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Introduction

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



Figure 1.1 Periglacial landscape of the North Slope of Alaska (69° N), looking towards the Brooks Range. Though this area is underlain by permafrost and subject to severe winter freezing, the broad outlines of the landscape differ little from those in other environments.
Source: Courtesy of Matthias Siewert.

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 (Schoor *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.

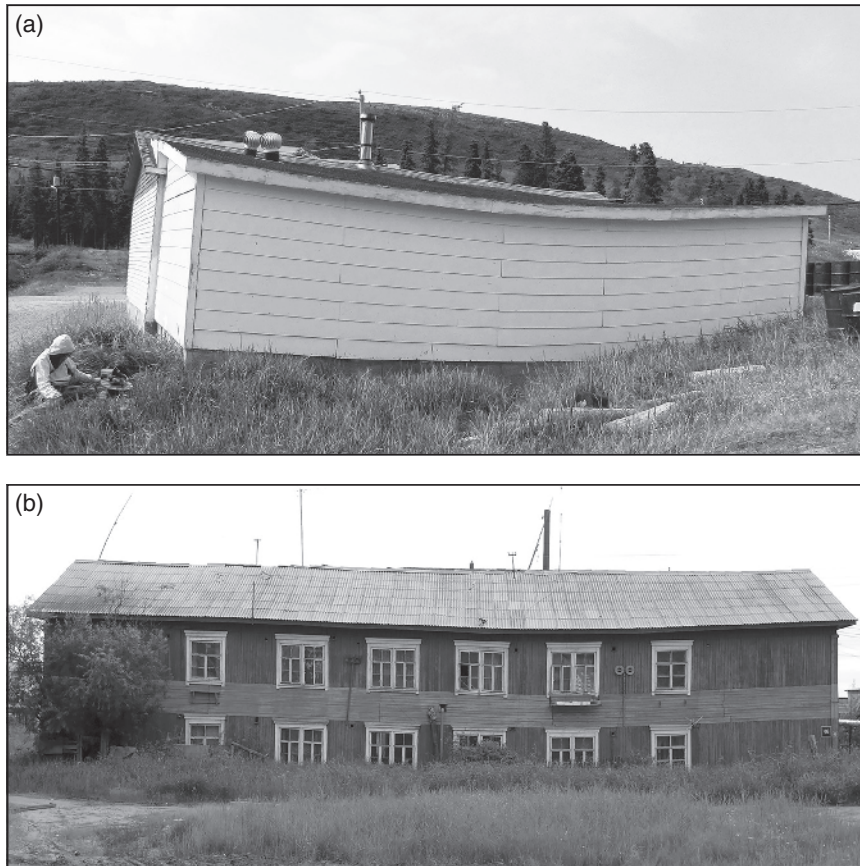


Figure 1.4 Subsidence of buildings due to thaw of underlying permafrost in (a) Alaska and (b) Yakutsk. *Source:* Courtesy of (a) Matthias Siewert and (b) Robert Way.

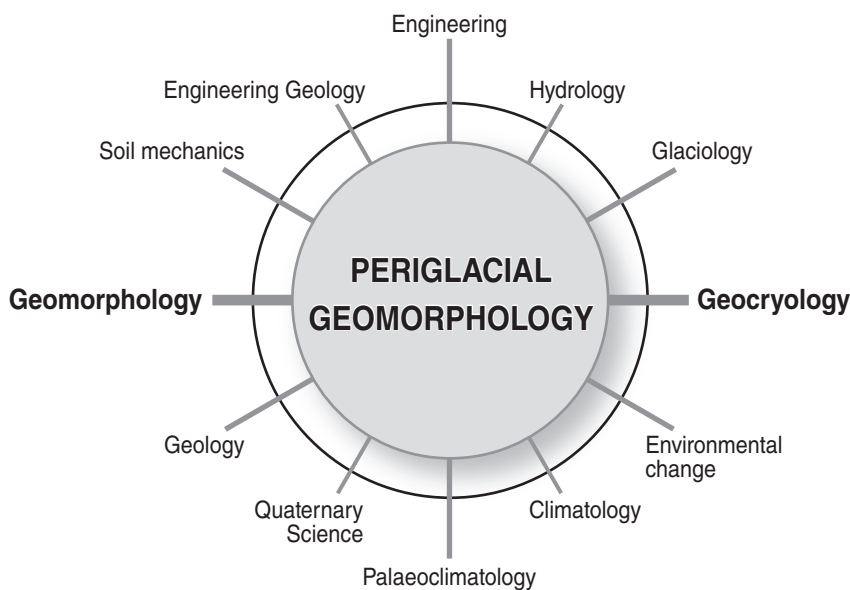


Figure 1.5 Relationship between periglacial geomorphology and cognate sciences.

