Impacts of subglacial processes on underlying bedrock

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Cover Picture: Glacier and exposed bedrock in Valais, Switzerland. Picture provided by Pixabay.

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Abstract: Historically, the field of glacial geology has put much focus on the processes within the subglacial environment, their effects on unconsolidated sediments and the landforms they produce. Subsequently, the impact of subglacial processes is fairly well documented and understood regarding unconsolidated sediments. However, except for processes of abrasion and quarrying, not much focus has been dedicated to what effects these processes exert on the underlying bedrock. Recent studies have though shown that generic subglacial conditions do not only impact subglacial unconsolidated sediments but affect the underlying bedrock as well. These impacts are mainly due to the variation and containment of porewater pressures within the subglacial environment. When these pressures are elevated to levels exceeding the bedrock´s shear strength, hydrofracturing occur with pene-contemporaneous injection of dilated/liquefied sediments. Strong similarities have been demonstrated between subglacial- and industrial hydrofracture systems, formed from a process commonly referred to as ‘fracking’. This have shown that industrial hydrofracturing in turn can be used as a tool to understand the dynamics of subglacial hydrofracture systems. In addition, hydrofracture systems are believed to exert a strong influence on the structural integrity and hydrogeological conditions of the bedrock. It also seems that they exert a controlling factor regarding quarrying and till continuity in postglacial areas that have undergone hydrofracturing.

Keywords: Subglacial processes, Liquefaction, Hydrofracturing, Bedrock, Fracking

Supervisor: Sven Lukas

Subject: Quaternary Geology

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Subglaciala processers inverkan på berggrunden

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Sammanfattning: Historiskt sett har forskningen inom glacialgeologi fokuserat på processerna inom den subglaciala miljön, deras effekter på okonsoliderat material och de landformer dessa bildar. Därav är effekterna från subglaciala processer relativt väl förstådda och dokumenterade gällande okonsoliderade material. Däremot, med undantag av abrasions- och lossbrytningsprocesser, har begränsat fokus dedikerats till att undersöka effekterna av dessa processer på den underliggande berggrunden. Ny forskning indikerar dock att generiska subglaciala processer inte bara påverkar okonsoliderade sediment utan även den underliggande berggrunden. Denna påverkan är huvudsakligen ett resultat av varierande porvattentryck samt utbredningen av dessa tryck i den subglaciala miljön. Vid förhöjda porvattentryck kan berggrundens skjuvhållfasthet överskridas vilket leder till hydraulisk spräckning av berggrunden och påföljande injektion av likvifierat material. Starka liknelser har dragits mellan subglaciala- och industriella hydrauliska spräckningssystem, bildade från en process känd som 'fracking'. Detta har visat att industriell spräckning i sin tur kan användas för att förklara processerna och bildningsförloppet hos subglaciala hydrauliska spräckningssystem. Dessa hydrauliska spräckningssystem kan utöva en stark påverkan på berggrundens strukturella integritet och hållfasthet samt den rådande hydrogeologin i det utsatta området. De utövar även sannolikt en stark kontroll på lossbrytningsprocesser samt massbalansen av morän i postglaciala områden som utsatts av subglacial hydraulisk spräckning.

Nyckelord: Subglaciala processer, Likvifaktion, Hydraulisk spräckning, Berggrund, Fracking

Handledare: Sven Lukas

Ämnesinriktning: Kvartärgeologi

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1 Introduction

Subglacial processes and their effects on unconsolidated material are part of a field with a long history of research. Consequently, our understanding of how these processes effect unconsolidated material and their respective landforms are well understood. However, how these processes effect the underlying bedrock is much less explored due to the inherent difficulty of studying bedrock compared to unconsolidated sediments. Despite this difficulty progress has lately been made in our understanding of how these processes effects the bedrock. Specifically through the process of hydraulic fracturing resulting from high confined porewater pressures. Historically the structures created by hydraulic fracturing have often been overlooked or simply disregarded. However, through publications such as Evans et al. (2006), van der Meer et al. (2009), Phillips et al. (2013a), Phillips et al. (2018) and others, these structures are now given serious consideration.

This paper thus aims to gather information regarding generic subglacial processes in order to investigate commonalities, differences and possible consequences of corresponding processes observed in bedrock. In addition, modern analogues are taken into consideration to better understand these processes.

2 Methods

This paper is a literature analysis in which scientific publications have been collected and reviewed in order to create an overview and achieve the aforementioned aim. The literature has been collected using the discovery systems google scholar and LUBsearch and the databases therein. The keywords that have been used in the search for literature are *subglacial processes*, *bedrock*, *hydrofracturing*, *hydraulic fracturing*, *glacitectonite*, *glaciotectonite*, *clastic injection*, *sediment injection*, *sediment infill*, *icequake*, *glacial seismicity* and *fracking*. In addition, the geolibrary of Lund University has been used in the search for literature.

Literature regarding subglacial erosional processes, e.g. abrasion of bedrock surfaces, has not been taken into consideration as they are not included in the scope of this study. The same is true for the effects of bedrock uplift due to lowering of ice overburden.

3 Background

3.1 Subglacial processes

Subglacial processes consist of a vast spectrum of different depositional environments that give rise to an equally vast spectrum of sedimentary structures. These range from deformation, flow, sliding, lodgement to ploughing processes that all coexist underneath temperate glaciers, all working towards mobilization and final deposition of sediments (Evans et al. 2006). Due to the high spatial and temporal variability in each of these processes many glaciologists have moved away from this type of process-specific diamict description method to a more encompassing mosaic model of the glacier bed (Piotrowski & Kraus 1997; Boyce & Eyles 2000; van der Meer et al. 2003; Piotrowski et al. 2004; Evans et al. 2006; Lee & Phillips 2008; Meriano & Eyles 2009). This is done in order to better represent the temporal and spatial continuum of processes operating at the glacier sole and thus also one of the resulting products, subglacial till. This has proved to be an important tool as the deciphering of detailed subglacial processes within the subglacial continuum in accordance with the traditional classification, e.g. lodgement, deformation etc., has proven to be virtually impossible. In addition, this way of broadening the nomenclature in part contributed to the introduction of the concept of subglacial traction till that serves to better represent the conceptual models of subglacial till deformation (Evans et al. 2006), see figure 1.

3.1.1 Dilation and liquefaction due to elevated porewater pressures

One of the major factors influencing and determining these processes is the presence or absence of porewater within subglacial sediments, more precisely the degree of porewater pressure (Boulton et al. 2001). Higher water contents are believed to weaken electrostatic bonds between particles as well as increase the distance between clastic components, which in turn result in an increase in the volume or dilation of the sediments. Furthermore, this leads to the lowering of the sediment's cohesive and frictional strength (Evans et al. 2006), see figure 1. In essence grains are more easily mobilized in relation to each other during shear (Dowdeswell 1993) which creates an active zone of displacement, see figure 1. This could be why finite strains are generally much lower than expected in subglacial sediments (Evans et al. 2006). If the subglacial drainage systems are insufficient porewater pressures will be elevated, possibly resulting in water saturated sediments crossing over into a liquefied state. This entails a drastic increase in volume of the sediments as well as a strong decrease in its cohesive and frictional strength (Evans et al. 2006). A lack of drainage could be due to low hydraulic conductivity of subglacial material or permafrost (van der Meer et al. 1999). If liquefaction occurs the sediments will not undergo-solid state deformation, e.g. folding or faulting, due to the loss of a coherent matrix-till framework. Instead it will rather flow than deform. This dilation of the sediment reduces the effective pressures which in turn allows further dilation and further inhibition of the formation of a till-matrix framework. As a consequence it has the potential to lower the friction between the glacier and underlying bed, possibly resulting in ice-bed decoupling (Evans et al. 2006). Deformation of the sediments will only reoccur in the presence of a deformable till-matrix framework which after liquefaction is re-established when porewater pressure decreases and the till-matrix framework reach a semi-solid and eventually a solid state (Evans et al. 2006). Iverson et al. (1998) show that the process of dilation and or liquefaction may lead to dilatant hardening which add to the frictional strength of the sediments, making them more competent and resistant to deformation. This is because a high porewater content weakens the sediment, as density then is low and porosity is high. This makes it easier for water to drain out from the system, resulting in a net water loss. The reduced water content in turn hardens the sediment (Iverson et al. 1998). This is however reliant on water not being reintroduced into the system and that drainage pathways are present. Porewater content and subsequent porewater pressure varies throughout the sediment pile, typically having the highest values by the glacier bed interface where the pressure is lower. Further down the pile pressure increases, resulting in decreased porewater content/pressure. This give rise to the different zones within the traction till model (Evans et al. 2006), see figure 1. Important to note is that such porewater pressure distributions, with gradually lower levels further down the sediment section, only occurs in homogenous material. Since most sediment sequences rarely exhibit this kind of homogeneity a more fluctuating vertical distribution of porewater pressure is usually the case, as is illustrated by Evans et al. (2006), see figure 2.

