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Super slippery surface concepts: A novel explanation for the dynamics and flow instability of glaciers and ice sheets

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Abstract

The driving mechanisms of glacier fast flow and the cyclical instability inherent in ice streams and surging glaciers are not fully understood. Current theories suggest fast flow is driven by glacier sliding and basal deformation facilitated by water at the ice–bed interface and/or the presence of weak till. However, the wettability of sediments and the physics driving these sediment–water interactions have yet to be fully explored. Here, we review recent work on superhydrophobicity, hydrophobic soils and lubricated surfaces, and bring together aspects of materials science, biophysics and geoscience, to propose three modes by which a subglacial environment could become super slippery. Those modes are via (i) hydrophobic chemistry, (ii) microbial biofilms or (iii) the incorporation of oil. We then hypothesise how ice flow on super slippery sediments would result in enhanced sliding and deformation by introducing or increasing a lubricated interface and/or creating zones of sediment weakness and instability. We propose that future research should further explore this potential paradigm to soft bed deformation and sliding.

1. Introduction

Instability in glacial systems describes the unpredictable behaviour and sometimes erratic changes in ice sheets and glaciers during ice streaming and surging. Interest in fast flow and instability has increased in recent years due to their importance for predicting and estimating glacier and ice sheet response to a changing climate (Bennett, 2003; Kjær and others, 2006; Nuth and others, 2019). The mechanisms behind fast flow and instability are driven by subglacial processes, sliding and basal deformation, making understanding and characterising conditions at the ice–bed interface key to constraining this erratic behaviour (Fig. 1) (Boulton and Hindmarsh, 1987; Fischer and Clarke, 2001; Kjær and others, 2006).

However, some of these instabilities and fast flow conditions have been difficult to predict with current theory. For example, the instability observed in surging glaciers around the world cannot be explained in a unified way by (i) the hydrological switch model (e.g. Kamb and others, 1985, Kamb, 1987), (ii) the thermal switch model (e.g. Robin, 1955; Murray and others, 2000; Sevestre and others, 2015) nor (iii) the enthalpy balance model (e.g. Benn and others, 2019a, 2019b, 2023), suggesting there are a number of factors at play that are still to be fully considered. A single surge theory becomes increasingly difficult when we are also made to consider friction laws and hydrology of most glacial systems (Benn and others, 2023). This is particularly the case where soft-bed dynamics could be driving parts of the surge mechanism. In larger ice sheets, ice stream flow is also heterogeneous, showing degrees of instability with flow speeds varying over spatial and temporal scales (Stokes and others, 2007). Ice stream instability takes the form of 'switch on' and 'switch off' events, as well as changes to ice stream positioning (Conway and others, 2002; Joughin and others, 2004; Dowdeswell and others, 2006; Ó Cofaigh and others, 2010; Winsborrow and others, 2010). There are a number of possible mechanisms for this, from topographic controls (e.g. McIntyre, 1985) the presence of sticky spots caused by bedrock bumps (e.g. Schoof, 2002; McKenzie and others, 2023), an absence of till (e.g. Alley, 1993; Ashmore and others, 2014), well-drained till (e.g. Anandakrishnan and Bentley, 1993; Anandakrishnan and Alley, 1994; Boulton and others, 2001; Ashmore and others, 2014) and localised freeze-on (e.g. Anandakrishnan and Alley, 1997; Vogel and others, 2005; Stokes and others, 2007).

However, one factor that has remained difficult to observe and parametrise in our existing theories is the micro- and macro-scale sedimentological properties of the till (Kyrke-Smith and others, 2018; Narloch and others, 2020). The complex nature of sediment and sediment interactions at a micro-scale means that even in a 'simple' homogeneous till model basal deformation and sediment failure could occur through grain boundary sliding, rolling and larger granular flows (Fowler, 2003; Minchew and Meyer, 2020). Furthermore, the interface physics of wettability, a recently rapidly developing field of surface physics (e.g. Lafuma and Quéré, 2003;
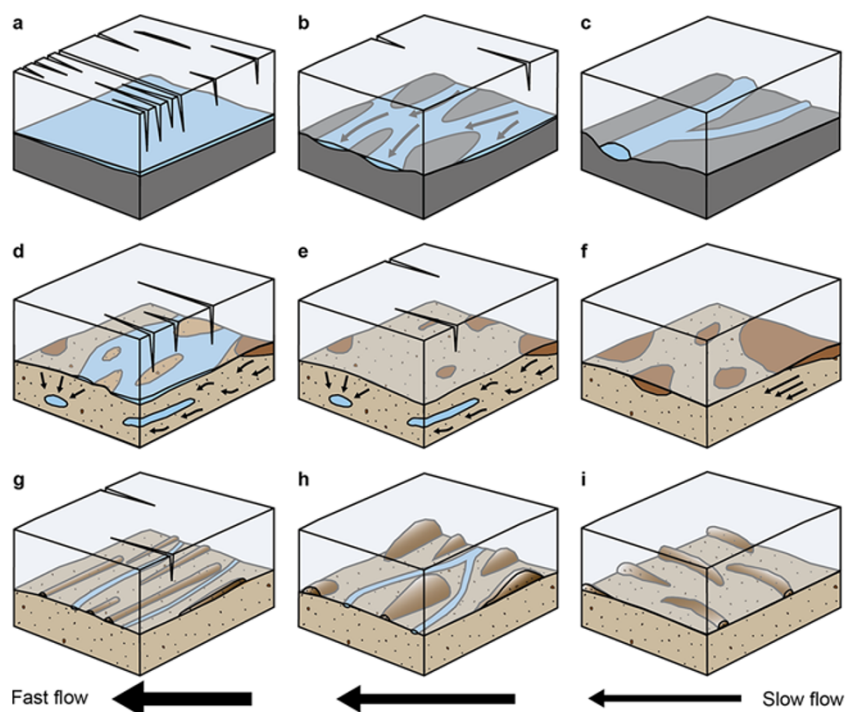
Figure 1. Transitions between slow and fast ice flow driven by basal deformation and basal sliding due to changes in subglacial hydrology and roughness. (a) Transition between inefficient sheet flow promoting fast ice flow, to (b) a system of more efficient connected channels, to (c) a fully channelised system resulting in slow ice flow. (d) Transition between highly deformable oversaturated till with high pore water pressure promoting fast flow, to (e) a reduction in water pressure and stiffening of till, to (f) an unsaturated stiff till resulting in slow ice flow. (i-h) n ice sheets and ice streams, large macro-scale roughness with large and/or transverse perturbations dominates in interior slow flow regions. (j) Further downstream areas of low macro-scale roughness promote fast flow resulting in the formation of more linear streamlined bedforms.

Quéré, 2008; Gao and Yan, 2009; Nosonovsky, 2011; McHale and others, 2020) has rarely been considered in glacial environments. We propose that expanding our considerations of potential mechanisms driving fast glacier flow may help to explain some fast flow, surging and ice streaming observations.