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 landforms can be found at high altitudes (>5000 m) even on subtropical mountains, where nocturnal clear-sky radiative cooling results in disturbance of the ground by shallow frost action. Subdividing the periglacial realm into distinctive periglacial environments is difficult, however, because individual categories merge into one another and their characteristics are influenced locally by relief and vegetation cover.

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-plateau 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 continuous permafrost in the interior and by discontinuous permafrost farther south. Finally, *subtropical high mountain periglacial landscapes*, notably found in the Andes, support a range of periglacial features related to diurnal freezing and thawing of ground above about 5000 m. Like all attempts to subdivide the Earth’s surface, this broad categorization involves extensive generalization: even at a particular latitude, there may be significant differences in temperature and precipitation regime, often reflecting climatic contrasts between coastal environments and continental interiors, and some areas defy ready classification. The Svalbard archipelago (76–81° N), for example, is at similar latitudes to Ellesmere Island in 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 geocryology in Russia. It is arguable, however, that the origins of periglacial geomorphology as a scientific subdiscipline lie 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 Dylík 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 periglacialiation 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; Tsytoivitch, 1964; Kudryavstsev, 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

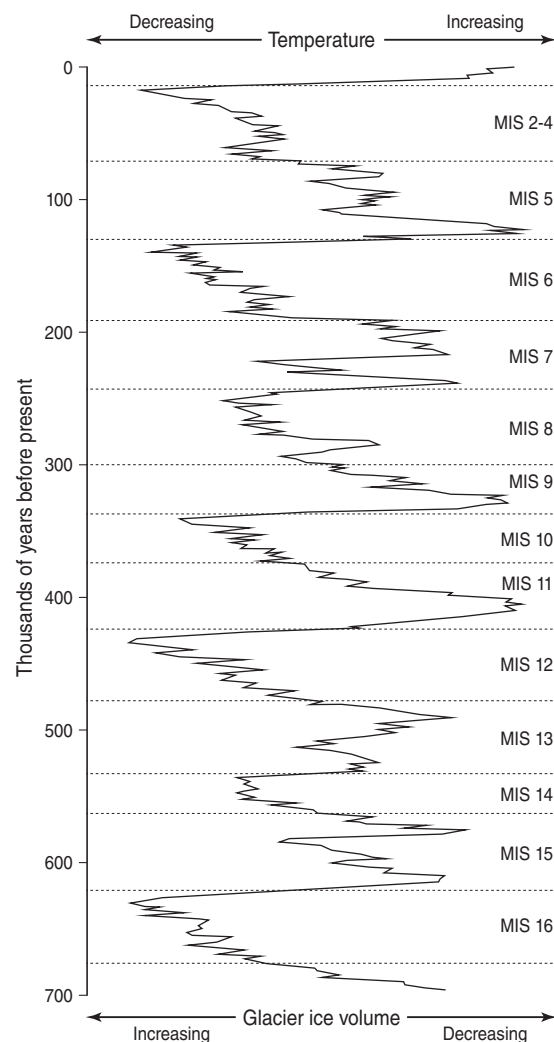


Figure 1.6 Marine oxygen isotope stage (MIS) record of glacial-interglacial oscillations during the past 700 ka. Changes in the $\delta^{18}\text{O}:\delta^{16}\text{O}$ ratio in benthic foraminifera in deep ocean cores record the expansion and contraction of global ice sheets, and thus changes in global temperatures. Dashed horizontal lines mark the main boundaries between glacial stages (even numbers) and interglacial stages (odd numbers).

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 glacial deposits, and periglacial soil structures are developed in glacial 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 stades 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 unglaciated 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 45 ka, though with isotope-enrichment techniques ages of up to 60 ka 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 150–200 ka 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 ~705 ka 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.