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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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