In addition to this vertical variation in porewater pressure there are also temporal variations. This occurs both on an annual scale, where the changing of seasons results in the variation of water content in the subglacial system, but also on a diurnal scale (Hubbard et al. 1995). Hubbard et al. (1995) identified the variable pressure axis, VPA, underneath the Haut Glacier d'Arolla in Valais, Switzerland, which was the result of a subglacial channel within a greater drainage system. This produced diurnal porewater fluctuations in which porewater pressure increased during the afternoon as a transverse hydraulic gradient forced water out of the channel and into the surrounding sediments. The gradient then reversed, forcing water into the channel overnight, resulting in lower porewater pressures in the surrounding sediments. The water migration propagated through a vertically confined sediment layer and occurred within a distance of 70m perpendicular to the VPA (Hubbard et al. 1995). Such fluctuations would likely have a strong impact on the porewater pressure conditions and rheology of the materials (Evans et al. 1998) and might also constitute a potential control for liquefaction of the sediments.

An important effect of liquefaction is that it lowers or even inhibits the transmission of the simple shear stress exerted on the underlying sediments and/or bedrock from the overriding glacier, essentially insulating the underlying material from glacial simple shear stresses (Phillips et al. 2018). Any deformation would rather be a result of compression or layer-parallel extension due to the ice overburden, assuming that the state of liquefaction is maintained within the sediments (Evans et al. 2006). If porewater pressures were to be lowered, the transmission of the shear stresses will be reinstated.

3.1.2 Hydrofracturing

If the escape of porewater is inhibited, either through impermeable sediments, bedrock or permafrost, the porewater pressure can become unsustainable, resulting in hydrofracturing (van der Meer et al. 1999). Hydrofractures, also known as water escape-features or clastic dykes, are the result of marked fluctuations within glacial hydrogeological systems. They are created by the widening and pene-contemporaneous filling of a fracture, in either unconsolidated sediment or bedrock, the walls of which were formerly in contact with each other. Closed fractures may exist prior to

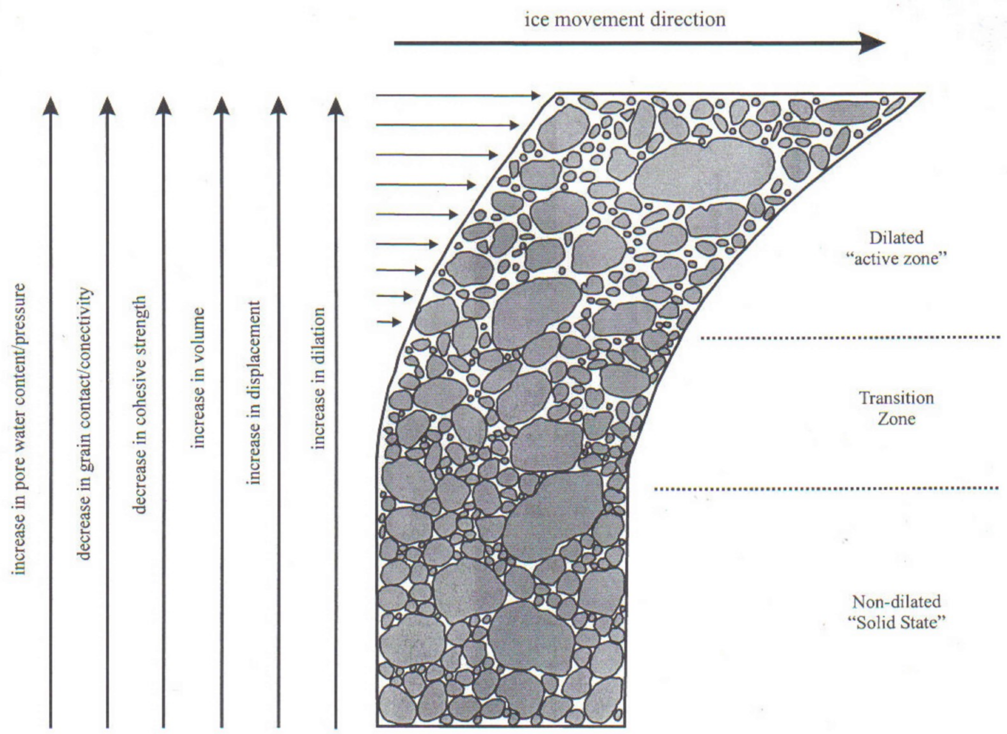

Fig. 1. Principal illustration of a relatively homogenous subglacial traction till showing vertical variations in dilation, displacement, volume, cohesive strength, grain contact/connectivity and porewater content/pressure as well as the zonation resulting from these variations (Evans et al. 2006).

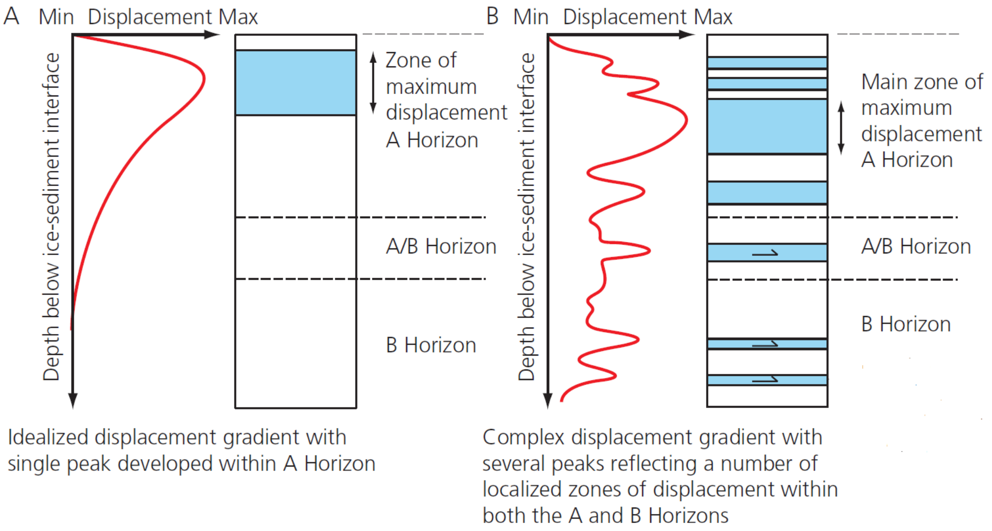

Fig. 2. **A**. Principal illustration of displacement due to variation in porewater pressure in a homogenous subglacial till. **B**. A more realistic representation of displacement due to varying porewater pressures resulting from inhomogeneous and/or varying material (Evans 2018).

hydrofracturing depending on the degree of consolidation and history of the host rock/sediment. In such cases these pre-existing structures are reactivated due to the elevated hydrostatic pressures (Phillips et al. 2013a). Alternatively, brittle fracturing may be a direct result of the hydrofracturing process, described by Larsen & Mangerud (1992) as instantaneous cut and fill. This occurs when the porewater pressures exceeds the tensile strength of the host sediment or bedrock (Ravier et al. 2015). Hydrofracturing and the pene-contemporaneous sediment infill can propagate both downwards, *per descensum*, and upwards, *per ascensum*, creating dykes. They can also propagate laterally and are then referred to as sills or clastic sills (Ravier et al. 2015). Usually hydrofracture systems are structurally complex, consisting of a mixture of (sub-) vertical dykes and (sub-) horizontal sills of varying length and thickness as seen in Sólheimajökull, Iceland (Ravier et al. 2015), and in the Meads of St John, Scotland (Phillips et al. 2013a), see figure 3&4. Therefore, all these features are usually included when referring to hydrofractures, water escape structures and clastic dykes (van der Meer et al. 2009).

Field measurements from previous studies show that hydrofracture propagation follows a typical pattern depending on where they are formed within the glacial environment, subglacialy, submarginaly or proglacialy. This is due to the inherent differences in pressure conditions generated by ice overburden in each environment. These have in turn resulted in conceptual models of hydrofracture propagation within glacial environments (van der Meer et al. 1999; Phillips et al. 2013b; Ravier et al. 2014), see figure 5&6. Essentially, the differential loading due to the thinning of the glacier exert the primary control on the direction of hydrofracture propagation and fluid flow in subglacial to proglacial hydrofracture systems (Piotrowski 2007). In subglacial environments, where glacial overburden and subsequent pressures are high, hydrofractures form with a downwards propagation tilting towards the ice margin where the pressure is lower due to reduced ice overburden (van der Meer et al. 1999), see figure 5&6. Within the submarginal to proglacial environments, hydrofractures propagate towards the ice margin as sills due to the lower pressures exerted by the ice as its thickness reduces (Phillips et al. 2013a). Further into the submarginal and proglacial environments the reduction or depletion of ice overburden as well as the inherent density contrast between the injected fluid and the host material, leads to the formation of upward oriented hydrofractures (Abou-Sayed et al. 1984; Phillips et al. 2013a), see figure 5&6. Depending on the inclination of the ice margin hydrofractures of different characteristics are produced. A gently inclined ice margin leads to a gradual lowering of overburden pressure, resulting in gently inclined climbing hydrofractures. On the contrary, a steeply inclined ice margin results in a more drastic reduction in overburden pressure, leading to a relatively narrow zone of steeply inclined climbing fractures (Phillips et al. 2013a), see figure 6B. If the reduction in pressure is sufficient these climbing hydrofractures could possibly make up the underground plumbing for proglacial springs or even blow-out structures (Boulton et al. 1993; Phillips et al. 2013a). Due to the oscillating nature of glacial migration, hydrofracture systems are unlikely to display such a clear progression and distinction of typologies as seen in figure 5&6. More likely is a complex system of older and younger, possibly cross-cutting, phases of dykes and sills due to oscillating ice margins, inhomogeneous materials and varying porewater pressures (van der Meer et al. 1999; Evans et al. 2006; Phillips et al. 2013a; Ravier et al. 2015), see figure 7.

