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Glacier-Permafrost Interactions

Richard I. Waller

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Dedication

This book is dedicated to the memory of my father, John Waller, a fellow academic and eternally supportive father who would have enjoyed discussing the contents of this book.

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Author Biography

Richard I. Waller is a Senior Lecturer in Physical Geography at Keele University in the United Kingdom. Following the completion of a PhD degree in 1997 at the University of Southampton, he spent five years working as a Postdoctoral Research Fellow in Glaciology at Greenwich University prior to moving to Keele in 2001. His research interests focused initially on the formation, deformation and mechanisms of debris transfer associated with debris-rich basal ice layers, subsequently broadening to encompass subglacial processes, the development of glacial landsystems and the processes and products of glacier–permafrost interactions that form the focus of this book. Being largely field based, this research has provided opportunities to work extensively on modern and ancient glacial and permafrost environments in Alaska, Canada, Iceland, Greenland and Scandinavia as well as the United Kingdom. This work has led to the publication of papers within several peer-reviewed journals as well as book chapters, although this is his first sole-authored research text. He has been actively involved with the Quaternary Research Association, the International Glaciological Society and the International Permafrost Association and has presented at a number of events including the International Conference on Permafrost and the INQUA Congress. He is a passionate believer in the importance of outreach and widening participation and has worked with the British Science Association, the Geographical Association and the Royal Geographical Society to create a range of educational resources designed to foster a wider appreciation and interest in the Earth's cold environments and the impacts of climate change. In his spare time, he enjoys any time spent in the 'great outdoors' whether by foot, by bike or by kayak.

Preface

In a year that has witnessed record-breaking temperatures around many parts of the planet, there has been an increasing public consciousness of the accelerating impacts of climate change in the form of heat waves, wildfires and floods. Associated media interest has extended to the global cryosphere and as I write, there is recent news of the lowest recorded extent of Antarctic sea ice since satellite observations commenced in 1979. Against this backdrop, it is surprising that so little research attention has focused on the extent, nature and significance of the interactions between glaciers and permafrost as two of the most significant components of the cryosphere. This is in part a legacy of a longer-term disciplinary divide that has seen those studying glaciers and those studying permafrost working largely if not entirely in isolation. The primary aim of this book is consequently to showcase the distinctive processes and products associated with glacier–permafrost interactions that have not previously received the attention they deserve.

From the perspective of research priorities, one of the main reasons why glacier–permafrost interactions have received limited attention is that glaciers and permafrost have traditionally been considered to be largely mutually exclusive with significant thicknesses of glacier ice, active basal processes and the production of meltwater considered inimical to the preservation of subglacial permafrost. Recent field studies however have indicated that subglacial permafrost can extend for several kilometres beneath ice margins. Meanwhile, modelling studies have indicated that subglacial permafrost can persist for millennia beneath advancing ice sheets due to its thermal inertia whilst also suggesting that it can re-form and aggrade during periods of recession and downwasting.

With the thermal regime of a glacier or ice sheet having long been considered a key determinant of their dynamic behaviour, another reason for the limited research interest has been the assumption that glaciers overlying permafrost are by definition ‘frozen to their beds’ such that basal processes are inactive and ice flow is limited to internal creep. With research agendas focusing very much on the states of fast ice-flow driven by basal processes, cold-based glaciers associated with very low velocities have been considered of limited intrinsic interest. Again, more recent research has however indicated that these ice masses can be much more dynamic than previously thought with the potential for basal processes to persist at temperatures well below the bulk freezing point.

More recently, the glaciological literature has increasingly focused on hydrology as a key driver of various facets of glacier behaviour. Whilst this work has largely targeted temperate glaciers in environments lacking permafrost, the few studies undertaken in permafrost environments have revealed complex connections between glacier thermal regimes, hydrological pathways and velocities capable of driving significant seasonal variations in the generation, storage and release of meltwater. Looking at polar catchments more broadly, following the pioneering work of Olav Liestøl, ongoing research has demonstrated the landscape-scale hydrological interconnectivity of glaciers and permafrost and the consequent need to treat them as coupled components of a wider system. This has become apparent in the explanation of one of the more paradoxical impacts of polar climate change whereby climate warming has led to glacier recession and cooling, a reduction in the extent of warm-based ice critical for groundwater recharge and the shutdown of spring systems.

When viewed from the perspective of geomorphologist and geologists, cold-based glaciers associated with permafrost have traditionally been associated with a lack of geomorphic activity, providing another reason for the limited prior research interest. However, it is precisely this ability to preserve preglacial features – including biologically viable vegetation – that is arguably one of the most enigmatic and consequential aspects of their behaviour that is worthy of further investigation. Glacier–permafrost interactions can nonetheless be associated with the creation of a variety of distinctive landforms, sediments and landsystems, although these are often markedly different from the well-known ‘textbook’ examples associated with temperate glaciers. With the landscape record containing an inherent bias towards warm-based conditions and the potential for misinterpretations of landforms and sediments, elucidating their landscape impacts and expression can be considered a key priority. Looking to the future, it is also likely that glacier–permafrost interactions will play an influential role in determining landscape responses to climate change in high mountain and high latitude regions, with the potential for major rockfalls and related hazards in the former and the exposure and subsequent melt-out of massive ground ice in the latter.

