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Invited review

Glacier–permafrost interactions: Processes, products and glaciological implications

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ABSTRACT

Glaciers and permafrost represent key components of the global cryosphere. Widely held assumptions that: (1) they are largely mutually exclusive and, (2) glaciers resting on permafrost are slow moving and geomorphologically ineffectual have meant that glacier–permafrost interactions have been given little attention within the research literature. Recent research, however, has demonstrated that such interactions are likely to have been more extensive than previously thought, particularly during periods of ice-sheet growth when glaciers would have advanced over pre-existing permafrost. Work in both modern and ancient environments has revealed that subglacial processes such as basal sliding and subglacial sediment deformation can remain active at temperatures below the pressure melting point due to the persistence of premelted liquid water. Consequently, cold-based glaciers resting on permafrost are potentially more dynamic than previously thought and are capable of creating subglacial features typically viewed as only forming beneath warm-based ice. In addition, the active coupling of cold-based ice with ice-marginal permafrost means such ice masses are capable of deforming sediments and occasionally bedrock to depths of tens or even hundreds of meters and are commonly associated with the development of a range of distinctive ice-marginal landforms including push or thrust moraines and hummocky or controlled moraines. This reflects the influence of permafrost on the entrainment of debris-rich basal ice as well as the hydraulic transmissivity of the groundwater system and the associated porewater pressures within the substrate.

This review considers the key characteristics of permafrost and its formation, likely extent and rheological behaviour within glacial environments. Traditional conceptions regarding the motion and landscape impact of cold-based glaciers resting on permafrost are considered before their re-examination in light of recent work demonstrating the operation of basal processes at sub-freezing temperatures. The implications for our understanding of the dynamics of glaciers and ice sheets as well as landforms and sedimentary sequences indicative of glacier–permafrost interactions are explored and exemplified with reference to modern and ancient glacial environments. Gaps in our existing knowledge are identified and profitable areas for future research suggested.

1. Introduction

Glacier–permafrost interactions have received limited research interest (Haeberli, 2005; Harris and Murton, 2005), because glaciers and permafrost have commonly been viewed as mutually exclusive, with substantial thicknesses of glacier ice insulating the substrate from the prevailing climate and the heat generated by basal processes rapidly degrading any permafrost present. In addition, where glaciers have been observed to overlie permafrost, the resulting cold-based ice is usually thought to preclude processes such as basal sliding and subglacial-sediment deformation. As these processes are associated with states of fast-ice flow and with active erosion and entrainment, cold-based glaciers are commonly regarded as slow moving and geomorphologically inactive. Finally, glacial geomorphologists and geologists have tended to study areas glaciated by warm-based ice or characterized by hard bedrock, for example the Fennoscandian and Canadian shields. Consequently, they have seldom considered the interaction of cold-based Pleistocene glaciers with permafrozen sediments that underlie vast areas of western Siberia and Arctic Canada (Brown et al., 1997).

In recent decades, there has been a small but growing recognition that glaciers and permafrost sometimes interact to a significant degree. Whilst the extent of permafrost beneath large ice masses may be limited during steady-state conditions, field observations and numerical modeling experiments have demonstrated that the spatial extent of glacier–permafrost interactions is generally greatest during periods of ice advance, when pre-existing permafrost is overridden and persists for significant periods due to its thermal inertia (Mathews and Mackay, 1960; Cutler et al., 2000). Field observations

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in both modern and ancient cold environments have also demonstrated the ability for basal processes to remain active at subfreezing temperatures and thereby to influence glacier dynamics and their geomorphological and geological impacts (see Waller, 2001).

This paper reviews the processes, products and wider implications of glacier–permafrost interactions, particularly in terms of their geomorphological and sedimentological expression in lowland regions, where glacially-deformed sedimentary sequences are most likely to be preserved in the geological record. Section 2 considers the key characteristics of permafrost within modern and ancient glacial environments, the rheology of permafrost sequences, and the geographical and temporal extent of glacier–permafrost interactions. Section 3 discusses the processes and products of glacier–permafrost interactions in both subglacial and proglacial environments, issues that are illustrated through three case studies in Section 4. Finally, Sections 5 and 6 identify areas of limited understanding and outstanding research questions. Glacier–permafrost interactions in mountain environments, beyond the scope of this paper, are reviewed by Haeberli (2005) and Etzelmüller and Hagen (2005). Rock glaciers, a distinctive feature indicative of glacier–permafrost interactions in mountains, are reviewed by Haeberli et al. (2006).

2. Permafrost in modern and ancient glacial environments

2.1. Thermal and physical properties

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, 2010). This definition is therefore based on temperature and time, which is more precise than its original definition as "perennially-frozen ground" (Muller, 1943). Whilst glaciers and ice sheets are ordinarily regarded as separate entities within the cryosphere, some authors consider them a subset of permafrost as they fulfill the definition outlined above (Hughes, 1973).