Modelling results from Brenner & Gudmundsson (2004) show that hydraulic pressures within active hydrofractures vary linearly, having maximum values at its centre and zero at the propagating tip, that is the leading edge of water penetration within the hydrofracture. However, if the hydrofracture propagation follows a pre-existing plane of weakness the fracture may propagate ahead of the waterfront, creating what Brenner & Gudmundsson (2004) referred to as a unwetted or dry zone.

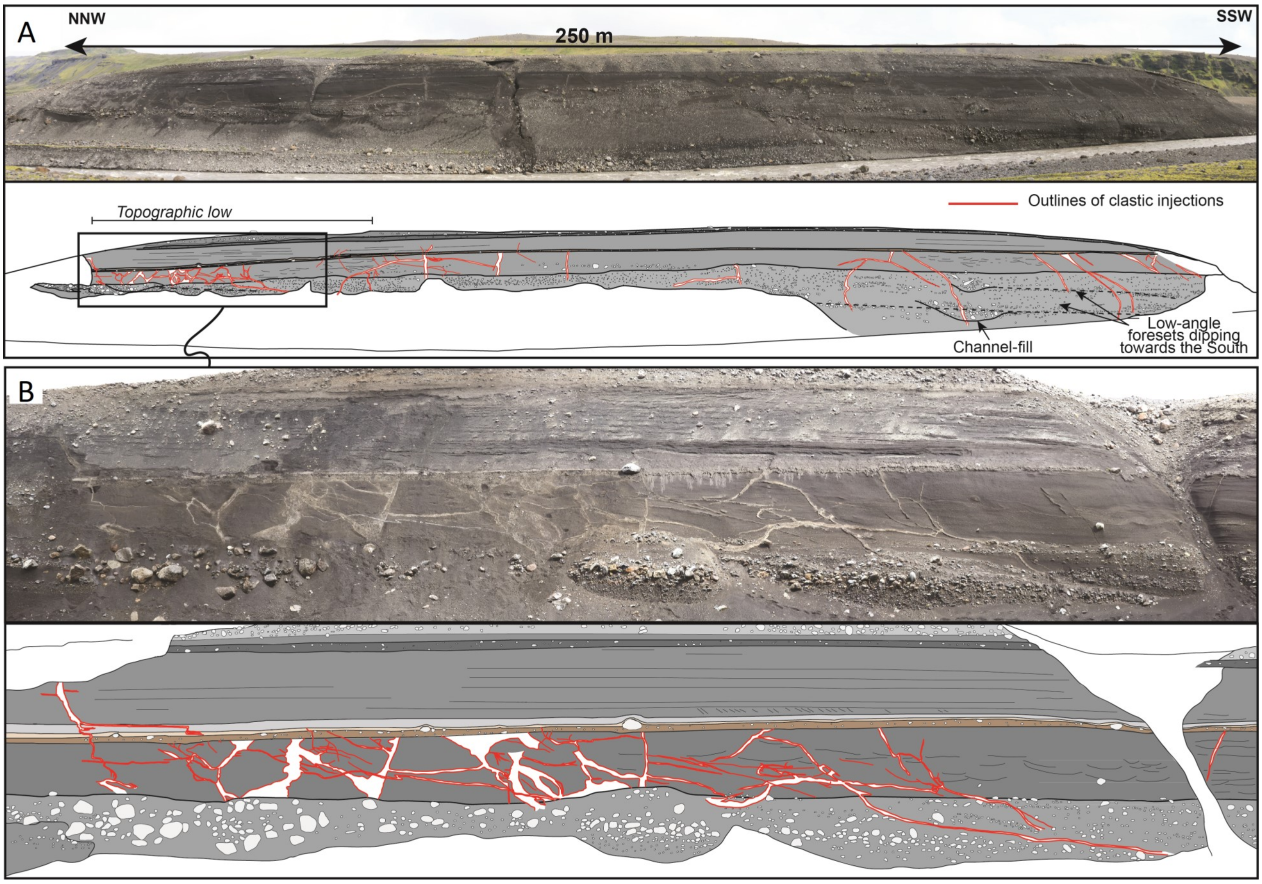

Fig. 3. Till section from Sólheimajökull, Iceland containing hydrofracture systems. **A**. Panoramic photograph of a sedimentary till section and interpretation of sedimentary facies. The contours of cross-cutting per ascensum and per descensum dykes and sill hydrofractures with pene-contemporaneous sediment injections are highlighted in red. **B**. Close up of the northern part of the section in which hydrofractures and subsequent sediment injection are most occurring. Modified from Ravier et al. (2015).

Fig. 4. Picture of the hydrofracture system within the sandstone of the Meads of St John, Scotland. Reproduced with permission from S. Lukas.

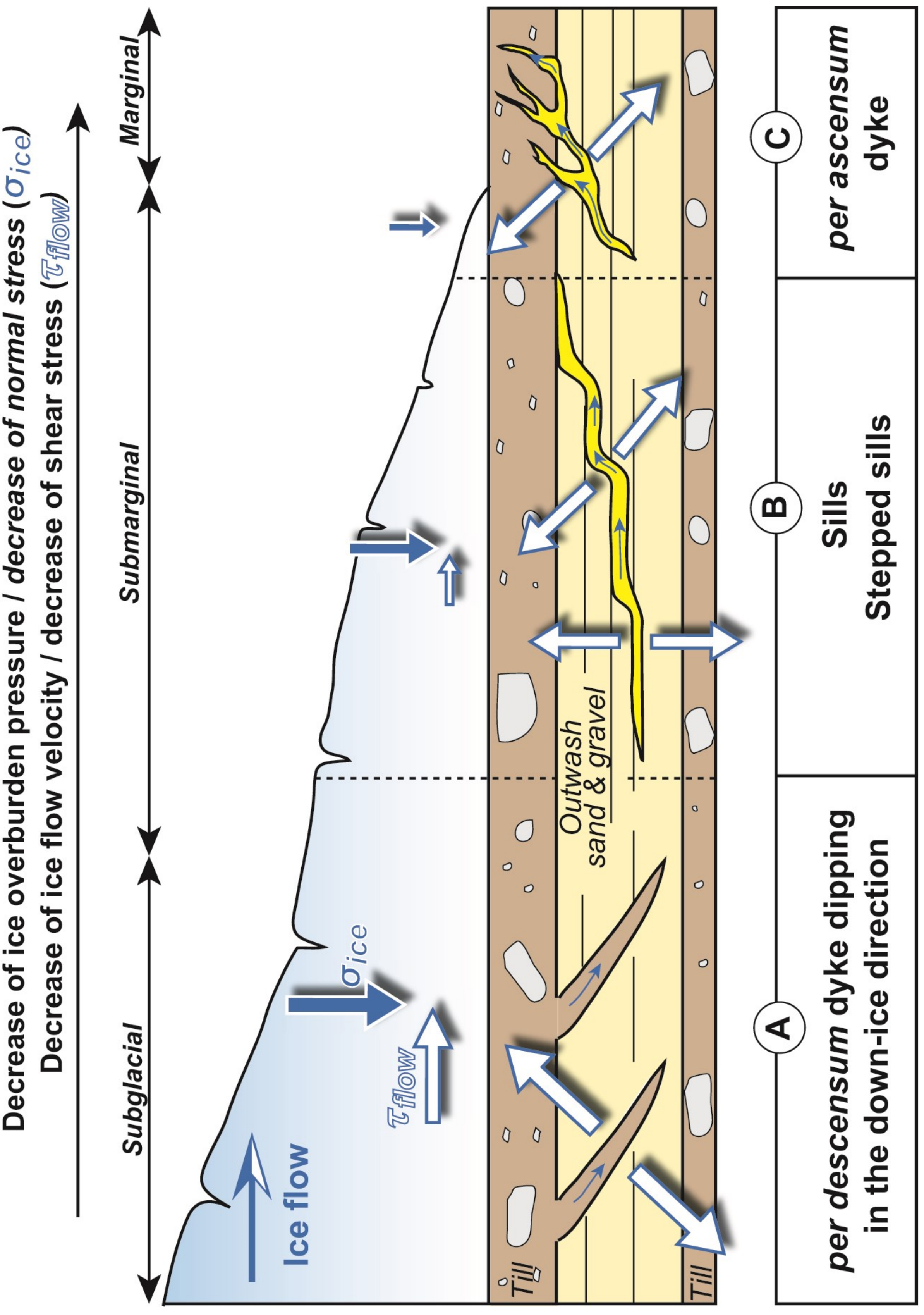

Fig. 5. Principal illustration of the theoretical distribution of different hydrofracture- and subsequent sediment infill morphologies within different subglacial environments. The orientation of the fractures is controlled by the stresses exerted on the glacier bed during hydrofracturing. **A**. Per descensum dykes formed in the subglacial environment under high overburden pressures. **B**. The lower overburden pressures within the submarginal to marginal environment results in the formation of sills or stepped sills during hydrofracturing. **C**. The reduced overburden pressures at the ice margin results in per ascensum dykes (Ravier et al. 2015).