The book has been designed to provide a systematic overview of these themes, developments and the fundamental underlying concepts:

- **Chapter** 1 provides a short introduction to the research context of the book and the significance of glacier–permafrost interactions.
- **Chapter** 2 provides an introduction to permafrost considering its thermal and physical properties, its formation and extent and its rheological properties.
- **Chapter** 3 considers the distinctive characteristics of glaciers found within permafrost environments and the influence of glacier–permafrost interactions on subglacial and ice-marginal processes.
- **Chapter** 4 provides an integrated overview of the hydrological and dynamic behaviour of glaciers that interact with permafrost before considering their implications for glacial sediment transfer.
- **Chapter** 5 addresses the landscape expression of glacier–permafrost interactions, considering the concept of glacial protectionism, the broad range of associated landforms, sediments, structures and landsystems and finally, the paraglacial landscape adjustments in which they play a prominent role.
- **Chapter** 6 concludes by exploring a range of potential avenues for future research.

Ultimately, it is hoped that this book will encourage those studying cryospheric environments to view glaciers and permafrost not as separate entities, but as part of a thermally, mechanically, hydrologically and geologically integrated system. At the same time, it is hoped that this recognition will encourage more collaborative research activity between glaciologists and permafrost scientists. This can only be to the benefit of both disciplines and to the collective and pressing need to fully comprehend the accelerating impacts of climate change in those parts of the world that continue to be dominated by ice.

Richard I. Waller

Acknowledgements

With this book focusing on the interactions between glaciers and permafrost, I would like to express my sincere gratitude to all those who have stimulated my interest in glaciers, in permafrost and more recently, in the interactions between the two that have culminated in this contribution to the research literature. Special thanks in particular to Jane Hart, who provided me with the opportunity to develop my nascent interest in glaciers, to Julian Murton who introduced me to permafrost and the 'wonderful world of underground ice' and to Peter G. Knight without whose encouragement this book would never have happened.

Since the late 1980s, I have been privileged to travel to a range of spectacular Arctic and sub-Arctic locations to undertake field work with some remarkable people and to benefit from their company, knowledge, expertise and enthusiasm. In addition to those already mentioned, these include Dave Evans, Matthew Bennett, Colin Whiteman, Mike Hambrey, Zoe Robinson, Brian Moorman, Emrys Phillips amongst others who I've undoubtedly forgotten to recognise. They have all contributed to some of the most enjoyable and memorable experiences of my life that continue to shape my views of the natural world. I'm especially grateful to the individuals and organisations who enabled these opportunities and provided the financial support necessary.

I would also like to acknowledge the pioneers whose work on cold-based glaciers and glacier–permafrost interactions has provided the foundation and inspiration for this book. In addition to those mentioned above, the research findings, insights and conceptual frameworks provided by Wilfried Haeberli, Bernd Etzelmüller, Sean Fitzsimons, Cliff Atkins and Art Dyke have proven invaluable.

Thanks to all those at Wiley who have been supportive and patient over the years this book has taken to complete. I'd like to thank Mandy Collison and Indirakumari Siva in particular, without whose guidance this book would never have come to fruition. Special thanks also to Sean Fitzsimons, Jason Gulley and Mike Hambrey who kindly allowed the reproduction of their images within the book.

Finally, I would like to thank my wife for her patience as I've disappeared for hours or days at a time whilst writing this book. Rest assured - it'll be some time before I attempt another writing project of this magnitude! I would also like to thank my wonderful mother to whom I owe so much. I hope you get the chance to finally see this book in print.

1

Introduction

1.1 Research Context and Academic Background

Glaciers and permafrost constitute two of the most important elements of the global cryosphere, a dynamic component of the Earth system dominated by cold climatic conditions and water in its solid form. Modern-day glaciers and ice sheets alone are estimated to cover a total area of over 16 million km^2 with the majority occurring in the form of the Antarctic and Greenland Ice Sheets (covering c. 14 million and 1.7 million km^2, respectively; NSIDC, 2019), with the remaining ice being distributed between 198,000 smaller glaciers and ice caps (Pfeffer *et al.*, 2014). Meanwhile, permafrost regions are estimated to occupy an additional area of almost 23 million km^2 in the Northern Hemisphere alone, which equates to almost 24% of the Earth's exposed land area (Zhang *et al.*, 2003). In combination therefore, the global cryosphere can be estimated to currently cover a total area of almost 40 million km^2, occurring primarily within the polar regions and high-altitude continental interiors.

In spite of their obvious geographical associations within similar climatic settings, surprisingly little research activity has focused on an examination of the nature and potential significance of the interactions between glaciers and permafrost. Part of the reason for this limited interest in glacier–permafrost interactions within the glaciological research community in particular relates to two widely held assumptions. First, that glaciers and permafrost are largely mutually exclusive with substantial thicknesses of glacier ice insulating any underlying permafrost from the prevailing climatic conditions and the heat generated by basal processes rapidly degrading any permafrost present. Second, where glaciers are observed to rest on permafrost, the resulting cold-based thermal regime is thought to preclude the operation of processes such as basal sliding and subglacial-sediment deformation that are in turn associated with dynamic ice flow and significant landscape modification. In addition to explaining the lack of targeted research activity, both assumptions emphasise the central importance of basal thermal regimes to any consideration of the connections between glaciers and permafrost (Section 3.2).

