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In situ monitoring and physical modelling of subglacial deformation at Skalafellsjökull

by

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ABSTRACT

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IN SITU MONITOURING AND PHYSICAL MODELLING OF SUBGLACIAL DEFORMATION AT SKALFELLSJÖKULL

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The controls on glacial movement remain one of the most poorly understood elements of the glacial system, largely due to the inaccessibility of the subglacial environment. Here a geotechnical study is presented that investigates the behaviour of till under pore pressure controlled decreases in normal effective stress. This is supplemented with field data from subglacial wireless probes, dGPS, GPR and a UAV survey of the glacial foreland to provide a broad view of subglacial deformation at Skalafellsjökull, Iceland

The geotechnical laboratory investigation was undertaken on till sampled from an ice marginal location at Skalafellsjökull, close to the probe deployment site. This showed that the till adhered to the Mohr-Coulomb model, behaving plastically. In addition, a back pressure shear box was used to model pore pressure controlled reductions in normal effective stress. Linearly reducing normal effective stress by increasing back pressure resulted in episodic increases in horizontal strain rates. Small reductions in shear stress resulted in large strain rate reductions but dilation hardening did not occur. Dilation hardening has previously been suggested as a causal factor in stick-slip glacial motion and a reason for the apparent scale dependence of till rheology, but these experiments suggest it may not be as significant as previously thought.

High spatial variability was found throughout the field investigation in probe, dGPS and mapping data from the UAV survey. dGPS deployed above *in situ* subglacial probes recorded hourly ice movement indicative of stick-slip motion but it was not possible to link this motion to subglacial processes *via* probe data. Pore pressure data suggested spatially variable coupling to the subglacial hydrological system and inconsistent forcing by surface melt. Tilt data showed consistent movement patterns and lacked regular up-glacier movements previously thought to indicate ice-bed decoupling and sliding. The lack of evidence for forcing of velocity variability from the *in situ* data suggests a global forcing mechanism at this site, probably longitudinal or lateral coupling to higher velocity areas of the glacier. The spatial variability of the subglacial data has similarities to the metre scale spacing of flutes on the foreland mapped with the UAV imagery, suggesting flute formation has potential to result in complex probe behaviour.

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Hackney, Christopher and Clayton, Alexander (2015) 2.1.7. Unmanned Aerial Vehicles (UAVs) and their application in geomorphic mapping. In, Clarke, Lucy and Nield, Joanna M. (eds.) Geomorphological Techniques. London, GB, British Society for Geomorphology.

DECLARATION OF AUTHORSHIP

I, Alexander Ian Clayton declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

***In situ* monitoring and physical modelling of subglacial deformation at Skalafellsjökull**

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
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3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
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I thank the Geography departments of Southampton University and Durham University for the generous use of their facilities and equipment. Southampton kindly entrusted me with a UAV and Durham with a back pressure shear box. Both were broken to some degree during the research and both institutions were extremely forgiving in the aftermath of each incident. I am indebted to laboratory technicians at both institutions. Neil Tunstall and Chris Longley at Durham provided hours of tuition and support as I learned geotechnical laboratory techniques. Dr Tom Bishop at Southampton kindly aided me in the field and proved incredibly patient in the face of taxing UAV deployment requests.

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For Isaac

Chapter 1: Introduction

1.1 Research background

The controls on basal glacial movement remain one of the most poorly understood elements of the glacial system and consequentially the topic remains at the forefront of glaciology. The fundamental difficulty in studying this field is the inaccessibility of the subglacial environment that we now know is central to understanding glacial movement (Boulton, 1986, Iverson, 2010). This has led to different models for sediment behaviour and subglacial dynamics (Hindmarsh, 1997; Tulaczyk, 2006; Sane *et al*., 2008).

As well as difficulties obtaining insights into the specifics of the processes controlling glacial movement, progress in the field has also been hampered by a deficit of information on the manner in which glaciers move. This is partially a technological difficulty with GPSs (Global Positioning Systems) capable of recording at the spatial and temporal resolution required only available in recent years, and InSAR (Interferometric Synthetic Aperture Radar) analysis (Gray *et al*., 2005) and image based equivalents (Immerzeel *et al*., 2015) only recently becoming widespread. Furthermore, although working on the glacier surface is logistically easier than working subglacially, it remains challenging (Murray *et al*., 2015).