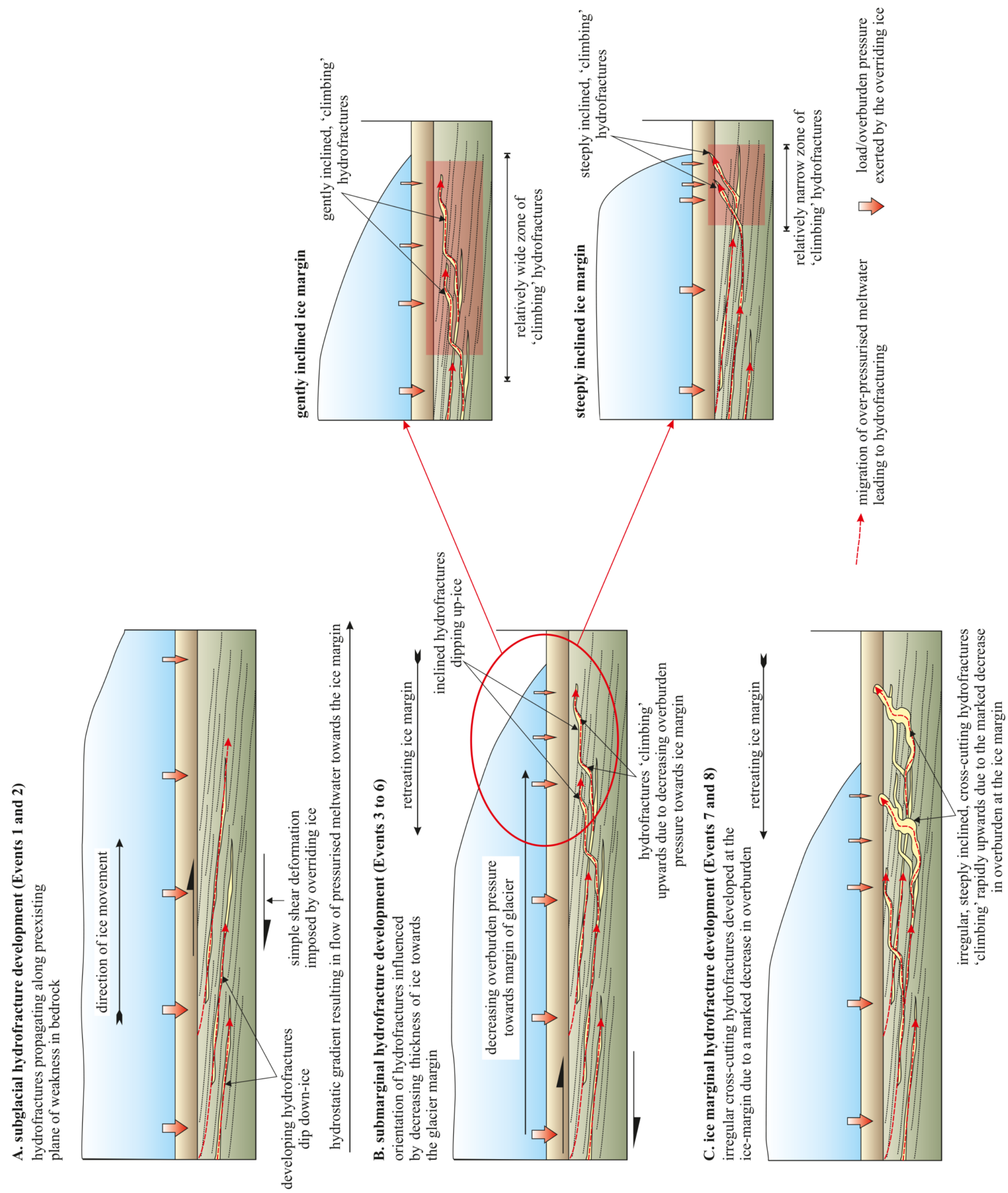

Fig. 6. Conceptual model of hydrofracture propagation within subglacial to proglacial environments. **A**. Down-ice propagation of hydrofractures along pre-existing planes of weakness. **B**. Hydrofracture orientation influenced by reduced overburden pressures exerted by the ice, showing differences between gently- and steeply inclined ice margins. **C**. Cross-cutting hydrofractures resulting from marked decrease in overburden pressure (Phillips et al. 2013a).

3.1.3 Sediment injection/infill

As is shown by both macroscopic and microscopic observations hydrofracture systems generally consist of several dilation/fluidization events, see figure 7, during which dilated/liquefied sediments are injected into the fractures of the host material, consisting of either unconsolidated sediment or bedrock. This is indicated by the character of the fracture fills which form varying laminations of different grain sizes, parallel to the margins of the dykes and sills with symmetrical distributions (Ravier et al. 2015). This type of formation is thus attributed to a complex formation history including multi episodical sediment injection, variation in fracture opening rates as well as variations in velocity and rate of injected sediments (Peterson 1968; Ravier et al. 2015), all of which are secondary results of the interplay between varying porewater pressure and the consolidation or hardness of the materials involved (Evans et al. 2006). Furthermore, older generations of injected sediments may be remobilized during subsequent flow events, leading to deformation of these structures, as can be seen in the microstructures of multiphase deposition and deformation within the hydrofracture system in the Meads of St John, Scotland (Phillips et al. 2013a), see figure 7.

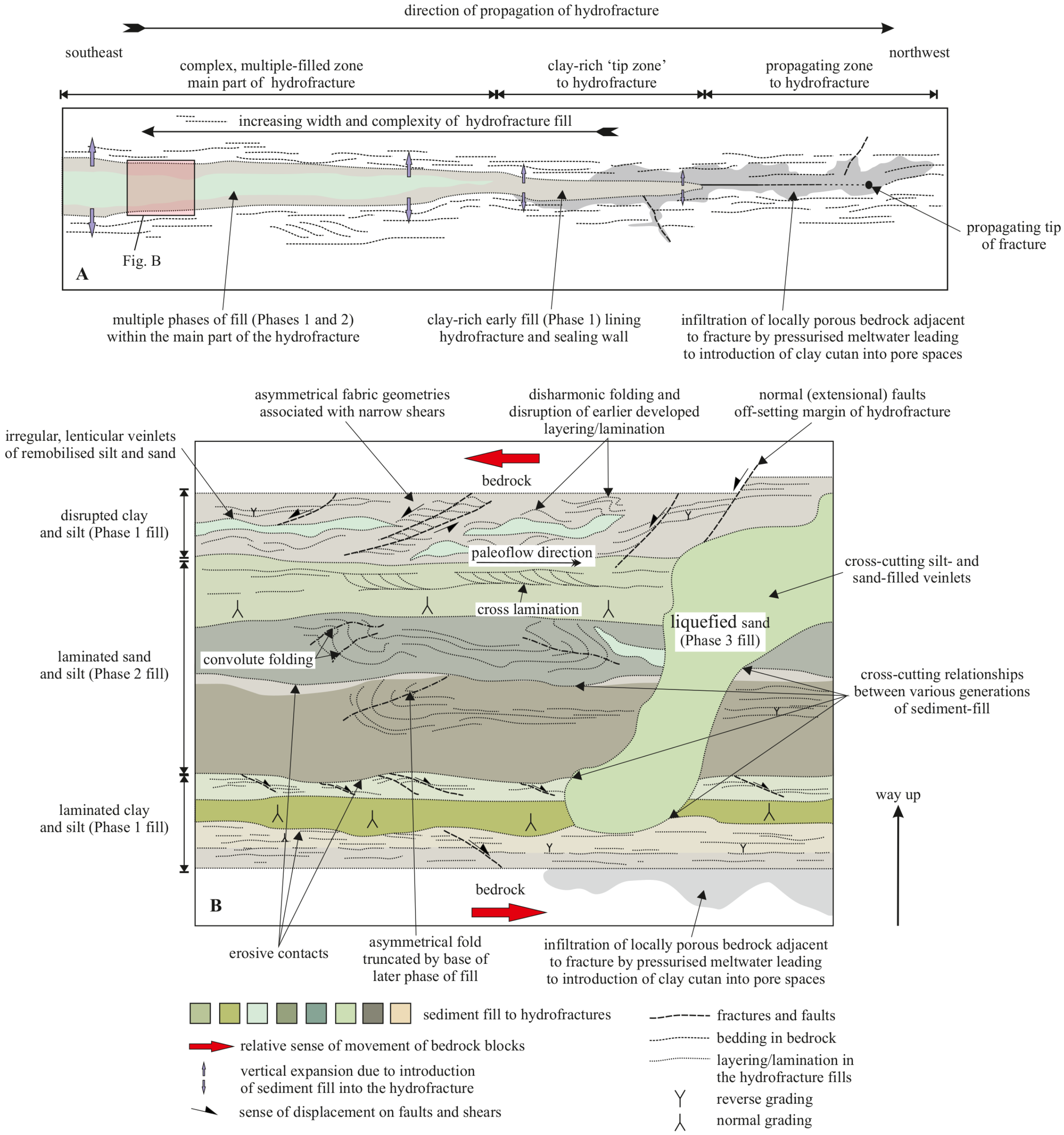

Fig.7. **A**. Illustration of a propagating hydrofracture with subsequent lining/plastering of clay, injection of clay cutan into pore spaces and subsequent phases of sedimentation. **B**. Microstructures generated by the consecutive phases of sediment infill within the bedding parallel sill like sections of the Meads of St John hydrofracture system (Phillips et al. 2013a).