In both materials science and sedimentology, it is widely understood that the interaction of water with a surface or substrate is dependent on two distinct properties, (i) the physical properties (roughness, texture or porosity) and (ii) the wetting properties (the extent of hydrophobicity or hydrophilicity) (Cassie and Baxter, 1944; de Gennes, 1985; Adamson and Gast, 1997; Quéré, 2008; Shirtcliffe and others, 2010). In extreme cases, hydrophobicity in combination with surface roughness or porosity can create super slippery surfaces, such as superhydrophobicity where air acts as a lubricant (Barthlott and Neinhuis, 1997; Neinhuis and Barthlott, 1997). Alternatively, surface roughness or porosity may be impregnated by a lubricant liquid to create a slippery liquid-infused porous surfaces (SLIPS) (Lafuma and Quéré, 2011; Wong and others, 2011). In these cases, extreme water-repellent and water-shedding surfaces can be created (Fig. 2) (McHale and others, 2020).

Superhydrophobicity in sediments has been proposed by McHale and others (2005, 2007) and Shirtcliffe and others (2010). It has also been physically modelled by McCerery and others (2021), which demonstrated the formation of air plastrons between individual sediment particles supporting water droplets and enhancing water-shedding abilities. It has also been observed that a finer particle size sediment will exhibit more extreme hydrophobicity with the potential for superhydrophobicity and SLIPS on fine-silt size particles (Hamlett and others, 2011; McCerery and others, 2021). Previous works on fluvial and marine sediments containing microbial biofilms have also shown improved abilities to buffer shear stresses compared to biofilm-free sediments as they behave as an elastic membrane (Vignaga and others, 2013; Chen and others, 2017).

Here, we review the current literature on sediment wettability and super slippery surfaces and we use this knowledge to suggest a series of possible models by which glacial sediment could become super slippery in the context of grain size, geochemistry, oil mobilisation and microbial action. By investigating each of these in turn, and collectively, we propose a novel way to explain observable instability in some glaciers and ice sheets. It is important to note that we do not set out to apply this to all fast-flowing ice, or all glaciers that experience flow instability. We do propose new ways by which till could inherit slipperiness properties and provide theoretical models for the consequences on flow behaviour and suggest this warrants further consideration and field investigation.

2. Mechanisms for super slipperiness in glacial systems

Here we focus on two types of super slippery surfaces that could exist in sediments and glacial tills: superhydrophobicity and SLIPS. Each mechanism uniquely alters the proportion of the solid–liquid interface using air or liquid lubrication to enhance water shedding.

2.1. Sediment grain sizes

A necessary condition for super slipperiness in sediments is an appropriate grain size and shape. Physical modelling by McCerery and others (2021) showed that the ideal grain size to meet the material physics definitions of super slipperiness was clay-silt sized particles, although extreme water repellence was also observed on sand grain sizes (Fig. 2a–c). The smaller particle sizes are able to support super slipperiness through the enhanced roughness structure and the optimally sized gaps between individual particles which reduce the solid–liquid contact. In direct soil systems studies, it has been demonstrated that sand-sized grains are optimal for inducing hydrophobic properties, however this is mainly associated with the supply of the hydrophobic geochemistry and reduced

Figure 2. Hydrophobic slippery liquid-infused porous surfaces (SLIPS) strategies to create slippery surfaces in sediments: (a, b) Hydrophobic strategy initiated by high aspect ratio roughness/texture with hydrophobic solids to reduce liquid–solid contact. (c) Corresponding photograph of a droplet on clay-silt sized particles with a hydrophobic geochemistry. (a–d) SLIPS strategy initiated by the introduction of a lubricant such as oil or biofilm into the surface roughness/texture to convert to liquid–lubricant/solid or liquid–lubricant contact. (e) Corresponding photograph of a droplet on a clay-silt sized particle with a hydrophobic geochemistry and oil impregnation.
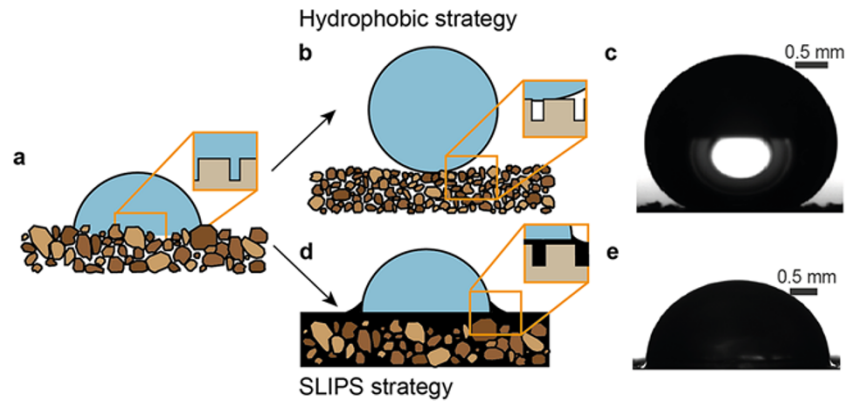
surface area of sand-sized particles as opposed to finer particle sizes being less hydrophobic (e.g. Doerr and others, 1996, 2007; de Jonge and others, 1999; McHale and others, 2007).

In glacial systems, these grain sizes are provided by glacial erosion of the underlying substrate. The evolution of till through the subglacial system exposes rocks and sediments to repeated abrasion and shearing processes constantly resupplying fines to the ice–bed interface (Hooke and Iverson, 1995; Altuhafi and Baudet, 2011). This constant resupply means there is often freshly eroded material within the grain size range of clay-silt and sand sized particles that can exhibit super slipperiness under the right conditions.

2.2. Inherited hydrophobic geochemistry

One possible mechanism for creating super slipperiness at the glacier bed is through inherited historic processes creating hydrophobic chemistry in sediments prior to glaciation. Hydrophobicity can be induced though chemical coatings on sediments from organic matter (Doerr and others, 2007; Hallett, 2007; Mao and others, 2016) and/or deposition of volatile organic compounds from wildfires (DeBano and Krammes, 1966; Doerr and others, 2006). The presence of organic compounds and their inherent hydrophobic properties also extends into sediments originating from organic-rich sedimentary rocks such as shales and coals which are rich in preserved organic material (Hedges and Keil, 1995; Cai and others, 2023).

The type or style of sediment failure associated with hydrophobicity in soils and sediments is also partly controlled by where in the soil or sediment profile the hydrophobicity occurs. During a rainfall event, where the hydrophobicity is buried beneath a wettable layer, the surface sediment will become oversaturated as water is not able to percolate past the hydrophobic layer (Gabet, 2003; Parise and Cannon, 2012). This results in discrete mobilisation of the oversaturated material forming a discrete shallow landslide and debris flows (Parise and Cannon, 2012). Where a hydrophobic layer is present on the surface of the soil, rainwater erosion of the material results in increased rilling and sheet-wash (Parise and Cannon, 2012). This has the potential to initiate large debris flows from continued sediment entrainment and incorporation into water (Parise and Cannon, 2012; Wall and others, 2020).