Because permafrost frequently contains water, either as a liquid or a solid (ice), it is important to differentiate between its temperature and state. The temperature-related terms "cryotic" (≤ 0 °C) and "non-cryotic" (>0 °C) frequently employed in permafrost literature complement the more widely used terms "frozen" and "unfrozen" that refer to the state of any constituent water (e.g. Williams and Smith, 1989). Significantly, the thermal boundaries between cryotic/non-cryotic and frozen/unfrozen can differ by a few degrees Celsius, because the temperature at which ice starts to nucleate in porous media can be lowered by dissolved salts and pressure melting. Consequently, a warm-based glacier could overlie entirely unfrozen ground which is above the pressure melting point but which is defined as permafrost as it has remained ≤ 0 °C. In this case, the presence of permafrost is of limited consequence.

Liquid water and ice can also remain in equilibrium at temperatures below 0 °C. Such liquid can be referred to as "premelted" (Dash et al., 2006), and the process of premelting within a porous media such as sediment or bedrock occurs for two reasons (Rempel et al., 2004; Rempel, 2011). (1) *Curvature-induced premelting* occurs where the equilibrium freezing temperature is depressed at a solid-melt interface whose centre of curvature is in the solid (i.e. the ice interface is convex outwards); the result is supercooled pore water. (2) *Interfacial premelting* occurs where long-range (van der Waals and electrostatic) intermolecular forces between different materials and phases cause melt at free surfaces and at interfaces in contact with another material; the result is unfrozen liquid films, usually nanometres thick, that separate soil particles. This occurs along flat interfaces and along concave interfaces that separate the ice lens from soil particles directly beneath. It is these thin films that facilitate liquid transport and ice segregation at sub-zero temperatures.

As cold ice-cemented soil warms (e.g. from −15 °C or −10 °C), the liquid water content progressively increases as the premelted films of liquid water thicken at the expense of the ice substrate. At such cold temperatures, the liquid water in the premelted films dominates the total liquid fraction of the soil. But as the soil warms to within approximately 1 to 2 °C of the melting temperature of ice, the liquid water content is increasingly supplemented by supercooled pore water, which dominates the total liquid fraction present near the melting temperature of ice. Further discussion about the temperature-dependency of ice and liquid water in soil is given by Williams and Smith (1989), and recent summaries of premelting microphysics in porous media are provided by Rempel et al. (2004), Dash et al. (2006) and Rempel (2007, 2010, 2011). What is particularly significant to the discussion here is that ice-bearing permafrost, especially that in silt-clay soils or fine-grained porous bedrocks, tends not to be fully frozen but instead is partially frozen, especially where the permafrost is warm, i.e. within just a few degrees of 0 °C.

The equilibrium depth of permafrost (z_p) can be determined according to the long-term mean annual ground surface temperature (T_s) and the geothermal gradient, which is in turn controlled by the heat flux (Q_G) and the thermal conductivity of the substrate (K) (Williams and Smith, 1989):

$$z_p = T_s \cdot K/Q_G$$

This equation indicates that under steady-state conditions, the thermal conductivity of the substrate is equally as important as surface temperatures in determining permafrost thickness, with thick permafrost promoted by low surface temperatures, low heat flow and high thermal conductivity. In practice, permafrost thickness is complicated by additional factors, most notably the geological history and the presence of ice and water close to their phase transition temperature. The presence and state of water can significantly modify the thermal conductivity of a material, an influence further complicated by the volume fraction of ice and liquid water being itself temperature-dependent. In addition, the high heat capacity of water and the release of latent heat on freezing can substantially slow the rate of permafrost aggradation. Finally, temperature gradients in frozen sediments drive the migration of unfrozen water which results in additional heat fluxes. Recent summaries of the thermal regime of permafrost are provided by Burn (2004, 2007) and French (2007).

Most permafrost is sub-aerial in origin. But it can also grow and persist beneath shallow rivers and lakes and within submarine and subglacial environments so long as the interface between the permafrost and overlying medium remains cryotic for over two years. In glacial environments, this boundary condition indicates that subglacial permafrost ordinarily underlies cold-based ice, where the temperature of the basal ice is below the pressure melting point. As pure ice has a substantially higher thermal conductivity than snow (Williams and Smith, 1989), cryotic temperatures and ground ice within subglacial permafrost can be maintained beneath substantial ice thicknesses. For example, beneath 1375 m of the Greenland Ice Sheet at Camp Century, a basal ice temperature of −13 °C has been recorded (Herron and Langway, 1979). Beneath warm-based ice, the heat flux associated with both active basal processes (i.e. sliding and sediment deformation) and production of large volumes of meltwater are usually considered inimical to the survival of permafrost.

The properties of the substrate along with the availability of water sources determine the amount and type of "ground ice" present. Ground ice can be defined as ice within frozen or partly-frozen ground, irrespective of the form of occurrence or origin of the ice. Ground ice can be an important component of permafrost. It occurs in highly variable amounts and takes numerous forms that can be described and classified in terms of cryostructure, cryofacies and ice contacts (French and Shur, 2010). Ground ice originates via a variety of processes, some of which take place within pre-existing sediments,