The spatial and temporal heterogeneity of the glacial environment and system exacerbate all these issues. They complicate data collection by necessitating a broader sampling regime if reliable insights are to be provided. When this is not possible, as it rarely is due to the difficulties covered above, instead it becomes sensible to approach the subject from multiple perspectives. This has resulted in glacial movement being studied via field investigation but also numerical and analogue modelling.

Largely because of the inaccessibility of the subglacial environment, the significance of soft sediments underlying glaciers was not fully realised until the late 1970s (Boulton & Jones, 1979). The use of *in situ* experiments revealed that glaciers were capable of deforming the sediments and that this might account for 80% of glacial movement. This significant discovery, hailed as a ‘paradigm shift’ (Boulton, 1986) was taken up rapidly by the glacial community. However, it has taken time to develop an understanding of the precise processes occurring in subglacial deformation, and how and when it contributes towards glacial movement.

Early elaborations on this theory towards a governing relationship of till deformation demonstrate how the scale at which we study subglacial deformation can influence the outcome. Boulton and

Hindmarsh (1987) proposed a linear viscous model of subglacial deformation and this relationship was backed by further studies (e.g. Alley *et al.* 1987; Alley, 1989; Clarke, 1987). However, through a change of approach to the subject Kamb (1991) demonstrated that actually a plastic rheology better suits till deformation. This caused some confusion, as a plastic rheology is problematic to combine with large scale movement of ice. However, Hindmarsh (1997) suggested that both were reasonable models of glacial movement but the disparities were due to issues of scale. It does appear that relationships such as the linear viscous model, that are effective at the macro scale, do not always match up with meso-scale observations. Despite this debate initially emerging in the early 1990's it remains very current and is a key stumbling block in predicting glacier dynamics (e.g. Ritz *et al.*, 2015).

In situ and laboratory work has been prominent over the last 20 years in tackling this discrepancy. Laboratory work has generally been more direct and extensive, helped by the accessibility of equipment in many universities and the applicability of a wealth of geotechnical literature. *In situ* sensing has perhaps more potential for elaborating on subglacial processes purely due to its observational nature. However, attempts to produce useful data have been often frustrated by the difficulty of both implementing the studies and making sense of frequently complex data from novel equipment.

1.2 The gap in the literature

Developing a full understanding of how subglacial processes control glacial movement is essential for accurately predicting how the cryosphere will contribute to sea level change and the hydrological cycle as climate warms. The two largest ice sheets, Antarctica and Greenland, lose large proportions of their mass via calving, and future variability is partially regulated by basal controls on the drawdown of ice from the interior of the ice caps.

Uncertainty still lies in how the plastic rheology of till can be effectively incorporated into large scale modelling and this directly impacts the degree to which future sea level rise can be forecast (Ritz *et al*., 2015). There have been a number of significant findings such as the role of sticky-spots (Alley, 1993; Fischer *et al*., 1999; Stokes *et al*., 2007), the manner in which ice on deformable beds switches between subglacial deformation and soft-bed sliding (Iverson *et al*., 1999a; Winberry *et al*., 2011) and the role of dilation strengthening in maintaining quasi-stable shear (Moore & Iverson, 2002). However, there remain relatively few data led studies in this field and few replications of key research. Additional studies in this area seem likely to produce new findings and improve our understanding.

Cuffey and Paterson (2010, pg.256) succinctly identify the primary goal of current research as *'predict(ing) the shear stress that a deforming bed exerts on a glacier; such stresses resist the flow of the ice and govern the dynamics of many ice streams and mountain glaciers'*. To date this has not been achieved. This thesis will address this question with specific reference to glacial dynamics at Skalafellsjökull and it is hoped that this will provide additional resources for a more generalised prediction of shear stress and so ice dynamics.

1.3 Approach

This thesis attempts to combine multiple techniques. By approaching the question of how glacial movement is controlled by subglacial deformation in a holistic manner it is hoped that each method's merits will be more suitably applied, and *vice versa*. The starting point is an in depth and novel geotechnical laboratory investigation into the properties and manner of deformation of till collected from Skalafellsjökull. After initial characterisation of the till, a more specific investigation is conducted into the control of pore pressure increases on till deformation, and if dilatency is a controlling factor on increases in strain rate. The results from this are then used to help interpret data from the Glacsweb research group that conducts *in situ* sensing below Skalafellsjökull in Iceland. This is based on two major deployments, one in 2008 before the PhD commenced (Martinez *et al*., 2009) and one in 2012 (Martinez & Basford, 2012). These elements are complimented by a final smaller investigation into foreland geomorphology at Skalafellsjökull. This is based on a UAV (Unmanned Aerial Vehicle) survey.