Wildfires frequently occur in Arctic shrub tundra and boreal forests (Higuera and others, 2008; Rocha and others, 2012; Dietze and others, 2020). Furthermore, rapid changes in climate (common in glacial-interglacial transitions), can influence wildfire frequency by affecting (i) the frequency and intensity of precipitation, (ii) changes in spring and summer temperatures and (iii)

the amount of biomass available for burning (Marlon and others, 2009). Changes in fire frequency are observed in charcoal records from the most recent interglacial transition (15–10 ka) in North America and show an increase in wildfires during the most abrupt shifts in climate (Marlon and others, 2009). This would have created hydrophobic coatings in sediments at glacial margins during interglacial periods. Hydrophobicity within glacial sediments could therefore occur at the surface during glacier advance or be buried beneath more wettable sediments and re-exposed during glacial erosion. This may explain some of the surging glacier lobes at the margins of former ice sheets such as the Laurentide Ice Sheet and the Barents-Kara Ice Sheet, where the margins were underlain by permafrost sediments, which are likely to have wildfire coatings and some degree of inherited hydrophobicity.

2.3. Oil contamination and mobilisation

The second possible mechanism of slipperiness at the glacier bed is through oil contamination and mobilisation. The hydrocarbons present in oil and gas deposits can create a hydrophobic chemistry and in the fluid form they also create a lubricating layer immiscible to water acting as a SLIPS. Hydrocarbons can enter the environment as one-off events, or through the action of repeated glaciations. Hydrocarbon presence is common in large sedimentary basins, such as the North Sea and Barents Sea with isostatic changes caused by the Eurasian Ice Sheet Complex, resulting in the re-routing of hydrocarbon pathways and natural hydrocarbon spillages (Zieba and Grøver, 2016; Fjeldskaar and Amantov, 2018; Løtveit and others, 2019; Cathles and Fjeldskaar, 2020). Oil may also enter the ice–bed interface through glacial erosion, exposing oils within sedimentary basins. It is thought that one of the most important events leading to the development of surface oil deposits in the Athabasca region of Alberta, Canada, was glacial erosion, and glacial lake drainage which eroded and mobilised oil sands deposits (Paragon Soils and Environmental Consulting, 2006). Previous work has indicated that glacial erosion by the Laurentide Ice Sheet not only exposed oil deposits at the original source but that glacial erosion also mobilised oil sands materials—as they are present in glacial tills south of their original source in northern Alberta (e.g. Andriashek and Pawlowicz, 2002; Paragon Soils and Environmental Consulting, 2006; Andriashek, 2018; McCerery and others, 2023, 2024). This suggests that glacially mobilised oil may be widespread, at the ice–bed interface, particularly in areas that have oil deposits close to the surface and/or in regions which have experienced substantial isostatic change and resultant re-working and remobilisation of sediments.

2.4. Microbial action

A third possible mechanism of hydrophobicity at the glacier bed is through the action of certain microbes and their biofilms. Whilst some components of biofilms are hydrophilic, others can also exhibit hydrophobic properties (Rosenberg and others, 1980), and communities can respond to environmental stress by creating hydrophobic compounds such as extracellular polymeric substances (Seaton and others, 2019). In large enough quantities, biofilms can also give rise to bio-clogging in porous surfaces (Lee and others, 2019). In these cases, the cohesive nature and accumulation of biofilm in pores results in the lowering of the permeability of a surface or sediment (Lee and others, 2019; Gerbersdorf and others, 2020). This is particularly true in finer grained sediments where biofilms generate a less erodible, smoother sediment with lower hydraulic roughness (Gerbersdorf and others, 2020).

The subglacial zone is a low biomass environment (i.e. Skidmore and others, 2005; Kaštovská and others, 2007; Boetius and others, 2015), and thus such a hydrophobic mechanism may be rare. However, any developed hydrophobicity would impact the slipperiness of the surface, as well as the wettability and roughness properties of the glacier bed, changing the proportion of sliding at the ice–bed interface and the amount of basal deformation occurring in the system.

3. Potential implications of super slipperiness in glacial systems

3.1. Hydrophobic sediment

Previous research on soil–water interactions demonstrates that a reduction in the wettability of a sediment results in a reduction in the total water storage and runoff acceleration (Chau and others, 2014; Zheng and others, 2017; Müller and others, 2018). In the glacial environment, this physical process could result in lower till permeability and infiltration, leading to water pooling at the ice–bed interface. Where particle sizes are sufficiently small there is also potential for the formation of superhydrophobicity whereby pockets of air between the sediment particles acts as a lubricating interface. In cases where the till is fully saturated with all solid surfaces completely wetted and air–water–solid three-phase contact lines, superhydrophobicity could not occur. A layer of low wettability sediment will have different implications on glacier flow depending on where in the till profile the hydrophobicity occurs.

Where low wettability till occurs at the ice–bed interface (Fig. 3a–c), water infiltration into the sediment below would be impeded. With consistent delivery of water to the bed and little opportunity for infiltration, an increase in basal water pressure will occur as the water cannot be drained efficiently and ice–bed decoupling, and enhanced glacier sliding will ensue. This model also builds upon the scientific understanding of fast ice flow driven by a thin film of water at the ice–bed interface (e.g. Weertman, 1957, 1964, 1979; Bindschadler, 1983; Alley, 1989; Piotrowski and Tulaczyk, 1999), which, as shown here, can occur on soft beds with an appropriate hydrophobic chemistry without the need for a fully saturated or hard glacier bed.

A hydrophobic sediment could also occur within the till profile, buried beneath a more wettable material (as shown in Fig. 3d–f). By preventing infiltration further into the till profile oversaturation of the wettable till at the ice–bed interface would occur. If the till is strongly coupled to the ice, the till will weaken and begin to deform. The hydrophobic sediment would then also create a physical barrier preventing more pervasive deformation, thus

concentrating weak till at the ice–bed interface. A not dissimilar mechanism has been suggested as the driving process for surging activity at Bakaninbreen, Svalbard by Murray and others (2000) and Smith and others (2002), where the impermeable layer at the ice–bed interface is permafrost. It is also possible that multiple layers of hydrophobic chemistry exist in a till profile as the result of changes within and between glacial and interglacial cycles. During these cycles multiple layers of buried hydrophobic chemistry could occur, producing zones of weakness and slip between till layers, rather than slip only occurring directly at the ice–bed interface.