As shown by Phillips et al. (2013a) the first stage in the sediment injection process is the injection of clay. The high fluid pressures occurring during hydrofracturing events and subsequent sediment injection break the electrostatic bonds binding the clay particles, resulting in dilation/liquefaction and transport of the clay particles within the hydrofracture system at peak fluid pressure. Subsequently, these clays are the first sediments to be injected and deposited at the fluid tip of the propagating fracture, towards which fluid pressures gets progressively lower (Phillips et al. 2013a), see figure 7. As the fracture widens due to the elevated pressures and continued injection of coarser material, the initially injected fines are pushed towards the fracture margins, essentially plastering them to the fracture walls (Phillips et al. 2013a). This creates a general hydrofracture lamination with coarser grains towards the centre of the fracture and finer grains towards the fracture walls (Ravier et al. 2015), see figure 8. The process of clay sedimentation is subsequently dramatically different within hydrofracture systems compared to traditional environments of clay deposition, such as lacustrine and fluviatile environments. As stated by van der Meer et al. (2009) regarding sediment injection into hydrofracture systems, “ordinary sedimentological rules do not apply”. In traditional environments clay deposition is synonymous with low energy conditions. The duration of such conditions is extremely short within hydrofracture systems due to the rapid decrease in fluid pressure, see figure 9, which leads to closure of the system and termination of sedimentation. Thus, the time for clay particles to settle out of suspension within hydrofracture systems is extremely limited (Phillips et al. 2013a).

In addition to the plastering of clay particles to the fracture walls these may also get injected into the pore spaces of the wall rock immediately adjacent to the hydrofractures, either lining them or filling them with clay cutan. The cutan is introduced by the pressurized water bleeding out from the fracture into the pore spaces of the fracture walls (Phillips et al. 2013a). Phillips et al. (2013a) highlights how the combined effect of clay plastering and clay cutan injection into pore spaces effectively seal the fracture from the host material, resulting in concentrated peak fluid flow, further aiding the propagation of the hydrofracture, see figure 7.

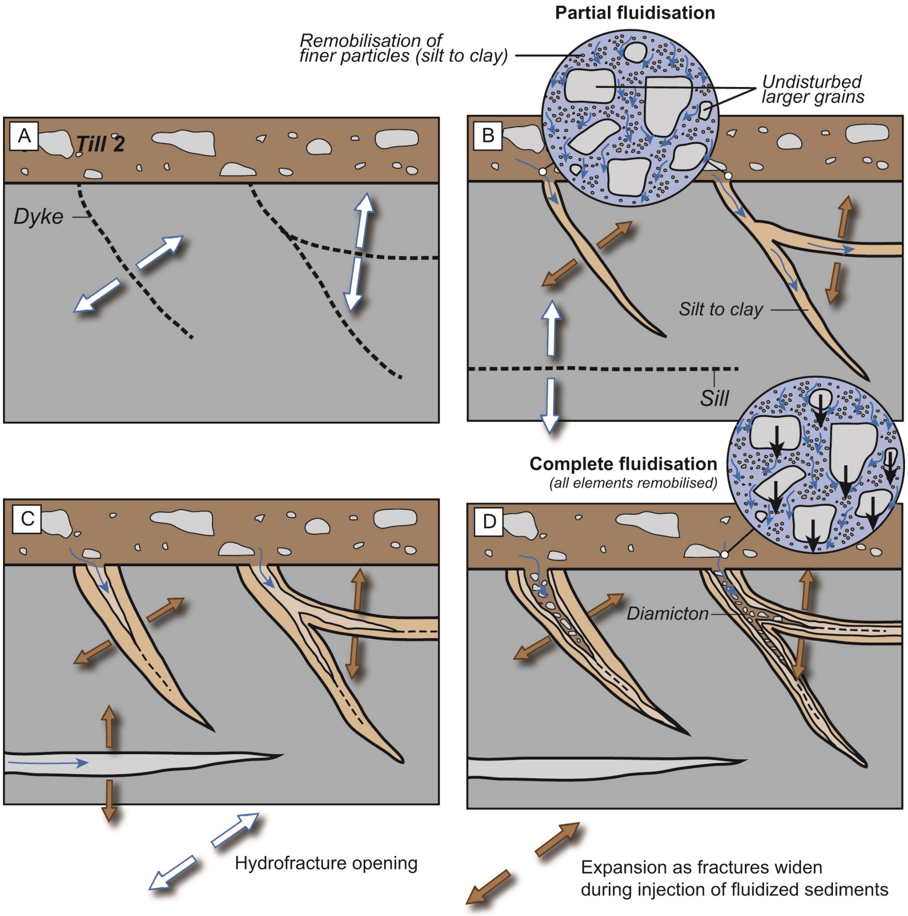

Fig. 8. Principal illustration of a sequence of hydrofracturing and subsequent injection of fluidized sediments resulting in laminated hydrofracture fills. **A**. Elevated porewater pressure exceeds the tensile strength of the host material which initiates hydrofracturing. **B**. Partially fluidized sediments are injected into the hydrofracture. These are initially consisting of clay and silt. **C**. A new episode of elevated porewater pressure leading to the reactivation of the hydrofracture system and a new phase of sediment injection. **D**. High porewater pressure results in the complete fluidization and injection of the sediments into the fractures (Ravier et al. 2015).

3.2 Subglacial hydrofracturing and subsequent sediment injection/infill compared to industrial hydrofracturing

Industrial hydraulic fracturing, more commonly known as 'fracking' or 'hydrofracking' is an industrial process used to increase the permeability of a reservoir in order to increase the possible uptake. It is traditionally used for the extraction of fossil fuels such as petroleum, natural gas, coal seam gas and similar substances (Smith & Montgomery 2015). The technique works by introducing highly pressurized fluid, containing a mix of fluids, sediments and chemical compounds into a borehole. The high fluid pressure then initiates fracturing and further fracture propagation through the reservoir rock. The fractures are kept open by the injected sediments in the fluid mixture (Smith & Montgomery 2015). This creates a network of permeable fractures into which the previously enclosed fuels are released, which in turn enables the extraction of these fuels. The two processes of industrial- and subglacial hydrofracturing thus display striking similarities, raising the question whether these processes can be seen as analogues.

The comparison carried out by Phillips et al. (2013a) between published engineering hydrofracking test data and macro- and microstructures of the sediment infill within the Meads of St John hydrofracture system indicates strong similarities between industrial and subglacial hydraulic fracturing. The comparison show that the style and timing of sedimentation and subsequent deformation at the Meads Of St John hydrofracture system can be directly related to variations in fluid pressure, P, seen in industrial hydraulic fracture data (Phillips et al. 2013a). The time and fluid pressure relations are shown in figure 9A which illustrates a single idealized hydrofracturing event, also referred to as 'flow event'. Flow events are preceded by the build-up of fluid pressures until a maximum pressure is reached which exceeds the bedrock's resistance to fracturing, this in turn initiates hydrofracturing (Phillips et al. 2013a). The propagation of the fractures goes in the direction of lower pressure which is controlled by the overhead load (Murdoch 1995). In a glacial environment this corresponds to a down ice direction, see section 3.1.2 above (van der Meer et al. 1999).

Following the peak fluid pressure value, P max, the pressure dramatically decrease due to fracture propagation within the bedrock dispersing the fluid pressures, see figure 9A. Afterwards a relatively stable period of gradually lowered pressures takes over which is characterized by small-scale variations in fluid pressures, indicated by variations in lamination in the Meads of St John hydrofracture system (Phillips et al. 2013a). These variations and alternating laminations suggest that water flow does not act as a continuous but rather pulsating stream. This could be the result of a 'crack-and-fill' type of sedimentation as a continuous sequence of hydrofracture opening and infilling occurs. Another possibility is that the fractures remain open and local flow constraints results in the varying lamination (Phillips et al. 2013a). In addition, sedimentary structures in the Meads of St John, such as ripple laminations, show that pressures within hydrofractures can be high enough to support open fluid filled fractures, enabling flowing water deposits to form (Phillips et al. 2013a).