The integration of *in situ* sensing and geotechnical testing is not new but is not standard either. The literature to date clearly demonstrates how each technology has extensive potential, but effective integration often is lacking resulting in partial understandings developing that hinder development of the field. Seminal advances have been made through concentration on any one technology, for instance Boulton's (1979) *in situ* work, or Kamb's (1991) geotechnical investigations, but more recently the combined approach appears more effective (e.g. Iverson *et al.* 1999a, 1999b). In this thesis, each technique's partial representation of the subglacial deforming system combines to provide a better understanding.

A UAV is used in the thesis to collect imagery that is then processed in a SfM (Structure from Motion) photogrammetric software package to produce a high resolution digital elevation model of the foreland of Skalafellsjökull. Over the course of the PhD UAVs have switched from being rare, expensive and used for proof of concept studies (e.g. Whitehead *et al.,* 2013) to appearing ubiquitously in consumer marketplaces and being applied as an effective methodology (e.g. Chandler *et al*., 2015; Ryan *et al,* 2015) . Here the UAV provides an opportunity to study the morphology and distribution of subglacial bedforms across the foreland and so inform interpretations of *in situ* data collected from the deforming zone.

1.4 Aims and objectives

The aim of this thesis is:

'…to constrain subglacial deformation's contribution to ice flow resistance in a holistic manner with the use of geotechnical, in situ, and high resolution survey technologies.'

The *in situ* sensing is specifically wireless *in situ* sensing which to date nobody has attempted to combine the results of with geotechnical work. Similarly, due to the general paucity of *in situ* sensing of the subglacial environment very few have been interpreted in light of geotechnical experiments based on the same till. The combination of techniques is, to date, a unique situation.

The objectives of the PhD are fivefold:

1. To establish the rheology of the till at Skalafellsjökull.
2. To establish if the rheology of the till at Skalafellsjökull is consistent across the different modes of investigation.
3. To assess how pore pressure variations impact the behaviour of till samples in geotechnical experimentation and to what extent the variations and behaviour is replicated at Skalafellsjökull (as observed by the *in situ* study).
4. To determine whether Skalafellsjökull moves in a 'stick-slip' manner and to what extent this can be explained by subglacial conditions.
5. To assess whether bedforms occur on a specific scale and therefore whether their formation is likely to have an impact on till mobility and associated probe behaviour.

1.5 Thesis structure

Following **Chapter 1** (*Introduction*) the *Literature Review* in **Chapter 2** explores the field of subglacial deformation. It presents how the field has developed and key areas of debate have emerged since the early 1970s, in particular the rheological debate that is perhaps the most fundamental to the field. Other smaller areas pertinent to the three methodologies employed are covered in an attempt to better contextualise analysis in later chapters e.g. the current understanding on the partitioning of strain within the subglacial zone.

Chapter 3 (*Field site*) introduces Skalafellsjökull, the field site used throughout the thesis. The foreland area and Glacsweb site higher up the glacier are introduced in turn and the scientific and logistical decisions behind their selection are outlined. As much of the Glacsweb project's preceding work is relevant to the thesis the previous field site, Briksdalsbreen, is compared to the current location.

Chapter 4 (*Geotechnical characterisation of Skalafellsjökull's till*) establishes the framework from which the experimentation in chapter 5 can be undertaken. By providing details on tests that establish the fundamental behaviour of the till samples from Skalafellsjökull it means the later experiments are more rigorously conducted and future workers can more easily conduct comparisons to the properties of their till. Test stress states are based on likely conditions at Skalafellsjökull where the *in situ* study has been conducted.

Chapter 5 (*Geotechnical PPR experimentation*) investigates the role of pore pressure increases on the deformation of till. The stress states chosen for these experiments broadly replicate the conditions likely to be found at Skalafellsjökull, but the investigation and results are have much wider their relevance to subglacial bed deformation. The experiments involve linear pore pressure driven decreases in normal effective stress under a constant deviatoric stress. Comparison to the similar but fundamentally methodologically different testing conducted by Moore and Iverson (2002) is undertaken, and the role of dilation controlled strengthening in stick-slip movement considered.

Chapter 6 (*Foreland Flute Distribution*) sets out the case for integrating bedform studies into a subglacial investigation. The link between foreland geomorphology and subglacial dynamics is explored via consideration of the scale and lateral spacing of flutes present on the foreland. This study is limited in scope compared to studies focusing on flute geomorphology but provides useful insights that help theorise about the level of disturbance to probe behaviour flute production may cause.