Cold-based glaciers occurring in areas of permafrost are therefore commonly conceptualised as being frozen to rigid and undeformable beds and to be both slow moving

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and geomorphologically impotent. They have consequently been disregarded as being of limited intrinsic research interest. In combination with their tendency to occur within remote regions that are typically difficult and costly to access, this has resulted in glacier scientists historically tending to focus primarily on temperate or warm-based glaciers, inducing a research bias that has resulted in our understanding of the behaviour of cold-based glaciers remaining limited in comparison. The same situation also applies to ancient glacial environments where glacial geomorphologists and geologists have tended to study areas glaciated by warm-based ice or characterised by hard bedrock, for example the Fennoscandian and Canadian Shields. In contrast, only a handful of studies have been published in international research journals that consider the potential interactions between cold-based ice sheets and the permafrozen sediments that underlie huge swathes of western Siberia and Arctic Canada and where permafrost is believed to have persisted throughout entire glacial cycles (e.g. Astakhov *et al.*, 1996, section 5.4.3).

Some have argued that the limited interest in glacier–permafrost interactions is a reflection of a more fundamental and deep-seated dichotomy that has developed and persisted within the cryospheric sciences. Harris & Murton (2005) note that whilst the term 'geocryology' had originally been introduced to encompass both glaciers and permafrost, the introduction of the term 'periglacial' by Lozinski in the early 20th century resulted in a split between those interested in the study of glaciers and those interested in the study of frozen ground. These two communities have subsequently worked largely if not entirely in isolation, such that studies into the processes and products that occur at the interface between glaciers and permafrost have rarely received the focused and systematic research attention they deserve. They have instead been largely limited to isolated studies that have for example considered the potential role played by permafrost in promoting the development of large push moraines (e.g. Rutten, 1960; section 5.3.2). This enduring schism between the two disciplines is further illustrated by the usage of the term glaciology. Whilst this literally means the study of ice, it is widely regarded as referring more exclusively to the study of glaciers whilst the study of glaciers and ice sheets has been seen to be beyond the remit of permafrost scientists.

As a rare example of someone who has worked extensively across this research divide, Haeberli (2005) has argued that this schism has been to the detriment of both disciplines, resulting in terminological confusion and a hampering of research progress in both fields that have ultimately limited the credibility of cryospheric research as a whole. The lack of collaborative research appears particularly perverse when one considers shared research interests in the behaviour of ice-sediment mixtures for example (e.g. Waller *et al.,* 2009a). Glacier scientists recognise the potential influence of the debris-rich ice that commonly occurs at the base of glaciers and ice sheets on their dynamic behaviour, sediment transport and geomorphic impact. At the same time, permafrost researchers have made significant progress in describing the nature, origin and engineering properties of different types of ground ice commonly found within permafrost regions. However, in spite of these overlapping areas of mutual interest relating to the study of essentially identical materials using similar techniques, the amount of collaborative research has remained limited until relatively recently (Section 2.5.1).

The resolution of a series of major research challenges relating for example to hazard mitigation in cold-climate regions, the secure burial of radioactive waste in cold regions and the potential impacts of future climate change on the global cryosphere have led to the recognition of a pressing need for a more integrated approach to the study of the cryosphere and renewed calls for the two research communities to collaborate more actively. This provides the opportunity to open up a 'new scientific land' (Haeberli, 2005, p36) in which workers in both communities can recognise and actively incorporate rather than ignore and exclude the findings of the other discipline. Such collaborative approaches are essential for the resolution of a range of interdisciplinary research questions that span the two subject areas. These include the accurate interpretation of buried ice within permafrost environments hypothesised to constitute buried glacier ice that has been preserved within the permafrost since deglaciation (Section 5.3.4). Similarly, recent work exploring the link between the dynamic behaviour of ice streams, basal freezing and till rheology has benefitted from the application of pre-existing models of frost heave originally devised by permafrost engineers (Section 4.3.3). These two brief examples provide an insight into the potential benefits that could be enabled by a more integrated approach. Most importantly, the fostering of a more interdisciplinary approach can prevent the promulgation of misconceptions and theoretical shortcomings that could have devastating implications in the context of natural hazards in high mountain areas (Section 5.6.1).

Whilst there are signs of a growing awareness of the importance of glacier–permafrost interactions, coupled with attempts to bridge the existing gap between glacier science and permafrost research, the fact remains that 'the geological and geomorphological processes at the interface between glaciers and permafrost have received less attention than they warrant, and the influence of the one on the other has been largely neglected' (Haeberli, cited by Harris & Murton, 2005, p2). It is hoped that this book will go some way to appreciating, emphasising and promoting the importance of glacier–permafrost interactions through a consideration of the historical roots of these interactions and its attempts to review recent developments, the state of current knowledge, the key gaps in our understanding and profitable avenues for future research.

1.2 Overview of the Significance of Glacier–Permafrost Interactions

As mentioned in the previous section, one of the principal reasons behind a lack of research interest in glacier–permafrost interactions has stemmed from the assumption that glacier–permafrost interactions are of limited extent and that glaciers resting on permafrost are slow moving and geomorphologically ineffectual. Research over the past 30 years in particular has however demonstrated that these assumptions are by no means universally applicable. The rebuttal of these assumptions has in turn stimulated renewed interest in the nature and significance of glacier–permafrost interactions that are briefly reviewed within this section prior to their more detailed examination in the subsequent chapters.

Numerical ice-sheet modelling and field observations relating primarily to Pleistocene Ice Sheets have indicated that glacier–permafrost interactions are likely to have been more extensive and of longer duration than was previously thought (Section 2.4.1). This is particularly the case during the growth phases of continental ice sheets when they are most likely to have advanced over areas of pre-existing and potentially thick permafrost with a considerable thermal inertia. Conversely and more topically, ongoing glacier recession resulting from climate change in high-latitude regions such as Svalbard is resulting in an increase in the extent of subglacial permafrost as the glaciers thin and decelerate and the insulating effect of the ice decreases, suggesting that glacier–permafrost interactions can also be important during deglacial phases (Section 2.4.2).

