (−15 to −20 °C), and precipitation is moderate throughout the year. Both characteristics reflect the location of Svalbard in the North Atlantic cyclone track, so that relatively warm moist air crosses the archipelago in winter, moderating average temperatures and introducing frontal precipitation; rainfall is rare but not unknown in Longyearbyen in January.

Moving southwards to latitudes around 70° N, Tuktoyaktuk (69° 26’N) in the western Canadian arctic experiences a climate similar to that of Resolute Bay, but winter mean monthly temperatures are warmer (−20 to −30 °C) and summers are warmer and longer, with four months experiencing above-freezing average air temperatures (Figure 2.3). Tiksi (71° 36’N) on the Laptev Sea coast near the mouth of the Lena River has a similar temperature regime but twice as much precipitation, in part reflecting the easternmost reach of the North Atlantic storm belt; the northern Eurasian coast also experiences maximum frontal frequencies in summer, due to differential heating of the Arctic Ocean and land surface. However, Murmansk (68° 58’N) near the southern shore of the Barents Sea enjoys an arctic climate that is moderated by open water offshore and incursions of relatively warm maritime airmasses that bring precipitation throughout the year, together with longer, warmer summers. Of all the stations summarized in Figure 2.3, Murmansk alone lacks permafrost by virtue of its positive (+0.6 °C) MAAT.

2.2.2 Low-arctic and Subarctic Continental Interiors

In low-arctic and subarctic continental interiors between latitudes 55° N and 70° N, the dominant feature of climate is the extraordinarily wide range of mean monthly temperatures, reflecting the absence of moderating oceanic influences and the predominance of high-pressure systems during the winter months. A zone of high pressure over eastern Eurasia (the Siberian High) builds during the autumn in response to radiative cooling and persists until spring, resulting in the lowest winter temperatures anywhere in the northern hemisphere. Verkhoyansk (67° 33’N) experiences a mean January temperature of −48.3 °C and extremely limited winter snowfall, but for five months of the year mean monthly temperatures are above 0 °C, peaking at +17.2 °C in July. Canadian locations in this zone, such as Norman Wells (65° 17’N) and Churchill (58° 46’N) have similar, if less extreme, characteristics: very cold winters and moderately warm summers, with 4–5 months averaging >0 °C and mean July temperatures ranging from −15 °C to −25 °C (Figure 2.3). Where permafrost is present, the warm summers permit seasonal thaw to depths of 2–3 m, and where permafrost is absent, seasonal ground freezing can reach similar depths. MAP in subarctic continental interiors ranges from about 180 to 500 mm a⁻¹, with a pronounced summer maximum, in part resulting from convectional rainstorms. However, the relatively high summer temperatures also promote high rates of evapotranspiration, so there is a seasonal soil moisture deficit.

A notable feature of continental high-arctic, low-arctic and subarctic climates is that the air temperature at ground level crosses 0 °C comparatively infrequently – typically only about 20–50 times a year. This reflects the steepness of the spring warming and autumn cooling curves (Figure 2.3), so that periods of air temperature fluctuations around 0 °C are brief. Summer air temperatures tend to remain consistently above 0 °C and winter temperatures consistently below 0 °C, except in areas affected by winter cyclonic activity. Moreover, persistence of winter snowcover in spring and the insulating effects of vegetation cover in autumn further reduce the number of freeze–thaw cycles at the ground surface. In consequence, all of these areas are dominated by a single annual cycle of ground freezing and thawing, and short-term ground surface freeze–thaw cycles have very limited impact on periglacial processes in these zones.

2.2.3 Maritime Periglacial Environments

Maritime periglacial environments are those where conditions throughout the year are strongly influenced by the proximity of relatively warm oceanic waters and frequent cyclonic activity. They are characterised by a low annual temperature range and the absence of extreme cold, but also high precipitation, frequent cloudy conditions and strong winds associated with deep depressions, particularly in winter. Permafrost and deep seasonal ground freezing are usually absent, but air freeze–thaw cycles at ground level are frequent, and often associated with the passage of alternating warm and cold airmasses during autumn, winter and spring. The effects of relatively warm offshore ocean waters and frequent cyclonic activity are particularly evident in northwest Norway: Tromsø has an MAP of 1031 mm, an MAAT of +2.8 °C and a mean January temperature of −6.5 °C, and is thus climatically marginal for periglacial activity despite its high latitude (69° 41’N). Much of Iceland experiences similar or slightly warmer conditions,