Chapter 7 (*In situ sensing of the subglacial environment*) presents and analyses the subglacial probe and dGPS data collected by the Glacsweb project from 2008-2014. The chapter considers to what extent surface velocity can be explained by subglacial data, in particular the stick-slip style of motion, and whether any of the subglacial data informs as to the subglacial partitioning of strain. The data is considered in light of the results of Chapter 5 that helps inform the discussion about the likely cause of stick-slip motion at the site studied.

Chapter 8 (*Discussion*) opens with a discussion of the geotechnical experimentation and the wider applicability of the findings to subglacial bed deformation. The other findings are then discussed, beginning with a discussion of scale in the thesis. It then reflects on individual findings from the previous four chapters in the context of the findings in other chapters. The spacing of flutes on the foreland is considered alongside *in situ* data findings, dGPS and probe data is used alongside geotechnical data to see if till rheology is consistent across both areas. The chapter then closes with a discussion of glacial movement at Skalafellsjökull.

Chapter 9 (*Conclusions*) summarises the findings of the individual chapters and those that emerge from the discussion chapter.

Chapter 2: Literature Review

2.1 Introduction

This chapter outlines the theoretical framework for the research undertaken in this thesis. The current understanding of the mechanisms and manner of glacial movement is explored, and key areas of research are identified. This is then followed by separate sections on investigative approaches used in this thesis (*in situ* sensing and geotechnical experimentation). Previous work is examined, and where appropriate methodological improvements are identified and carried forward.

2.2 Glacial Motion

Glaciers move primarily due to their presence on a slope and the force of gravity exerted on them. The manner in which they do this can be broken down into three processes; deformation of the ice, sliding between the ice and the substrate and deformation of the substrate itself. This thesis is concerned largely with the latter two processes and particularly the latter process, but at times all three are significant.

This ‘system’ approach reflects these processes not being mutually exclusive. All three processes will be present within many glaciers, at least over a season. Some distinctions should be drawn though. Whilst subglacial sliding and deformation can occur in the same location, two major types of sliding can be differentiated. Rigid bed sliding and soft bed sliding differ due to the underlying substrate. Rigid bed sliding occurs on a non-deformable bed that precludes subglacial deformation. Conversely, soft bed sliding occurs on a substrate that permits subglacial deformation.

Because the processes of sliding and bed deformation happen in a relatively discrete part of the glacial system, they are often referred to as basal motion or basal slip. Throughout the thesis, basal slip is used when a combined term is required following Cuffey and Patterson (2010).

2.2.1 The deforming bed

Before the 1970s, our understanding of the significance of these processes was limited. Research on glacial movement focused on ice deformation and hard bed sliding with models assuming a rigid bed (Cuffey and Patterson, 2010) due either to underlying bedrock or hard over-consolidated sediments incapable of shearing under the forces applied by glaciation (Kazi and Knill, 1969).

There was evidence for soft bed sliding and deformation (McGee, 1894; MacClintock and Dreimanis, 1964) but little from field or laboratory work on modern glacial processes. A series of studies initiated by G. S. Boulton (Boulton *et al.* 1974; Boulton, 1975; Boulton and Paul, 1976; Boulton, 1979) begin a 'paradigm shift' (Boulton, 1986) in our understanding of the relevance of deformable beds of sediment underlying glaciers.

The addition of modern evidence of deforming beds understandably appealed to much of the glacial community. Ice is often known to be underlain by sediments rather than bedrock. Evidence for this is easily seen in the huge tracts of land overlain by ice in previous glacial periods that are covered by sediments where observations of deformed structures are common (Hart, 1995). This new evidence provided the link between this observation and the subglacial mechanics of movement.

From the perspective of a worker in modern glaciology where technology and mathematically complex science is commonplace, it is perhaps easy to discount the impact of this work. The 'paradigm shift' description by Boulton (1986) certainly can look overly self-publicising from afar, but comments on Boulton's use of physics (Boulton *et al.*, 1975) by Vita-Finzi (1976) belie the state of the science at that time. Referring to the general lack of physics in glaciology they remark '*the fact that it* (physics) *generally still is* (lacking) *may help to explain why so much of the glacial record remains ambiguous, and its conversion into ice (let alone climate) a highly speculative operation'*.