The basal thermal regime of a glacier or ice sheet is widely regarded as one of the principal controls of its dynamic behaviour (Section 3.2). With glaciers resting on permafrost by definition being cold-based in character, this establishes clear process-related connections between permafrost, basal thermal regimes, subglacial hydrology and dynamic behaviour. Cold-based glaciers resting on permafrost are commonly referred to as being 'frozen to their beds', which suggests that they are only able to move via internal creep and are very slow moving as a consequence (Section 3.4). This is in marked contrast to warm-based glaciers where the active production of meltwater enables the basal processes such as basal sliding and subglacial-sediment deformation that are central to states of fast ice flow and flow instabilities. Recent work in both modern and ancient glacial environments has demonstrated however that these basal processes are not restricted to warm-based glaciers as was previously thought and that these processes can remain active at temperatures well below the pressure-melting point due to the presence of 'premelted water' (Section 3.5). This means that glaciers interacting with permafrost may flow more rapidly than was previously assumed to be the case, although the magnitude and significance of any increase in velocity remains as yet unclear. In addition, the identification of deep-seated permafrost deformation beneath former cold-based ice sheets raises the intriguing possibility of glaciers mechanically coupling with permafrost to create an integrated dynamic system (Sections 3.5.5, 5.4.3).

Further consideration of the basal thermal regime of glaciers and their position within hydrological catchments highlights the hydrological implications of glacier–permafrost interactions both for the glacier and the wider catchment (Section 4.2). Glaciers occurring in permafrost areas exhibit distinctive hydrological regimes and experience far less basal melting than glaciers in more temperate environments. Cold-based glaciers are commonly associated with deeply incised supraglacial drainage systems that are reactivated during the melt season to feed lateral meltwater systems. Larger polythermal glaciers with ice thicknesses sufficient to produce areas of warm-based ice are capable of generating perennial subglacial drainage which can lead to the development of proglacial icings during the winter months. These zones of basal melting beneath polythermal glaciers are often associated with taliks or unfrozen zones in the permafrost. Their connection with wider catchment groundwater systems means that they constitute one of the few sources of groundwater recharge in areas of extensive permafrost. This can in turn drive perennial spring systems and lead to the formation of distinctive permafrost landforms such as pingos. Ongoing recession and thinning of glaciers in Svalbard and the shrinking of areas of warm-based ice has as a result been observed to lead to a reduction in groundwater recharge and the drying up of springs, once again highlighting the importance of viewing glaciers and permafrost as part of a connected system.

The conceptual framework used to understand glacier–permafrost interactions also has important implications for the geomorphological processes and products associated with glaciers occurring in permafrost environments. With active glacial erosion traditionally being associated with warm-based glaciers and processes such as basal sliding, cold-based glaciers resting on permafrost have typically been characterised as settings featuring limited geomorphological activity and landscape change. As such they have been associated largely with the preservation of preglacial landforms rather than with the active generation of distinctive glacial landforms, with some arguing their principal geomorphic impact is limited to the isostatic effects associated with crustal loading (Section 5.2). Some studies have however recognised that glacier–permafrost interactions can lead to the creation of a range of distinctive landforms (Section 5.3), for example by enabling the transmission of glacier-induced stresses into a permafrozen foreland and facilitating the development of large push moraine complexes (Section 5.3.2). Others have suggested that the lateral meltwater flows characteristic of cold-based glaciers can create distinctive flights of meltwater channels that can provide a rather different landscape record of ice-margin recession to the moraine sequences more commonly employed within palaeoglaciological reconstructions (Section 5.3.1).

The recognition that basal processes can remain active at temperatures below the pressure melting point has been central to a more recent reappraisal of their continued ability to erode, entrain, transport and deposit sediment (Section 3.5). In this regard, the association of polythermal glaciers terminating in permafrost regions with thicker debris-bearing basal ice layers and higher glacial and fluvioglacial sediment loads suggests that the enhanced availability of sediment in permafrost areas may in fact more than compensate for their lower ice velocities (Section 4.4). Greater interest in and scrutiny of the forelands of cold-based glaciers in permafrost regions has demonstrated that even those glaciers occurring in the coldest regions of Earth, such as the Dry Valleys in Antarctica, are associated with some degree of geomorphological activity and the development of a range of subtle yet distinctive landforms (Section 5.5.4). Work in past glacial environments where glaciers have advanced over and coupled with permafrost have also revealed distinctive sedimentological and structural signatures relating to the deformation and mobilisation of permafrost (Section 5.4). Therefore, rather than being characterised by an absence of geomorphological and geological activity, it is becoming increasingly clear that glaciers interacting with permafrost are associated with a range of distinctive landform-sediment assemblages the nature and diversity of which are only starting to become clear (Section 5.5). This remains a nascent area of enquiry where much work is required to establish the diagnostic links between process and product that provide the fundamental foundations for geomorphological inverse models and palaeoglaciological reconstructions.