3.2. Sediment-SLIPS

Previous work by McCerery and others (2023) first outlined the implications of an oil at the ice–bed interface on glacial flow, from geochemical evidence of glacially mobilised oil sands deposits in Alberta, Canada, using two models of a sediment-SLIPS. In the macro-scale model, an immiscible working fluid and lubricating fluid create a slippery interface, and in the micro-scale model, the liquid-liquid interface occurs between individual sediment grains, which under pressure, would create a hypermobile slurry of sediments, oil, and water. We note that this could also apply to the formation of biofilms creating a quasi-liquid lubricated substrate.

In the macro-scale model, enhanced slip at the ice–bed interface is most analogous to the classic *Nepenthes* pitcher plant style of SLIPS described by Bauer and Federle (2009), Wang and others (2015) and Yong and others (2017). As the bed is infused with a lubricant, sliding may be initiated at lower basal water pressure than is required for ice–bed decoupling. Furthermore, sliding over the lubricated substrate will limit laterally extensive basal deformation. Where the lubricant (be it oil or biofilm) is less viscous (and potentially hardened), it could act as an impermeable seal, impeding drainage. As water is not able to efficiently drain into the till in this instance, it will pool at the ice–bed interface and increase basal water pressure. This would result in more rapid ice–bed decoupling than would be expected for a soft bed.

In the micro-scale SLIPS model (Fig. 3g–i), the hypermobile slurry could induce a style of basal deformation similar to the ideas of icequake-induced till liquefaction. In icequake-induced till liquefaction first proposed by Phillips and others (2018), the sudden delivery of energy to the saturated till causes an increase in intergranular pore water pressure. This results in reduced sediment cohesion; allowing grains to move over one another easily and thus deforming in a transient liquefied state (Phillips and others, 2018).

### 3.3. Spatial and temporal sediment instability

For any of the slipperiness mechanisms we outline above to establish in sediments, a number of conditions must be met in the system (i) the particle sizes of the till must be small enough (fine sand to clay dominated) to support a micro-scale roughness; (ii) he subglacial hydrology must achieve a balance between a steady stream of water (to lubricate the bed) but not too dynamic a water flow as to destroy or remove the lubricating agent, i.e. the biofilm or hydrophobic chemistry; and (iii) the lubricating interface or hydrophobic chemistry/biology must be immiscible to water (for SLIPS) and the subglacial sediment must be preferentially wetted by one of the liquids. Furthermore, as the subglacial zone has been shown to be a low biomass environment (i.e. Skidmore and others, 2005; Kaštovská and others, 2007; Boetius and others, 2015), it may be unable to grow or sustain a thick biofilm. With these constraints, the slipperiness mechanisms we describe may be both spatially
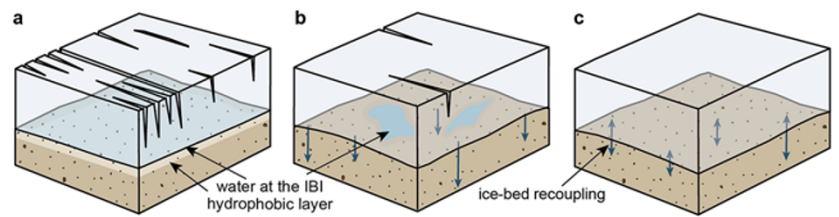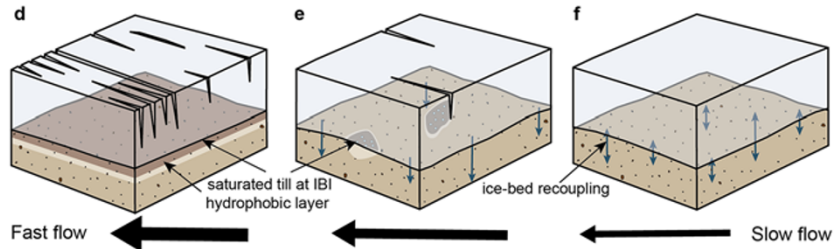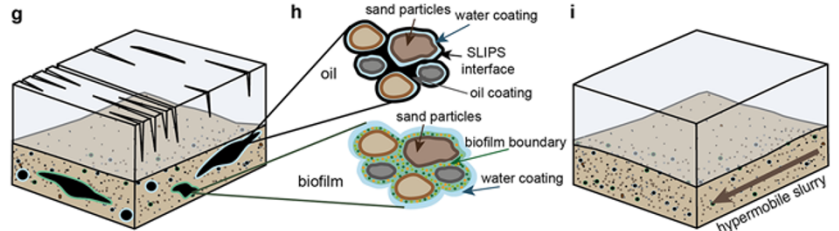
Figure 3. Schematic diagram of the hypothesised hydrophobic and slippery liquid-infused porous surfaces (SLIPS) scenarios at the glacier bed. In the first model of hydrophobicity, (a–c) a hydrophobic sediment layer at the ice–bed interface impedes water infiltration and enhances basal sliding through ice–bed decoupling. The gradual degradation of the hydrophobic layer results in resumed infiltration and a recoupling of the ice and bed. Alternatively, if the hydrophobic sediment layer occurs within the till profile, (d–f) an oversaturated sediment would form at the ice–bed interface. This would result in a thin layer of enhanced basal deformation, before complete degradation of the hydrophobic layer results in resumed infiltration further down the till profile and a reduction in the degree of basal deformation. In a SLIPS system facilitated by oil or biofilms, (g–i) sediment particles can create a water–oil interface or a slippery biofilm interface between the individual sediment particles. Under the pressure of overlying ice the sediment bed would be able to deform, generating a hypermobile slurry through the creation of a SLIPS between the individual grains (figure adapted from McCerery and others, 2023).

(i.e. where the location of slipperiness may change in a system) and temporally (i.e. erosion of slipperiness properties or reestablishment such as the cyclical growth and destruction of biofilm surfaces) rare. Where all of the necessary conditions are met, these processes could explain the occurrence and spatial heterogeneity of past or present unstable and/or fast flow regimes, particularly in areas where current theories cannot account for observations and records of enhanced flow.

Due to the micro-scale-level nature of slipperiness in sediments, it is likely that multiple factors combine, and that in large glacial systems there will also be other drivers of instability contributing to fast flow. For example, in surging glaciers any single or combination of existing mechanisms could be driving a glacier towards fast or unstable flow and the geochemistry or microbiology of the sediment could then be acting as the either the starting point or final tipping point to achieve fast and unstable conditions. In the case of ice streams, the presence of slippery or super slippery sediments could account for localised slippery spots.

The stability of these super slippery properties is an important consideration if we are to apply these theories to a highly pressurised and dynamic system such as the subglacial environment. Research in materials, soils science and hydrology has shown that during prolonged wetting hydrophobicity is degraded and the material will eventually become wettable, then after drying the hydrophobic state is reinitiated (Quyum and others, 2002; Lourenço and others, 2015). This suggests that chemical hydrophobicity may be short lived in subglacial systems and could occur unpredictably, particularly where the overburden pressure of the ice could force wetting of the hydrophobic grains. Conversely in the SLIPS model, these surfaces are typically more stable and retain their super slippery properties for longer and over more harsh

erosive conditions. This is evident in soil contamination research where water repellence post-oil spill persists for decades (e.g. Roy and McGill, 1998; Roy and others, 1999).