By the termination of the flow event, see figure 9A, the fluid pressure once again drastically falls and the activity of the hydrofracture system ceases as the fracture walls close, leading to compression and possibly deformation of the injected sediments. This could either be due to the depletion of the source of pressurised liquid or because the fracture becomes choked/sealed with sediment (Phillips et al. 2013a).

Phillips et al. (2013a) describe how fracking within wells and boreholes generally only need few fluid pressure events to achieve the desired flow enhancement from reservoirs. They also demonstrate how the degree of fluid pressures, P max, as well as the durations of each pressure event decrease for each consecutive hydrofracturing event, see figure 9B. Thus, if these conditions are transferrable to subglacial environments, they could provide important limitations for the development and longevity of subglacial hydrofracture systems (Phillips et al. 2013a). For each hydrofracture event, the permeability of the glacier bed increases as a system of hydraulic pathways is constructed. Such an increase in the permeability of the glacier bed could lead to the decreased ability of the glacial system to produce the high-pressure events needed to further support hydrofracture initiation and propagation (van der Meer et al. 2009). Thus, hydrofracturing has been described as a self-limiting process by Phillips et al. (2013a) as hydrofractures would be progressively abandoned due to the gradual decrease in fluid pressures, see figure 9B. However, Phillips et al. (2013a) also describe how temporal variations regarding meltwater discharge has the potential to repeatedly build up the meltwater content and pressures within the subglacial system, see section 3.1.1. This in turn has the potential to lead to the reactivation of hydrofractures, see figure 9C, resulting in continued fracture propagation, sediment injection, erosion/deformation of earlier injected sediments or fracturing of the adjacent wall where pre-existing fractures are choked/filled with sediments, a process through which new sections are created in the hydrofracture system. Alternatively, a combination of these processes occur during the same flow event in different parts of the hydrofracture system due to inhomogeneity and variability throughout the fracture network (Phillips et al. 2013a).

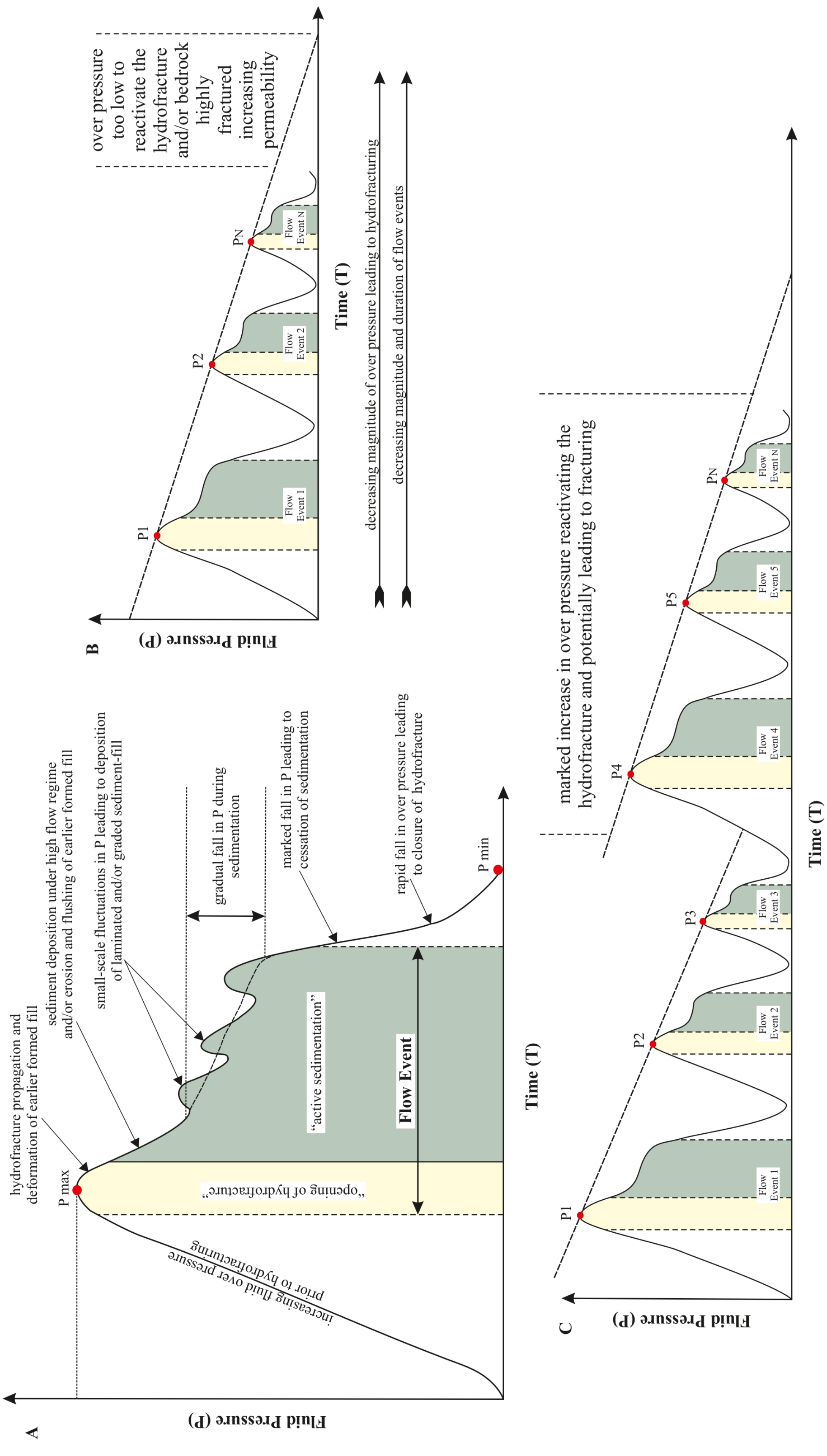

Fig. 9. Representation of idealized fluid pressure fluctuations during hydrofracturing. **A**. A single flow event depicting the relations between fluid pressure, hydrofracturing and sediment injection over time. **B**. Series of flow events that shows the decrease of maximum fluid pressure for each flow event. **C**. Reactivation of the hydrofracture system, possibly through fracturing of the adjacent wall rock, relating to the elevated fluid pressure (Phillips et al. 2013a).

3.3 Controls on liquefaction and hydrofracturing

As discussed above, the series of events leading to hydrofracturing and subsequent sediment injection in subglacial environments follows a process of elevated porewater pressure within constrained sediments, hydrofracturing and injection of dilated/fluidized sediments into the fractures (Jolly & Lonergan 2002). The initial and controlling factor of these processes is thus the level of porewater pressure within the subglacial system. In turn, the triggers for elevated porewater pressures and subsequent dilation/liquefaction has been attributed to many factors, such as seismicity, subglacial volcanic eruption, sediment loading, fluid migration, ice load, etc (Larsen & Mangerud 1992; Obermeier 1996; Hildebrandt & Egenhoff 2007; Phillips et al. 2018). Presented below are mainly the triggering mechanisms for liquefaction, and subsequent hydrofracturing, as described by Phillips et al. (2018) since they encompass many of the triggering factors within the categories of *pressurized meltwater*, *glaciotectonism* and *glacier related seismicity*.

Introduction of pressurized meltwater into the subglacial environment is one of the most widely attributed factors for enhanced porewater pressures (Phillips et al. 2018). This factor is strongly coupled with the seasonal meltwater variations throughout the year, where higher input of meltwater occurs during the spring and summer months. Additionally, diurnal variations in porewater pressure play into these conditions (Iken & Bindschadler 1986; Hubbard et al. 1995; Nienow et al. 2005). The subglacial environment's ability to constrain the meltwater is an important factor regarding the build-up of fluid pressures, i.e. the porosity and permeability of the sediments as well as the efficiency of the subglacial drainage systems (Evans et al. 2006; Werder et al. 2013). An enhanced meltwater input does not necessarily entail higher porewater pressures. If the subglacial bed consists of low to moderately permeable sediments a sudden increase in pressurized meltwater is more likely to result in stable drainage systems, probably in the form of channels, rather than increased porewater pressures within the sediments. This is due to the inability of such low permeable sediments to effectively process a rapid input of meltwater into the pore spaces, which instead leads to dewatering of the bed through the drainage channels (Phillips et al. 2018). In addition, periods of lower water levels within subglacial drainage systems has shown to create a hydrostatic gradient towards subglacial drainage channels, resulting in the dewatering of the sediments around such drainage networks (Hubbard et al. 1995). Another possible process which can result in increased porewater pressures is the increase of pressure within the subglacial meltwater system. An increased ice overburden would work to increase the effective pressure, essentially pushing meltwater at the ice-bed interface into the underlying sediment, potentially overcoming any limiting factor presented by the permeability of the sediment (Phillips et al. 2018). This process could however directly lead to hydrofracturing of either the sediment/bedrock or the overlying ice if the pressures were to exceed the shear strength of any of the surrounding materials (Phillips et al. 2018). Thus, a big contributor to the onset of hydrofracturing is likely to be differences in hydraulic properties between neighbouring sedimentary units. Coupled with potential pre-existing planes or lines of weakness these factors likely exert a major control for the location and orientation of subglacial hydrofracturing (Phillips et al. 2013a; Phillips et al. 2018).