Finally, the consideration of glaciers and permafrost as complex, coupled systems is central to an understanding of the geomorphological consequences of climate change in modern-day glaciated permafrost regions and the risks they pose to the resident populations. The Kolka-Karmadon rock/ice slide that occurred in the Caucasus Mountains in 2002 claiming an estimated 120 lives provides a dramatic illustration of the large-scale and catastrophic slope failures that can result from a combination of glacier recession, slope debuttressing and permafrost degradation. High mountain areas featuring glaciers and permafrost are therefore experiencing a transitional phase of rapid change associated with profound landscape disequilibria and the development of complex process chains (Section 5.6.2). In addition, a significant increase in the frequency and intensity of summer storm events has resulted in the exposure and degradation of buried ground ice within large areas of the western Canadian

Arctic and Siberia and the formation and dramatic expansion of ‘megaslumps’ (Section 5.6.3). With much of this ice being considered to comprise relict Pleistocene glacier ice preserved by permafrost within ice-cored moraine complexes, recent climate change has resulted in a renewed phase of deglaciation and thermokarst activity. This has significant regional implications for regional water quality and transport infrastructure and global implications in terms of the stored carbon these processes are helping to release.

1.3 Explanation of the Book Structure

Chapter 2 considers the distinctive characteristics and properties of permafrost within the specific context of their occurrence of modern and ancient glacial environments. The chapter focuses initially upon thermal and physical properties of permafrost paying particular attention to the presence and significance of water as both a liquid and a solid (Section 2.2). It then explores the conditions and processes associated with its formation, preservation and degradation in both subaerial and subglacial environments (Section 2.3) before considering the spatial extent of glacier–permafrost interactions and the temporal changes related to modern-day and ancient glacier fluctuations (Section 2.4). Finally, detailed consideration is given to the highly variable mechanical and rheological properties of permafrost and the key causes the complex behaviours that have been observed (Section 2.5).

Chapter 3 considers the influence of permafrost on the operation of a diverse range of glacial processes. The chapter starts by reviewing the thermal regimes associated with glaciers occurring in permafrost environments (Section 3.2) before considering the basal boundary conditions associated with both rigid and soft-bed glaciers (Section 3.3). It then examines the traditional glaciological assumptions regarding basal conditions and processes associated with cold glaciers with ‘frozen beds’ (Section 3.4) before considering the evidence that has led to a recent reappraisal of the activity of subglacial processes at temperatures below the pressure melting point (Section 3.6). The final section examines a range of ice-marginal and proglacial processes that have been specifically related to glacier–permafrost interactions (Section 3.7).

Chapter 4 examines the hydrology, dynamic behaviour and sediment fluxes associated with modern and ancient non-temperate glaciers that are central to understanding the varied roles and potential glaciological and geomorphological impacts of glacier–permafrost interactions. Section 4.2 focuses on the hydrological characteristics of non-temperature glaciers considering the distinctive flow pathways and their seasonal variability before considering their impacts on suspended-sediment and solute fluxes. The impacts of non-temperature glaciers on groundwater fluxes within the broader permafrost catchments are also explored. In view of the emerging connections between glacier hydrology and ice flow, this provides an important precursor to the consideration of the dynamic behaviour of non-temperature glaciers within Section 4.3. This explores the potential implications of glacier–permafrost interactions on glacier dynamics in relation to the velocities of modern-day, non-temperate glaciers, flow instabilities and ice streaming in ice sheets and the longer-term behaviours of Pleistocene Ice Sheets. Finally, Section 4.4 integrates the considerations of glacier hydrology and dynamics in considering their impacts on sediment pathways and fluxes within glaciated permafrost catchments.

Chapter 5 provides a detailed review of the distinctive products and landscape expressions of glacier–permafrost interactions. Section 5.2 starts by considering the broader debates concerning the geomorphic impacts of glaciers and the glacial protectionism and preservation of preglacial features thought to be characteristic of cold-based glaciers. Section 5.3 reviews a range of specific landforms that have been explicitly related to glacier–permafrost interactions before Section 5.4 considers the possible sedimentological features and structural signatures. Section 5.5 integrates these elements within a consideration of the distinctive glacial landsystems found within a range of contrasting glacial environments including those found on Mars. Section 5.6 concludes the chapter by examining the processes of paraglacial landscape adjustment in which glacier–permafrost interactions play a prominent role, including large rock slope failures and the degradation of ground ice.

Chapter 6 concludes by reflecting on the current state of knowledge and on the outstanding research gaps and areas of ongoing controversy whilst suggesting priority research themes and directions for the future.

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2

Permafrost in Modern and Ancient Glacial Environments

2.1 Introduction

Permafrost is a term that encompasses a diverse range of Earth surface materials that can display a remarkable range of characteristics and behaviours. The presence of water in materials with ambient temperatures close to the thermal transition between its solid and liquid phases results in a high degree of sensitivity to any thermal perturbations in particular. Seemingly minor changes in climatic variables (temperature or precipitation) or surface boundary conditions can sometimes elicit a striking non-linear response in the form of dramatic landscape changes. In addition, variations in pressure (depth), porewater salinity and grain size can add an additional level of complexity to unconsolidated sediments that commonly comprise dynamic mixtures of ice, water and sediment. This can result in highly variable rheological behaviours that can change rapidly over space and time.

This chapter provides an introduction to permafrost as encountered in both modern and ancient environments, which underpins any appreciation and understanding of its interactions with glaciers. The chapter focuses initially on the distinctive thermal and physical properties of permafrost (Section 2.2), before considering its formation within both subaerial and subglacial settings (Section 2.3), associated spatial and temporal variations in its extent (Section 2.4), and finally its complex rheological properties and behaviours (Section 2.5).