3.4. Till microstructure and morphology

A further consideration is the impact super slipperiness would have on the microstructures of deformed tills. Laboratory experimentation suggests till microstructures are influenced by ice velocity, water and clay content, deposition of carbonates and clay minerology (van der Meer and others, 2003). It is likely that the geochemistry and/or biophysics of the sediments and the resulting impact on interface physics between particles may influence till microstructures. For example, transient episodes of till dilation caused by changes in pore water pressure and effective pressure, results in shearing micromorphology in the till profile (e.g. Minchew and Meyer, 2020; Warburton and others, 2023). The processes that we hypothesise here could induce a similar effect where heterogeneous changes in the geochemical and/or biophysical properties within the till profile, both vertically and horizontally may generate and/or contribute to the existence of the stick-slip phenomena seen in studies by Phillips and others (2018) and Phillips and Piotrowski (2023).

The detection of super slipperiness inducing compounds in the Central Alberta Ice Stream in Alberta, Canada, also coincides with evidence of soft bed subglacial deformation (McCerery and others, 2023, 2024). This suggests the geomorphological impact of such sediment properties may fit our current observations. Thus, there may also be a micromorphological signature or signatures associated with the geochemical and/or biophysical properties of

sediments that can be detected in the sediment record. We therefore propose that further investigation into the biophysics, geochemistry and micromorphology of till in places where instability and/or fast flow occurs or has been known to have occurred should be investigated.

4. Conclusions and future challenges

Models of enhanced flow (generated by micro-scale processes occurring at the ice–bed interface) proposed in this paper highlight the importance of considering sediment geochemistry and microbiology in glaciated environments. This paper has presented the potential chemical, biological and physical processes occurring in subglacial sediment that could drive some fast flow and instability in contemporary and palaeo ice sheets and glaciers. We hypothesise that the necessary conditions for slipperiness in the context of interface physics could occur in glacial systems. We do not suggest that these conditions will be extensive, in fact, in most cases the theory of slippery surfaces is not required to explain observed fast flow. We do propose that where appropriate conditions occur, slipperiness will be an important contributor to fast and unstable flow—which may vary spatially (i.e. where the location of slipperiness may change in a system) and temporally (i.e. erosion of slipperiness properties or reestablishment such as the cyclical growth and destruction of biofilm surfaces). This novel approach therefore requires future work to fully understand and predict where slippery surfaces occur in glacial systems.

References

Adamson AW, and Gast AP (1997) *Physical Chemistry of Surfaces*, 6th edn. New Jersey, U.S.: Wiley.

Alley RB (1989) Water-pressure coupling of sliding and bed deformation: I. Water system. *Journal of Glaciology* **35**(119), 108–118. doi:10.3189/002214389793701527

Alley RB (1993) In search of ice-stream sticky spots. *Journal of Glaciology* **39**(133), 447–454. doi:10.1017/S0022143000016336

Altuhafi F and Baudet BA (2011) A hypothesis on the relative roles of crushing and abrasion in the mechanical genesis of a glacial sediment. *Engineering Geology* **120**(1-4), 1–9. doi:10.1016/j.enggeo.2011.03.002

Anandakrishnan S and Alley RB (1994) Ice Stream C, Antarctica, sticky spots detected by microearthquake monitoring. *Annals of Glaciology* **20**, 183–186. doi:10.3189/1994AoG20-1-183-186

Anandakrishnan S and Alley RB (1997) Stagnation of Ice Stream C, West Antarctica by water piracy. *Journal of Geophysical Research Letters* **24**(3), 265–268. doi:10.1029/96GL04016

Anandakrishnan S and Bentley CR (1993) Micro-earthquakes beneath Ice Streams B and C, West Antarctica: Observations and implications. *Journal of Glaciology* **39**(133), 455–462. doi:10.3189/S0022143000016348

Andriashek L (2018) On the Origin of Oil Sand and Related Bedrock Erratics in Glacial Sediments of Central Alberta, *Technical report: Alberta Energy Regulator and Alberta Geological Survey*, AER/AGS Open File Report 2018-13.

Andriashek L and Pawlowicz J (2002) Observations of Naturally Occurring Hydrocarbons (Bitumen) in Quaternary Sediments, Athabasca Oil Sands Area and Areas West, Alberta. Technical report: Alberta Energy and Utilities Board, Alberta Geological Survey.

Ashmore DW, Bingham RG, Hindmarsh RCA, Corr HFJ and Joughin IR (2014) The relationship between sticky spots and radar reflectivity beneath an active West Antarctic ice stream. *Annals of Glaciology* **55**(67), 29–38. doi:10.3189/2014AoG67A052

Barthlott W and Neinhuis C (1997) Purity of the sacred lotus, or escape from contamination in biological surfaces. *Planta* **202**(1), 1–8. doi:10.1007/s004250050096

Bauer U and Federle W (2009) The insect-trapping rim of Nepenthes pitchers. *Plant Signaling and Behavior* **4**(11), 1019–1023. doi:10.4161/psb.4.11.9664

Benn DI, Fowler AC, Hewitt I and Sevestre H (2019a) A general theory of glacier surges. *Journal of Glaciology* **65**(253), 701–716. doi:10.1017/jog.2019.62

Benn DI, Hewitt IJ and Luckman AJ (2023) Enthalpy balance theory unifies diverse glacier surge behaviour. *Annals of Glaciology*, 1–7. doi:10.1017/aog.2023.23

Benn DI, Jones RL, Luckman A, Fürst JJ, Hewitt I and Sommer C (2019b) Mass and enthalpy budget evolution during the surge of a polythermal glacier: A test of theory. *Journal of Glaciology* **65**(253), 717–731. doi:10.1017/jog.2019.63

Bennett MR (2003) Ice streams as the arteries of an ice sheet: Their mechanics, stability and significance. *Earth Science Reviews* **61**(3-4), 309–339. doi:10.1016/S0012-8252(02)00130-7

Bindschadler RA (1983) The importance of pressurised subglacial water in separation and sliding at the glacier bed. *Journal of Glaciology* **29**(101), 3–19. doi:10.3189/S0022143000005104

Boetius A, Anesio AM, Deming JW, Mikucki JA and Rapp JZ (2015) Microbial ecology of the cryosphere: Sea ice and glacial habitats. *Nature Reviews, Microbiology* **13**(11), 677–690. doi:10.1038/nrmicro3522

Boulton GS, Dobbie KE and Zatsepin S (2001) Sediment deformation beneath glaciers and its coupling to the subglacial hydraulic system. *Quaternary International* **86**(1), 3–28. doi:10.1016/S1040-6182(01)00048-9