Boulton's work (1979), although not substantiated in detail for nearly a decade (Boulton and Hindmarsh, 1987), was significant in a number of ways. It provided proof for the deforming bed theory, it set out a constitutive model for till rheology, and it was an early example of *in situ* field investigation. In a quite remarkable experiment an englacial tunnel was used to access the deforming layer, into which was inserted a column of markers (see Figure 1). Excavation of these markers after 10 days demonstrated that deformation of the till had accounted for up to 95% of the movement of the glacier. There are a number of points of debate about this work that are covered below but initially some more detail on subglacial deformation is required.

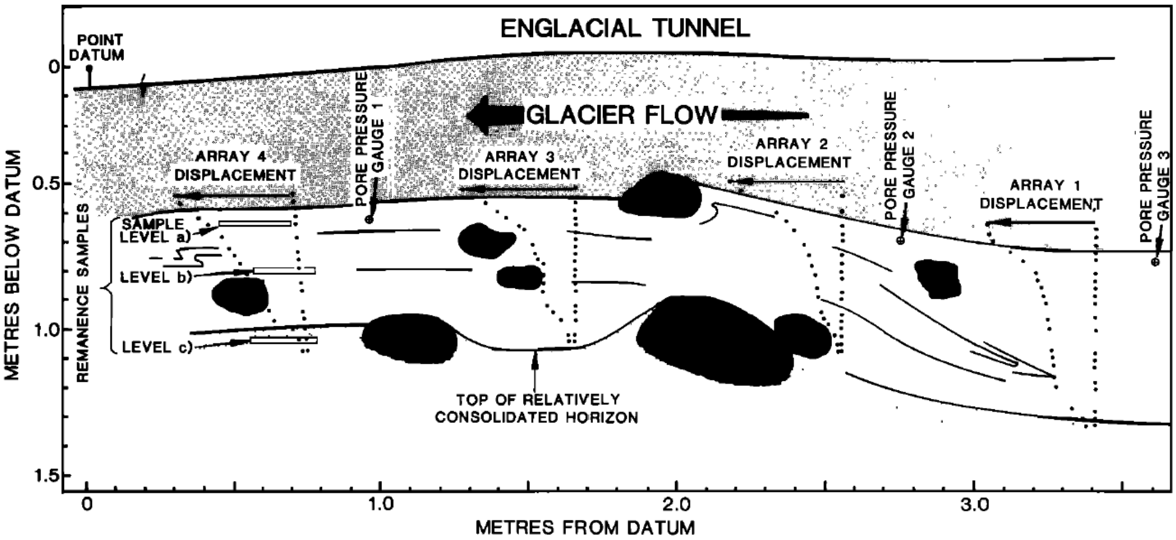


Figure 1: Diagram showing the tunnel and marker placements for an experiment at Breiðamerkurjökull in 1980. Similar experiments were conducted by Boulton and others (unspecified) in 1977, 1977/78, 1980 and 1983. Limited documentation exists of either the 1977 or 1977/78 experiments in Boulton & Jones (1979) and Boulton & Hindmarsh (1987) provides a more complete documentation of the 1980 experiment. Figure reproduced from Boulton & Hindmarsh (1987).

After the initial work in the 1970s, (Boulton *et al.* 1974; Boulton, 1975; Boulton and Paul, 1976; Boulton, 1979) a number of authors seized upon the theory of subglacial deformation and quickly a variety of papers emerged. These varied from observations of deforming layers in Antarctica (Alley, 1986) to 'repetitions' of the as yet unpublished experiments done by Boulton at Breiðamerkurjökull by Echelmeyer and Wang (1987).

2.2.1.1 Constitutive models of deformation

With the theory of till deformation established, Boulton and Hindmarsh (1987) made efforts to incorporate this behaviour into numerical models based on the field data available. This requires reducing the observed data on pore pressure and strain along with calculated shear and normal stresses into a rheological relationship via simple numerical modelling.

Based on this modelling they proposed that the rheology of the till could be expressed a nonlinear Bingham fluid or a nonlinear viscous fluid. The principle difference between them though is that the Bingham fluid model includes a failure criterion that shear stress applied by the glacier must exceed in order to deformation to occur. Alternatively, the nonlinear viscous fluid model simply states that deformation is nonlinearly proportional to the shear stress applied by the glacier. Albeit rather simplistically, this variation is an attempt to include lithology dependant pre-failure behaviour of till into the model that is discussed further in section 2.3.2.