2.2 Thermal and Physical Properties

2.2.1 Defining Characteristics

Permafrost is defined as ‘ground (soil or rock and included ice or organic material) that remains at or below 0 °C for at least two consecutive years’ (International Permafrost Association, 2020). Its modern-day definition is therefore dependent solely on temperature and time in contrast to earlier definitions that used the term as an abbreviation for ‘permanently frozen ground’ (Muller, 1943) and which therefore inferred the presence of water in a frozen state as a defining characteristic.

Glacier–Permafrost Interactions, First Edition. Richard I. Waller.

When viewed as a purely thermal and temporal condition, permafrost can in theory encompass any type or combination of Earth surface materials. Dry bedrock can therefore be considered to be just as much a permafrost material as an ice-rich sediment or peat deposit. In considering this book's focus on glacier–permafrost interactions, it is important to note that glaciers and ice sheets can themselves be considered a subset of permafrost as they constitute Earth surface materials that have by definition been at or below 0 °C for a significant period of time. Whilst most cryospheric scientists would see permafrost and glaciers as separate entities, the ability to consider both as part of the same definition illustrates the shared attributes, processes and features that will become increasingly apparent both in this chapter and the book as a whole.

This commonality is particularly evident when one considers the physical composition of glaciers and permafrost which typically comprise varied mixtures of ice, sediment, water and air. Where glaciers occur in permafrost environments, the two can become virtually indistinguishable on account of their very similar compositions (Figure 2.1). This has resulted in some confusion within the literature as to whether such mixtures should be considered to be part of the glacier (i.e. basal ice) or part of the glacier bed (i.e. frozen subglacial sediment). In specific relation to the formation of ice-pushed ridges, Kupsch (1962) for example concluded that 'the permafrost layer in essence constituted the lower part of the glacier, the bottom of which was not the top of the bedrock but the lower limit of the ground ice sheet' (p591). This association is made most explicitly by Hughes (1973), who coined the term 'glacial permafrost' to refer to the 'regolith-charged basal ice layer of a glacier or ice sheet' (p213), thereby illustrating what at times are indivisible connections between glaciers and permafrost. Whilst this might appear to be a question of semantics, it does have broader implications. If some basal ice comprises pre-existing permafrost entrained by an overriding glacier (Waller *et al.*, 2000), then this highlights the importance of glacier–permafrost interactions for the processes of debris entrainment and basal ice formation (Section 3.5.4). It also has important implications for our conceptualisation of the location and nature of the ice-bed interface that is associated with a variety of influential dynamic and geomorphological processes (Section 3.5.5).

Although ice and liquid water are not defining features, they are commonly found within permafrost areas and are central to many of the more distinctive processes and landforms for which these environments are renowned. Therefore, in considering the properties of permafrost, it is vitally important at the outset to differentiate between the thermal condition of the substrate and the state of any constituent water. The terms 'cryotic' (0 °C) and 'non-cryotic' (>0 °C) are generally used within permafrost literature to refer explicitly to the thermal condition in relation to the freezing/melting point of pure water at atmospheric pressure. These terms differ from the more widely used terms 'frozen' and 'unfrozen' that refer to the state of any constituent water (e.g. Williams & Smith, 1989).

Unfortunately, these seemingly subtle yet fundamental distinctions between temperature and state are frequently conflated or ignored within published literature, leading to the simplistic assumption that the freezing and thawing of water in bedrock or sediments invariably occur at a single bulk freezing temperature (typically 0 °C or the pressure melting point when considering subglacial environments). If this were the case, then water-saturated substrates would in essence constitute a binary system displaying two distinct states separated by a clearly defined thermal threshold, i.e. unfrozen, weak and permeable