Boulton GS and Hindmarsh RCA (1987) Sediment deformation beneath glaciers: Rheology and geological consequences. *Journal of Geophysical Research* **92**(B9), 9059–9082. doi:10.1029/JB092iB09p09059

Cai C, Cai J, Liu H, Wang X, Zeng X and Wang Y (2023) Occurrence of organic matter in argillaceous sediments and rocks and its geological significance: A review. *Chemical Geology* 121737. doi:10.1016/j.chemgeo.2023.121737

Cassie ABD and Baxter S (1944) Wettability of porous surfaces. *Transactions of the Faraday Society* **40**, 546–551. doi:10.1039/tf9444000546

Cathles L and Fjeldskaar W (2020) A Summary of "Future Advances in Basin Modeling: Suggestions from Current Observations, Analyses and Simulations." *Geosciences* **10**(12), 506. doi:10.3390/geosciences10120506

Chau HW, Biswas A, Vujanovic V and Si BC (2014) Relationship between the severity, persistence of soil water repellency and the critical soil water content in water repellent soils. *Geoderma* **221**-**222**, 113–120. doi:10.1016/j.geoderma.2013.12.025

Chen XD and 7 others (2017) Hindered erosion: The biological mediation of noncohesive sediment behaviour. *Water Resources Research* **53**, 4787–4801. 10.1002/2016WR020105

Conway H, Catania G, Raymond CF, Gades AM, Scambos TA and Engelhardt H (2002) Switch of flow direction in an Antarctic ice stream. *Nature* **419**, 465–467. doi:10.1038/nature01081

DeBano LF and Krammes J (1966) Water repellent soils and their relation to wildfire temperatures. *International Association of Scientific Hydrology. Bulletin* **11**(2), 14–19. doi:10.1080/02626666609493457

de Gennes PG (1985) Wetting: Statics and dynamics. *Reviews of Modern Physics* **57**(3), 827–863. doi:10.1103/RevModPhys.57.827

De Jonge LW, Jacobsen OH and Moldrup P (1999) Soil Water Repellency: Effects of Water Content, Temperature, and Particle Size. *Soil Science Society of America Journal* **63**, 437–442. doi:10.2136/sssaj1999.03615995006300030003x

Dietze E and 9 others (2020) Relationships between low-temperature fires, climate and vegetation during three late glacials and interglacials of the last 430 kyr in northeastern Siberia reconstructed from monosaccharide anhydrides in Lake Elgygytgyn sediments. *Climate of the Past* **16**, 799–818. doi:10.5194/cp-16-799-2020

Doerr SH, Ritsema CJ, Dekker LW, Scott DF and Carter D (2007) Water repellence of soils: New insights and emerging research needs. *Hydrological Processes* **21**(17), 2223–2228. doi:10.1002/hyp.6762

Doerr SH, Shakesby RA, Blake WH, Chafer CJ, Humphreys GS and Wallbrink PJ (2006) Effects of differing wildfire severities on soil wettability

and implications for hydrological response. *Journal of Hydrology* **319**(1-4), 295–311. doi:10.1016/j.jhydrol.2005.06.038

Doerr SH, Shakesby RA and Walsh RPD (1996) Soil hydrophobicity variations with depth and particle size fraction in burned and unburned Eucalyptus globulus and Pinus pinaster forest terrain in the Águeda Basin, Portugal. *Catena* **27**(1), 25–47. doi:10.1016/0341-8162(96)00007-0

Dowdeswell JA, Ottesen D and Rise L (2006) Flow switching and large-scale deposition by ice streams draining former ice sheets. *Geology* **34**(4), 313–316. doi:10.1130/G22253.1

Fischer UH and Clarke GKC (2001) Review of subglacial hydro-mechanical coupling: Trapridge Glacier, Yukon Territory, Canada. *Quaternary International* **86**(1), 29–43. doi:10.1016/S1040-6182(01)00049-0

Fjeldskaar W and Amantov A (2018) Effects of glaciations on sedimentary basins. *Journal of Geodynamics* **118**, 66–81. doi:10.1016/j.jog.2017.10.005

Fowler AC (2003) On the rheology of till. *Annals of Glaciology* **37**, 55–59. doi:10.3189/172756403781815951

Gabet EJ (2003) Post-fire thin debris flows: Sediment transport and numerical modelling. *Earth Surface Processes and Landforms* **28**(12), 1341–1348. doi:10.1002/esp.590

Gao N and Yan Y (2009) Modeling Superhydrophobic contact angles and wetting transition. *Journal of Bionic Engineering* **6**(4), 335–340. doi:10.1016/S1672-6529(08)60135-3

Gerbersdorf SU and 12 others (2020) Exploring flow-biofilm-sediment interactions: Assessment of current status and future challenges. *Water Resources* **185**, 116182. 10.1016/j.watres.2020.116182

Hallett PD (2007) An introduction to soil water repellency 8th International Symposium on Adjuvants for Agrochemicals Christchurch, New Zealand: Hand Multimedia Christchurch, New Zealand. 6–9.

Hamlett CAE and 6 others (2011) Effect of particle size on droplet infiltration into hydrophobic porous media as a model of water repellent soil. *Environmental Science and Technology* **45**(22), 9666–9670. doi:10.1021/es202319a

Hedges JI and Keil RG (1995) Sedimentary organic matter preservation: An assessment and speculative synthesis. *Marine Chemistry* **49**(2-3), 81–115. doi:10.1016/0304-4203(95)00008-F

Higuera PE, Brubaker LB, Anderson PM, Brown TA, Kennedy AT and Hu FS (2008) Frequent fires in ancient shrub tundra: Implications of paleorecords for Arctic environmental change. *PLoS ONE* **3**(3), e000174. doi:10.1371/journal.pone.0001744

Hooke RL and Iverson NR (1995) Grain-size distribution in deforming subglacial tills: Role of grain fracture. *Geology* **23**(1), 57–60. doi:10.1130/0091-7613(1995)023%3C0057:GSDIDS%3E2.3.CO;2

Joughin I, Abdalati W and Fahnestock M (2004) Large fluctuations in speed on Greenlands Jakobshavn Isbræ glacier. *Nature* **432**(7017), 608–610. doi:10.1038/nature03130

Kamb B and 7 others (1985) Glacier surge mechanism: 1982-1983 surge of Variegated Glacier, Alaska. *Science* **227**(4686), 469–479. doi:10.1126/science.227.4686.469

Kamb B (1987) Glacier surge mechanism based on linked cavity configuration of the basal water conduit system. *Journal of Geophysical Research* **92**(B9), 9083. doi:10.1029/JB092iB09p09083

Kaštovská K, Stibal M, Šabacká M, Černá B, Šantrůčková H and Elster J (2007) Microbial community structure and ecology of subglacial sediments in two polythermal Svalbard glaciers characterized by epifluorescence microscopy and PLF. *Polar Biology* **30**, 277–287. doi:10.1007/s00300-006-0181-y