Another possible trigger for dilation/liquefaction and hydrofracturing is glaciotectonism. This process may lead to locally increased overburden pressure due to deformation and subsequent increase in porewater pressure. This could be due to folding or imbrication of the subglacial sediments (Lee & Phillips 2008; Phillips et al. 2018). On the contrary it has also been argued that thrust planes and shear zones coupled with such deformation can act as hydraulic pathways (Benediktsson et al. 2008; Lee & Phillips 2008; Phillips et al. 2008). Thus, such deformation could rather lead to dewatering of the system and reduction of porewater pressures (Phillips et al. 2018).

The third possible trigger, presented by Phillips et al. (2018), is glacier related seismicity. Glaciers are seismically active due to fracture/crevasse propagation, calving, serac toppling, slip events at the ice base, opening and closing of englacial drainage conduits and movements of faults within the ice body or underlying bed (Ekström et al. 2003; Peng et al. 2014; Lipovsky & Dunham 2016; Podolskiy et al. 2016; Phillips et al. 2018). Glacial seismic processes can occur throughout the entirety of a glacier throughout the year and are therefore continually transmitting energy throughout the glacier and the subglacial bed (Phillips et al. 2018). The energy produced can radiate in all directions from the hypocentre. For example, a large calving event at the glacier margin can have effects several kilometres further up-ice (Phillips et al. 2018). According to Wiens et al. (2008) glacial seismicity events can over a period of up to 30 min release the equivalent amount of energy as a magnitude 7 earthquake, although with smaller amplitudes, e.g. Ms 3.6-4.2. The connection between seismicity and dilation/liquefaction is well documented regarding earthquakes (Holzer et al. 1989; Youd 2003) and provides support for similar liquefaction events to be induced by glaciers. Liquefaction by seismicity is dependent on a number of factors such as earthquake moment magnitude, shaking duration, depth to groundwater table, maximum ground motion, the sediments susceptibility to dilation/liquefaction as well as current porewater content/pressures in the sediments (Youd 2003). An important aspect is that dilated/liquefied sediments may continue to be unstable after the initial seismic event and may continue to be dilated/liquefied by consecutive smaller aftershocks (Phillips et al. 2018). As the energy released by a glacial seismicity event travels through the ice and into the bed it has the potential to trigger dilation/liquefaction of the sediments (Phillips et al. 2018) and possibly subsequent hydrofracturing. Seismically induced liquefaction is due to induced vibrations of the grains in the sediments which modifies the packing and leads to elevated porewater pressures, see figure 12. A liquefaction event would subsequently be followed by a stabilisation of the sediments, propagating from the hypocentre, as grain vibrations and subsequent porewater pressures diminish (Phillips et al. 2018). The oscillating ground motions caused by earthquakes produces repeated reversals of shear direction, leading to both repeated episodes of liquefaction as well as dilatant hardening (Youd 2003). Thus, these processes could compose important controls on dilation/liquefaction and hydrofracturing if they also apply to glacial seismological events (Phillips et al. 2018).

3.4 Quarrying & till production

As is presented by Drewry (1986), quarrying is the dominating mechanism of subglacial erosion. The findings presented by Evans et al. (1998) from Loch Quoich, northwest Scotland, Konowbreen, St. Jonsfjorden, Svalbard and Jardalen, Sogn-og-Fjordane, western Norway provide evidence of early stage bedrock plucking along sediment injected faults. Traditionally, many papers have presented interpretations of deforming tills containing angular clasts at the base. These have overall been used as evidence of pre-existing loose regolith being entrained during initial glacier advance. However, the material has been shown to potentially be the product of plucking of the underlying bedrock despite the possible existence of a till layer at the ice-bed interface (Evans et al. 1998), see figure 10.

Evans et al. (1998) describes how a process of fluctuating porewater pressures within subglacial tills represent the most efficient method for quarrying in their respective study sites. Conditions of high porewater pressures also present the most likely scenario for the injection of the fines observed in the fractures of the early stage plucking slabs, see figure 11. This is due to the high porewater pressures resulting in the dilation and possible liquefaction of the sediment, enabling their injection into the fractures (Evans et al. 2006). However, high porewater pressures limit the transmission of shear stress to the bed (Phillips et al. 2018), likely resulting in insufficient shear stress for the displacement of large slabs of bedrock (Evans et al. 1998). A reduction in porewater pressure would on the other hand support the transmission of shear stress throughout the system as the sediment stiffens. Bedrock fragments could then be removed by the brittle shear of the injected sediments or by sliding over underlying joints (Evans et al. 1998). Additionally, if any overlying sediments were to thin out sufficiently, an ice-bedrock contact could occur which could transfer the shear stress directly to the bedrock, also prompting displacement (Evans et al. 1998). Although the required porewater pressures could be reached in many different subglacial settings, subsequent high rates of quarrying are only likely to occur in areas of thin deforming till that is in contact with bedrock at least periodically. This is due to the dampening effect thick till layers have on both the porewater pressures as well as the transmission of shear stress (Evans et al. 2006). Consequently, if the conditions presented by Evans et al. (1998) is applicable to other glacial settings then areas with high amount of quarrying should have been influenced by fluctuating porewater pressures. When the pressure levels are high, sediment injection into bedrock fractures can occur and when the pressure lowers, the shear stress from the overlying glacier can reach the released bedrock slabs, prompting their displacement (Evans et al. 1998).

Croot & Sims (1996) indicated that the disaggregation of bedrock rafts at Fanore, western Ireland, play a major roll regarding the till production in the area. The till is here partly a product of the crushing of bedrock slabs rather than abrasion. This process of crushing of bedrock slabs thus has the potential to compose a major controlling factor for till production, till characteristics and till continuity, something that historically has not been taken into consideration in areas containing till layers at the ice-bed interface (Cuffey & Alley 1996; Evans et al. 1998). The addition of quarried clasts into an overlying till layer will contribute to a wide grain size distribution within the till which in turn promotes further erosion by abrasion, further contributing towards till continuity (Evans et al. 1998).

Fig. 10. Picture of locally plucked bedrock clasts entrained in subglacial till. The picture is taken from Loch Quoich, northwest Scotland. Reproduced with permission from D.J.A. Evans.

Fig. 11. Photograph of the lower bounding fracture of a bedrock slab in Konowbreen, St. Jonsfjorden, Svalbard. The fracture is filled with fines and the bedrock slab has been displaced in the direction of paleo ice flow rather than in the direction of local slope, indicating that the displacement cannot be the result of postglacial processes. Reproduced with permission from D.J.A. Evans.