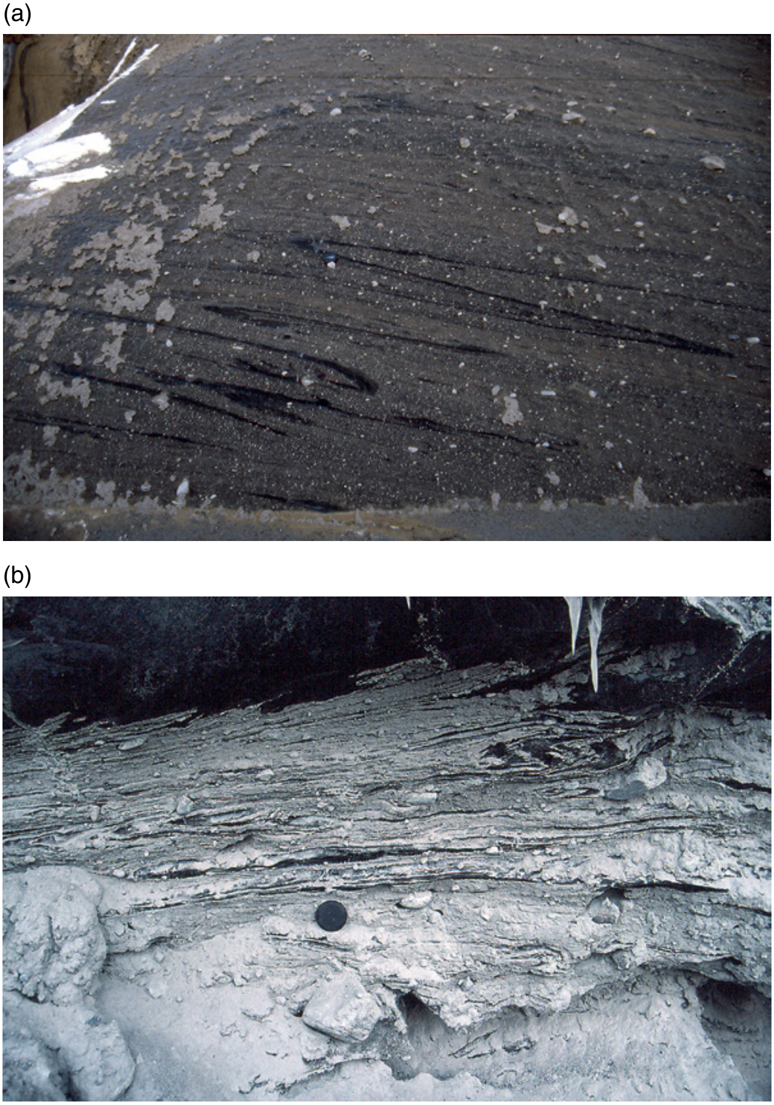

Figure 2.1 (a) Massive ground ice exposed at Mason Bay in the western Canadian Arctic and (b) basal ice exposed at the western margin of the Greenland Ice Sheet. Note the similar compositions in the form of folded debris laminations.

vs. frozen, rigid and impermeable. In reality, as discussed in more detail in the next section, the connection between the temperature of permafrost and the state of any water present is both highly complex and dynamic in nature. The thermal boundaries between cryotic/non-cryotic and frozen/unfrozen states can in fact differ by several degrees Celsius due to the freezing-point depression caused by a range of controls such as the presence of dissolved salts. Additionally, the freezing of water within permafrost substrates commonly occurs progressively over a broad range of temperatures rather than at a single temperature, resulting in a spectrum of states and behaviours rather than a convenient binary system with a clear boundary between frozen and unfrozen states.

The need to distinguish between temperature and state is illustrated for example by the concept of 'seasonally active permafrost', which is used to refer to a near-surface layer that seasonally thaws and which can be subject to mass movement but which remains cryotic and is therefore part of the permafrost layer. Similarly, a warm-based glacier could overlie entirely unfrozen ground with a temperature that exceeds the pressure melting point but is defined as permafrost as it has remained at or below 0 °C, in which case the presence of permafrost is of little consequence. The importance of this distinction has fundamental implications for the understanding of allied processes that will be explored further in Chapter 3 and consequently in relation to the hydrological and dynamic characteristics of glaciers in Chapter 4 and the generation of distinctive landforms, sediments and landscapes in Chapter 5.

2.2.2 Water in Permafrost

Permafrost frequently contains water as a liquid, a solid (ice) or in both states simultaneously. As such, permafrost can be 'unfrozen', 'partially frozen' or 'frozen' depending on the state of any water present. It is these variations in the presence, state and relative concentration of ice and liquid water that result in permafrozen substrates displaying such varied and complex behaviours, particularly in relation to their mechanical and rheological properties (Section 2.5). In contrast, if no water is present, the permafrost can be referred to as 'dry' and its characteristics are likely to be very similar to the non-cryotic substrates found in more temperate environments (French, 2017).

Water within porous media such as sediment and bedrock can occur in two forms: (i) 'bulk water' or 'free water' that occurs within the pore spaces and (ii) 'interfacial water' that occurs at the interfaces with ice or mineral particles for example. Pure bulk water at atmospheric pressure will freeze at 0 °C, which is therefore commonly considered to be the specific temperature at which changes in state occur. However, there are a number of factors that can result in a depression of the freezing point such that water can become 'supercooled' – in other words, remain in a liquid state at temperatures below the bulk freezing point. Within the context of glacial environments, glacier scientists have long appreciated that the freezing (and melting) point can be depressed beneath thick ice as a result of increasing confining pressures. Whilst the rate of freezing point depression with increasing pressure is relatively low (0.0074 °C per atmosphere), it can nevertheless lead to significant freezing point depressions under thick ice masses. Consequently, glaciological literature almost always refers to the pressure melting point rather than 0 °C as the temperature at which phase changes occur. For example, at the Byrd Station in Antarctica where the ice thickness is 2164 m (equating to 200 atmospheres), the pressure melting point at the base of the ice sheet is estimated to be −1.6 °C (Gow *et al.*, 1979).

The freezing temperature of bulk water can also be depressed through the addition of impurities. The addition of 2% by weight of sodium chloride for example will depress the freezing point by approximately 1 °C, and it is this influence that results in the widespread gritting of roads in countries such as the United Kingdom in order to prevent the formation of ice at cryotic temperatures (Davis, 2001). Within permafrost environments, the rejection of solutes during the freezing process can lead to the development of layers or lenses of highly mineralised porewater that form taliks or unfrozen zones within otherwise frozen substrates. Marine sediments in coastal permafrost environments commonly feature high levels of dissolved salts that can result in them containing significant amounts of unfrozen bulk water at cryotic temperatures. This can in turn compromise the structural integrity of buildings constructed in these settings. Site investigations associated with the construction of a coal mining facility in central Spitsbergen in an area characterised by marine clays with porewater salt contents of 60 g l^{-1} for example indicated that 40% of the porewater remained unfrozen in spite of a mean annual surface temperature of −6 °C (Gregersen *et al.*, 1983). A geomorphological consequence of the increased unfrozen water content of marine sediments is the predominance of push moraines on Svalbard below the Holocene marine limit, with these sediments facilitating the development of the décollement horizons required for the formation of these landforms (Etzelmüller *et al.*, 1996; see section 5.3.2 for more detail).