Kjær K and 8 others (2006) Subglacial decoupling at the sediment/bedrock interface: A new mechanism for rapid flowing ice. *Quaternary Science Reviews* **25**(21-22), 2704–2712. doi:10.1016/j.quascirev.2006.06.010

Kyrke-Smith TM, Gudmundsson GH and Farrell PE (2018) Relevance of detail in basal topography for basal slipperiness inversions: A case study on Pine Island Glacier, Antarctica. *Frontiers in Earth Science* **6**, 33. doi:10.3389/feart.2018.00033

Lafuma A and Quéré D (2003) Superhydrophobic states. *Nature Materials.* **2**(7), 457–460. doi:10.1038/nmat924

Lafuma A and Quéré D (2011) Slippery pre-suffused surfaces. *Europhysics Letters* **96**(5), 56001. doi:10.1209/0295-5075/96/56001

Lee J-H, Lee B-J, Yun U, Koh D-C, Kim SJ, Han D and Unno T (2019) In-situ microbial colonization and its potential contribution on biofilm formation in subsurface sediments. *Journal of Applied Biological Chemistry* **62**(1), 51–56. doi:10.3839/jabc.2019.008

Løtveit IF, Fjeldskaar W and Sydnes M (2019) Tilting and flexural stresses in basins due to glaciations—an example from the Barents Sea. *Geosciences* **9**(11), 474. doi:10.3390/geosciences9110474

Lourenço SD, Wang GH and Kamai T (2015) Processes in model slopes made of mixtures of wettable and water repellent sand: Implications for the initiation of debris flows in dry slopes. *Engineering Geology* **196**, 47–58. doi:10.1016/j.enggeo.2015.06.021

Mao J, Nierop KGJ, Rietkerk M, Sinnighe DJS and Dekker SC (2016) The influence of vegetation on soil water repellency-markers and soil hydrophobicity. *Science of the Total Environment* **566-567**, 608–620. doi:10.1016/j.scitotenv.2016.05.077

Marlon JR and 22 others (2009) Wildfire responses to abrupt climate change in North America. *Proceedings of the National Academy of Sciences of the United States of America* **106**(8), 2519–2524. doi:10.1073/pnas.0808212106

McCerery R, Esegbue O, Jones M, Winter K, McHale G and Woodward J (2024) Geochemical evidence for Alberta Oil Sands contamination in sediments remote to known oil sands deposits in Alberta, Canada. *Environmental Forensics*, 1–21. doi:10.1080/15275922.2023.2218304

McCerery R, Woodward J, McHale G, Winter K, Armstrong S and Orme BV (2021) Slippery liquid-infused porous surfaces: The effect of oil on the water repellence of hydrophobic and superhydrophobic soils. *European Journal of Soil Science* **72**(2), 963–978. doi:10.1111/ejss.13053

McCerery R, Woodward J, Winter K, Esegbue O, Jones M and McHale G (2023) Oil sands in glacial till as a driver of fast flow and instability in the former Laurentide Ice Sheet: Alberta, Canada. *Earth Surface Processes and Landforms* **48**(15), 3347–3362. doi:10.1002/esp.5700

McHale G, Ledesma-Aguilar R and Wells G (2020) Interfacial strategies for smart slippery surfaces. *Journal of Bionic Engineering* **17**(4), 633–643. doi:10.1007/s42235-020-0057-9

McHale G, Newton MI and Shirtcliffe NJ (2005) Water-repellent soil and its relationship to granularity, surface roughness and hydrophobicity: A materials science view. *European Journal of Soil Science* **56**(4), 445–452. doi:10.1111/j.1365-2389.2004.00683.x

McHale G, Shirtcliffe NJ, Newton MI, Pyatt FBB and Doerr SH (2007) Self-organization of hydrophobic soil and granular surfaces. *Physics Letters A* **90**(5), 054110. doi:10.1063/1.2435594

McIntyre NF (1985) The dynamics of ice sheets. *Journal of Glaciology* **31**(108), 99–107. doi:10.3189/S0022143000006328

McKenzie MA, Miller LE, Slawson JS, MacKie EJ and Wang S (2023) Differential impact of isolated topographic bumps on ice sheet flow and subglacial processes. *Cryosphere* **17**, 2477–2486. doi:10.5194/tc-17-2477-2023

Minchew BM and Meyer CR (2020) Dilation of subglacial sediment governs incipient surge motion in glaciers with deformable beds. *Proceedings of the Royal Society, Series A* **476**(2238), 20200033. doi:10.1098/rspa.2020.0033

Müller K, Mason K, Strozzi AG, Simpson R, Komatsu T, Kawamoto K and Clothier B (2018) Runoff and nutrient loss from a water-repellent soil. *Geoderma* **322**, 28–37. doi:10.1016/j.geoderma.2018.02.019

Murray T and 6 others (2000) Glacier surge propagation by thermal evolution at the bed. *Journal of Geophysical Research* **105**(B6), 13491–13507. doi:10.1029/2000JB900066

Narloch W, Phillips E, Piotrowski JA and Ćwiek M (2020) Patterns of deformation within a subglacial shear zone: Implications for palaeo-ice stream bed evolution. *Sedimentary Geology* **397**, 105569. doi:10.1016/j.sedgeo.2019.105569

Neinhuis C and Barthlott W (1997) Characterization and distribution of water-repellent, self-cleaning plant surfaces. *Annals of Botany* **79**(6), 667–677. doi:10.1006/anbo.1997.0400

Nosonovsky M (2011) Slippery when wetted. *Nature* **477**(7365), 412–413. doi:10.1038/477412a

Nuth C and 9 others (2019) Dynamic vulnerability revealed in the collapse of an Arctic tidewater glacier. *Scientific Reports* **9**(5541). doi:10.1038/s41598-019-41117-0

Ó Cofaigh C, Evans DJA and Smith RI (2010) Large-scale reorganization and sedimentation of terrestrial ice streams during late Wisconsinan Laurentide Ice Sheet deglaciation. *Geological Society of America Bulletin* **122**(5-6), 743–756. doi:10.1130/B26476.1

Paragon Soils and Environmental Consulting (2006) Hydrocarbons in natural oil sands soils: Field Survey. In *Technical Report: Cumulative Environmental Management Association*, Alberta. 1–42.