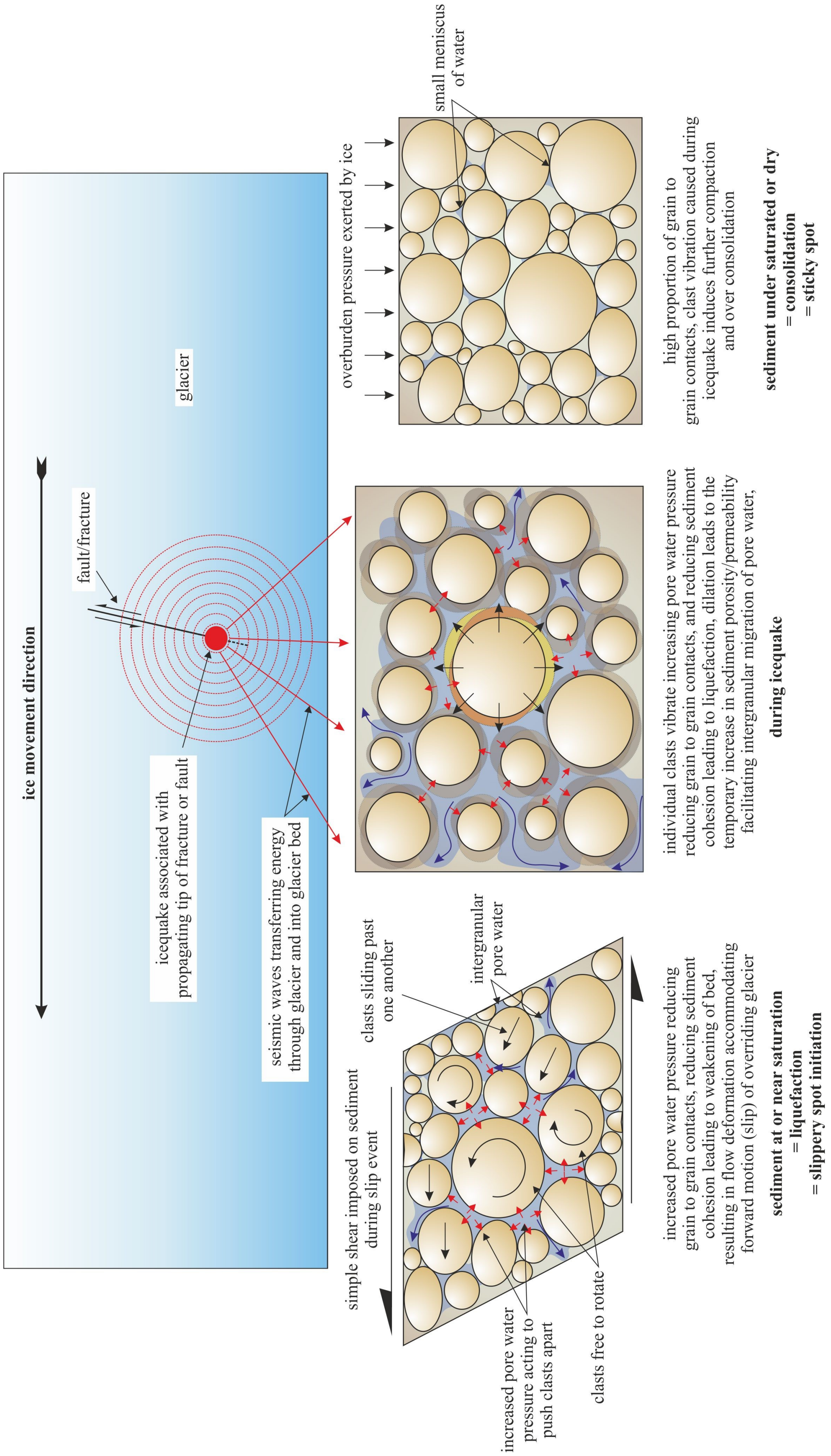

Fig. 12. Principal illustration of icequake induced seismic waves and their effects on unconsolidated subglacial sediments (Phillips et al. 2018).

4 Impacts of subglacial hydrofracturing on underlying bedrock

It is clearly shown in several case studies that subglacial processes can have an immense impact on the bedrock. Through the process of elevated subglacial porewater pressures and subsequent hydrofracturing and sediment injection these processes exert a control on the internal structure of the bedrock, either by creating new or further enhancing existing fracture systems (Phillips et al. 2013a). Thus, the most obvious implication is the deteriorating effect on bedrock integrity. This could prove to produce instability of the bedrock in glacial and postglacial areas characterized by subglacial hydrofracturing and subsequent infill. From a societal point of view this could prove to provide problems if such areas were to be urbanised as fractured bedrock areas often constitute difficulty regarding urban development. It is worth considering the possibility that known areas of fractured bedrock within postglacial areas may, at least to part, be the result of hydraulic fracturing. Even if exposed bedrock fractures in such areas lack the characteristic sediment injection these could be the remnants of subglacial hydrofracture systems as their infill could have eroded over time. A question of high uncertainty regards the maximum horizontal and vertical extent of subglacial hydrofracture systems. Very little research has been conducted on this topic and since this is likely to exert a major control on other impacts of hydraulic fracturing more research should be dedicated to determining the possible extent of subglacial hydrofracture systems. If some sort of relationship with fracture extent could be established, for example with ice thickness, this would constitute an important tool regarding our understanding of the possible extent of subglacial hydrofracture systems.

The fracture systems produced by hydrofracturing work as hydraulic pathways as water can flow through the permeable sediment-filled fractures (Phillips et al. 2018). This could exert an important control on the hydrogeology of hydrofractured areas. Such pathways could have an impact on the dynamics of potential groundwater reservoirs, possibly acting as either draining or refilling conduits. This could also have implications from a societal viewpoint regarding urbanisation efforts and possible extraction of groundwater.

An important and possibly limiting factor of water migration through hydrofracture systems is the character of the injected sediments. If the infill primarily consists of clay-rich sediments, the conductivity of the fracture system is likely to be considerably lower than if it were to consist of a higher grade of coarser material. The injection of clay into the pore spaces of the adjacent fracture walls and the plastering of clay to the fracture walls (Phillips et al. 2013a) could also act as impermeable barriers, essentially restricting waterflow to within the fracture. Whether or not the fracture has propagated to reach a more permeable layer is also a potential deciding factor regarding the degree of water flow through the fracture system. If these never were to reach more permeable systems or emerge as springs, they could potentially make up dead ends in the hydraulic system.

The processes described by Evans et al. (1998) in Loch Quoich, Scotland, Sogn-og-Fjordane, Norway and St Jonsfjorden, Svalbard display strong similarities with the processes of hydraulic fracturing and subsequent sediment infill. The process of sediment infill into fractures of preserved early stage plucking formations is attributed to variations in porewater pressures in the subglacial environment rather than postglacial sedimentation. The structures, type of sedimentation and triggering factor are thus very much comparable with those found within hydrofracture systems. Therefore, this raises the question if the fractures described by Evans et al. (1998) actually are the direct result of hydrofracturing? If this was the case, hydrofracturing would constitute a controlling factor for the quarrying of bedrock as well as for till production, till characteristics and till continuity. In addition, this would also indicate that hydrofracturing would become less likely with the presence of thick deforming till layers/traction tills.

The formation and direction of subglacial hydrofracture systems have been shown to be controlled by the variation in overburden pressure exerted by the ice. This results in fracture propagation to occur in a down ice direction with downward, *per descensum*, dykes in the subglacial environment, upward, *per ascensum*, dykes in the marginal and/or proglacial environment and sills in the intermediate environment (Ravier et al. 2015). This has prompted researchers to promote hydrofracture systems to be used as proxies for reconstruction of paleoenvironments and paleo-ice dynamics (Ravier et al. 2015). However, the effective use of these features as proxies are likely to be limited regarding hydrofractures and sediment infill in bedrock. This is due to the inherent difficulty of exposing and thus examine such features within bedrock compared to unconsolidated sediments. Hydrofracture systems within bedrock could however possibly be used for this purpose as well with the use of rock penetrating analysis techniques.

The comparison of the subglacial hydrofracture system within the Meads of St John with published engineering data made by Phillips et al. (2013a) shows that the timing and style of sedimentation as well as deformation within the system are directly related to fluid pressure variations during industrial hydrofracturing. Thus, if applicable to other subglacial hydrofracture systems, fracking could be an important tool for further understanding and explaining subglacial hydrofracture formation, propagation and subsequent sediment infill within different bedrock environments. In addition, the similarities between the processes of subglacial- and industrial hydrofracturing inherently bring with it the question of whether subglacial hydrofracture systems could be used for extraction of natural resources, as is done with industrial hydrofracturing. For this to be possible the fracture system would have to be emplaced within a reservoir containing viable amounts of natural resources. However, as mentioned above, the potential lowering of the conductivity between the fracture and adjacent wall rock due to clay plastering and clay injection into the wall rock might inhibit transport to the fracture, thus preventing extraction. This do not constitute a limiting factor within industrial hydrofracturing since the injected fluid-sediment mixture contains a controlled grain size composition. Alternatively, if the clay plastering and injection would prove to not inhibit transportation into the fracture then the question is if the fractures instead would lead to the escape of potential resources, resulting in the depletion of the reservoir. If this were the case subglacial hydrofracturing could potentially exert a strong environmental influence as they release compounds into the surrounding area or atmosphere. Another controlling factor regarding potential extraction of resources is the extent of the hydrofracture system. Whether the possible extent of subglacial hydrofracture systems in bedrock is sufficient to validate and support any potential resource extraction is currently unclear.

5 Conclusions

From the comparison of the articles investigated in this study several conclusions can be made regarding the impact of subglacial processes on underlying bedrock. Through the process of hydrofracturing it undoubtedly has a deteriorating effect on the structural integrity of the bedrock, which in turn leads to alteration of the hydrogeological conditions in such areas. More research should however be dedicated to the effects of clay plastering and clay injection into the wall rock within hydrofracture systems as this potentially exerts limits regarding the conductivity both through the fracture and between the fracture and the adjacent wall rock. The hydrofracturing process is also likely to play an integral part of the quarrying of bedrock and the continuity of till production and till characteristics. It is possible that hydrofracturing play a bigger part in the process of bedrock fracturing than has previously been acknowledged. Even if such fractures lack the characteristic sediment infill the fractures could possibly still be the result of hydrofracturing as the infilled sediments could have eroded over time. Thus, further research and/or revaluation regarding bedrock fracturing processes could be warranted within postglacial areas. Strong similarities have been demonstrated between subglacial- and industrial hydrofracturing, thus showing that fracking conditions can be used to explain subglacial hydrofracture processes and environments. To which degree this is applicable to different types of bedrock is however unknown and requires further research. Equally, whether the two processes of industrial- and subglacial hydrofracturing have a similar final effect on the bedrock environment and the conditions there is also unclear and thus demands further investigation.

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