Whilst pressure and impurities can explain freezing-point depression, it is the influence of molecular forces associated with interfaces within ice–water–sediment mixtures that is central to explaining the ability of liquid water and ice to coexist at temperatures below 0 °C. It is this ability for liquid water and ice to coexist in varying fractions over a range of cryotic temperatures that is one of the most fundamental and distinctive attributes of many permafrost substrates and a key reason for their complex rheological behaviours (Section 2.5).

When the temperature drops below the bulk freezing point, the ‘free’ porewater is the first to freeze. As freezing continues, the remaining liquid water is confined to progressively smaller spaces between the mineral particles and the growing ice crystals such that it becomes increasingly subject to capillary effects (Figure 2.2). Capillarity is an effect associated with confined interfaces. It refers to the migration or suction of liquids within narrow spaces that results from the combined influence of adhesive forces between the water and the nearby solid surfaces and the surface tension of the liquid itself. The molecular attraction between

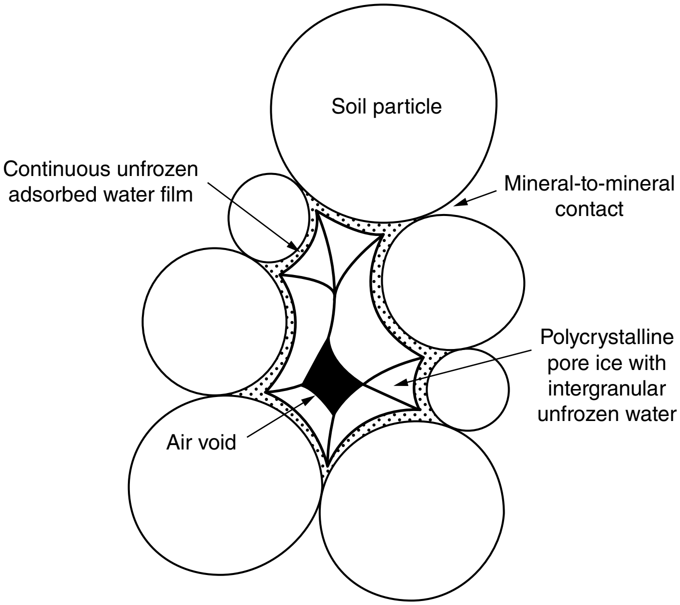

Figure 2.2 Key structural elements of a partially frozen, unconsolidated sediment (Williams & Smith, 1989/Cambridge University Press).

the water and the solid surfaces can also result in the water molecules adhering to the surface of constituent particles to produce thin, interfacial films through a process known as adsorption. Both capillarity and adsorption cause the free energy of the remaining liquid water to fall, resulting in a further depression of the freezing point such that progressively lower temperatures are required for the remaining unfrozen fraction to freeze. The associated development of free energy gradients within a substrate can result in the migration of water to areas of lower free energy that are typically the coldest regions. If these regions are associated with ice within the substrate, the combination of capillary effects and free-energy gradients can result in cryosuction and the migration of water to these ice lenses enabling their progressive growth within what are referred to as 'frost susceptible' substrates. This can however generate a negative feedback with the growth of ice within the capillaries reducing the hydraulic conductivity and limiting the flow of both water and heat (Watanabe & Flury, 2008). It is this bulk transfer of liquid of water within a 'frozen fringe' rather than the volumetric expansion of water upon freezing that is key to understanding the process of frost heave (Rempel, 2011) that is well known for its role in bedrock weathering in subaerial permafrost environments (e.g. Walder & Hallet, 1985; Murton *et al.*, 2006). As a further illustration of the complex process associations between glacial and permafrost environments, it is worth noting that the application of theories of frost heave to subglacial settings has provided new and novel insights into the processes of sediment entrainment beneath ice streams and in turn their dynamic behaviour (see Sections 3.5.4 and 4.3.3, respectively).

Ongoing research into frost heave within partially frozen porous media has further developed our understanding of the processes and circumstances in which unfrozen, or what is commonly referred to as 'pre-melted water', can persist at temperatures up to a few tens of degrees below the bulk freezing temperature (Dash *et al.*, 2006). The necessary depression of the freezing temperature occurs for two reasons (e.g. Rempel, 2007, 2010). First, curvature-induced pre-melting at a solid-melt interface (e.g. ice-water) that has a centre of curvature within the solid results in the development of supercooled water within the pore spaces. Second, interfacial pre-melting associated with the aforementioned molecular forces results in adhesion between the water and any constituent particles and the development of thin interfacial liquid films that encompass the particles. These films are typically only a few nanometres thick, although their thickness is temperature dependent with them becoming thinner as the temperature falls and vice versa.

These pre-melting effects result in porous substrates within permafrost regions displaying significant variations in the relative amounts of water and ice depending on both their temperature and their particle-size characteristics (Williams & Smith, 1989). The influence of interfacial effects within coarse-grained sediments such as sands and gravels is relatively minor. Most of the porewater is therefore bulk water that will tend to freeze rapidly once the temperature drops below the freezing point (Figure 2.3). Conversely, interfacial effects are much more pronounced in fine-grained materials in general and clays in particular, due to their high surface areas and the greater adhesive forces between the particles and the water molecules. As such, fine-grained sediments are capable of retaining significant quantities of unfrozen water content at temperatures well below the bulk freezing point.

A key point to note here is that fine-grained sediments can retain liquid water and therefore remain partially frozen over considerable cryotic temperature ranges. The bulk freezing point simply marks the temperature at which the freezing process can commence with the process continuing as temperatures fall further, resulting in a progressive change in the