Parise M and Cannon SH (2012) Wildfire impacts on the processes that generate debris flows in burned watersheds. *Natural Hazards* **61**, 217–227. doi:10.1007/s11069-011-9769-9

Phillips E, Evans DJA, van der Meer JJM and Lee JR (2018) Microscale evidence of liquefaction and its potential triggers during soft-bed deformation within subglacial traction tills. *Quaternary Science Reviews* **181**, 123–143. doi:10.1016/j.quascirev.2017.12.003

Phillips E and Piotrowski JA (2023) Modelling of till microstructure development during subglacial deformation using ring shear experiments. *Quaternary Science Reviews* **312**, 108168. doi:10.1016/j.quascirev.2023.108168

Piotrowski JA and Tulaczyk S (1999) Subglacial conditions under the last ice sheet in northwest Germany: Ice-bed separation and enhanced basal sliding? *Quaternary Science Reviews* **18**(6), 737–751. doi:10.1016/S0277-3791(98)00042-0

Quéré D (2008) Wetting and roughness. *Annual Review of Materials Research* **38**, 71–99. doi:10.1146/annurev.matsci.38.060407.132434

Quyum A, Achari G and Goodman RH (2002) Effect of wetting and drying and dilution on moisture migration through oil contaminated hydrophobic soils. *Science of the Total Environment* **296**(1-3), 77–87. doi:10.1016/S0048-9697(02)00046-3

Robin GDQ (1955) Ice movement and temperature distribution in glaciers and ice sheets. *Journal of Glaciology* **2**(18), 523–532. doi:10.3189/002214355793702028

Rocha A and 9 others (2012) The footprint of Alaskan tundra fires during the past half-century: Implications for surface properties and radiative forcing. *Environmental Research Letters* **7**, 044039. 10.1088/1748-9326/7/4/044039

Rosenberg M, Gutnick D and Rosenberg E (1980) Adherence of bacteria to hydrocarbons: A simple method for measuring cell-surface hydrophobicity. *FEMS Microbiology Letters* **9**(1), 29–33. doi:10.1111/j.1574-6968.1980.tb05599.x

Roy JL and McGill WB (1998) Characterization of disaggregated nonwettable surface soils found at old crude oil spill sites. *Candian Journal of Soil Science* **78**(2), 331–344. doi:10.4141/S97-039

Roy JL, McGill WB and Rawluk MD (1999) Petroleum residues as water-repellent substances in weathered nonwettable oil-contaminated soils. *Canadian Journal of Soil Science* **79**(2), 367–380. doi:10.4141/S97-040

Schoof C (2002) Basal perturbations under ice streams: Form drag and surface expression. *Journal of Glaciology* **48**(162), 407–416. doi:10.3189/172756502781831269

Seaton FM and 8 others (2019) Plant and soil communities are associated with the response of soil water repellency to environmental stress. *Science of the Total Environment* **687**, 929–938. 10.1016/j.scitotenv.2019.06.052

Sevestre H, Benn DI, Hulton NRJ and Bælum K (2015) Thermal structure of Svalbard glaciers and implications for thermal switch models of glacier surging. *Journal of Geophysical Research: Earth Surface* **120**, 2220–2236. doi:10.1002/2015JF003517

Shirtcliffe NJ, McHale G, Atherton S and Newton MI (2010) An introduction to superhydrophobicity. *Advances in Colloid and Interface Science* **161**, 124–138. doi:10.1016/j.cis.2009.11.001

Skidmore M, Anderson SP, Sharp M, Foght J and Lanoil BD (2005) Comparison of microbial community compositions of two subglacial environments reveals a possible role for microbes in chemical weathering processes. *Applied and Environmental Microbiology* **71**(11), 6986–6997. doi:10.1128/AEM.71.11.6986-6997.2005

Smith AM, Murray T, Davison BM, Clough AF, Woodward J and Jiskoot H (2002) Late surge glacial conditions on Bakaninbreen, Svalbard, and implications for surge termination. *Journal of Geophysical Research* **107**(B8), 2152. doi:10.1029/2001JB000475

Stokes CR, Clark CD, Lian OB and Tulaczyk S (2007) Ice stream sticky spots: A review of their identification and influence beneath contemporary and palaeo-ice streams. *Earth Science Reviews* **81**(3-4), 217–249. doi:10.1016/j.earscirev.2007.01.002

van der Meer JJ, Menzies J and Rose J (2003) Subglacial till: The deforming glacier bed. *Quaternary Science Reviews* **22**(15-17), 1659–1685. doi:10.1016/S0277-3791(03)00141-0

Vignaga E, Sloan DM, Luo X, Haynes H, Phoenix VR and Sloan WT (2013) Erosion of biofilm-bound fluvial sediments. *Nature Geoscience* **6**, 770–774. doi:10.1038/ngeo1891

Vogel SW and 7 others (2005) Subglacial conditions during and after stoppage of an Antarctic Ice Stream: Is reactivation imminent? *Journal of Geophysical Research Letters* **32**, L14502. 10.1029/2005GL022563

Wall SA, Roering JJ and Rengers FK (2020) Runoff-initiated post-fire debris flow Western Cascades, Oregon. *Landslides* **17**, 1649–1661. doi:10.1007/s10346-020-01376-9

Wang P, Zhang D and Lu Z (2015) Slippery liquid-infused porous surface bio-inspired by pitcher plant for marine anti-biofouling application. *Colloids and Surfaces B: Biointerfaces* **136**, 240–247. doi:10.1016/j.colsurfb.2015.09.019

Warburton KLP, Hewitt DR and Neufeld JA (2023) Shear dilation of subglacial till results in time-dependent sliding laws. *Proceedings of the Royal Society A* **479**(2269), 20220536. doi:10.1098/rspa.2022.0536

Weertman J (1957) On the sliding of glaciers. *Journal of Glaciology* **3**, 33–38. doi:10.1017/s0022143000024709

Weertman J (1964) The theory of glacier sliding. *Journal of Glaciology* **5**(39), 287–303. doi:10.3189/S0022143000029038

Weertman J (1979) The unresolved glacier sliding problem. *Journal of Glaciology* **23**(89), 97–115. doi:10.3189/S0022143000029762

Winsborrow MCM, Clark CD and Stokes CR (2010) What controls the location of ice streams. *Earth Science Reviews* **103**(1-2), 45–59. doi:10.1016/j.earscirev.2010.07.003

Wong T-S and 6 others (2011) Bioinspired self-repairing slippery surfaces with pressure-stable omniphobicity. *Nature* **477**, 443–447. doi:10.1038/nature10447

Yong J and 6 others (2017) Nepenthes inspired design of self-repairing omniphobic slippery liquid infused porous surface (SLIPS) by femtosecond laser direct writing. *Advanced Materials Interfaces* **4**(20), 1700552. doi:10.1002/admi.201700552

Zheng S, Laurenço SDN, Cleall PJ, Chui TFM, Ng AKY and Millis SW (2017) Hydrologic behaviour of model slopes with synthetic water repellent soils. *Journal of Hydrology* **554**, 582–599. doi:10.1016/j.jhydrol.2017.09.013

Zieba KJ and Grøver A (2016) Isostatic response to glacial erosion, deposition and ice loading. Impact on hydrocarbon traps of the southwestern Barents Sea. *Marine and Petroleum Geology* **78**, 168–183. doi:10.1016/j.marpetgeo.2016.09.009