Away from attempts to produce a rheological model for till, the Antarctic work referred to above had gathered apace (Alley et al., 1986, 1987a, 1987b, 1989a, 1989b; Alley *et al.,* 1989c;

Blankenship et al., 1987; Rooney et al., 1987; Macayeal, 1989). This was fuelled by an increasing awareness of the existence and importance of 'ice streams' that funnelled out ice from the interior of Antarctica at significantly higher speeds than the majority of the ice sheet (Bentley, 1987). Velocity observations (Bentley, 1987), seismic work (Blankenship et al., 1987) and coring (Engelhardt et al., 1990; Kamb, 1991) all either indirectly or directly supported the deforming bed model.

With the concept widely accepted, further work focused on the specifics of the rheological model that clearly needed to be well defined for modelling to progress (Alley et al., 1987b). Whereas Boulton and Hindmarsh (1987) approached this from the perspective of numerical modelling and in situ data collection, Kamb (1991) instead used geotechnical experimentation. This was not a new approach in glaciology but in the context of the deforming bed model it was novel. Significantly the experiments also used material recovered from the base of Ice Stream B (Engelhardt et al., 1990), an improvement on previous work (e.g. Radhakrishna and Klym, 1974; Boulton et al., 1976; Beget, 1986) as weathering or cementation of Pleistocene tills after deposition can significantly impact their rheological properties (Sladen and Wrigley, 1983).

Kamb's (1991) results countered Boulton and Hindmarsh's (1987) promotion of the Bingham fluid or nonlinear viscous model. He found that the till's rheology was better described by plastic Mohr-Coulomb behaviour and could only withstand very low shear stresses when tested at atmospheric pressure. The Mohr-Coulomb rule can be expressed as:

$$\tau = C_o + fN \approx fN$$

Equation 1

Where τ is the peak strength, exceeding which will cause failure, C_o is the apparent cohesion, f is the friction factor, and N is the effective normal stress on the material. The details of this are explored below (see section 2.3.2). This was a problematic discovery, not least due to the disagreement between the two studies. The plastic behaviour requires that once failure of the till has occurred there is little to halt the glacier's procession down slope. Clearly, this does not match actual observations of glacial movement. Echelmeyer and Wang's (1987) paper, and the subsequent addition by Huang (1992), was a significant addition at this stage. Whilst largely omitted by the recent major reviews (e.g. Benn & Evans, 2010; Cuffey and Patterson, 2010; Iverson, 2010) these studies presents complex but supportive evidence for deformation and a complex constitutive model of behaviour that somewhat aligns with the Mohr-Coulomb model. It is also an interesting example of combining in situ field investigations with laboratory studies. The study is similar to Boulton (1979) and Boulton and Hindmarsh's (1987) in that it involved the excavation of a tunnel below a glacier. In this case it was 70 x 2 x 1.6 m long through frozen till and ice, a presumably laborious undertaking. Strain markers were emplaced and monitored over time. The key findings were that despite the till being frozen deformation occurred over a 0.35 m section. There was enhanced deformation at the ice-till interface and in discrete areas termed 'shear bands' of ~0.02-0.04 m that commonly were a mix of ice and till. Strain rate appeared to be linear, varying inversely with depth. Comparison of strain rates within ice and the 'shear-bands' gave a calculated difference in viscosity of 100x. In summary, the study showed deformation occurs in this setting and that it in some way approximates the Mohr-Coulomb model.

The follow up study (Huang, 1992) tested the impact of sediment inclusion in ice in order to try and determine the reality of the ice vs mixed ice-till viscosity relationship. In a series of triaxial experiments conducted, importantly, at the sub-zero temperatures as measured in the field, sediment inclusion was shown to lower viscosity by no more than a factor of 3. Therefore, this strengthened the possibility that within areas of enhanced deformation the strain was actually taken up by discrete surfaces. This again supports the Mohr-Coulomb model of deformation.

Yet despite these advances on till's constitutive behaviour, a problematic disparity between theory and reality remained. Whilst in small experiments in the field and laboratory till displayed Mohr-Coulomb behaviour, glaciers themselves did not. The solution to this conundrum came from Alley (1993) who proposed that whilst some areas of the bed would reach a failure state there would be other areas, 'sticky spots', which would still resist flow. These might take the form of well drained sediments and topographic highs beneath the glacier, along with lateral drag from valley walls. Hindmarsh (1997), in a partial defence of the 1987 paper (Boulton and Hindmarsh, 1987), proposed that although the plastic Mohr-Coulomb relationship did best represent the rheology of till, the nonlinear viscous model better represented ice flow and so was preferable for macro numerical modelling. This practical solution helps combine the inverse modelling approach with the yet unachievable process based approach, but highlights a general lack of understanding in the discipline about exactly how glaciers move over soft beds.

At this point it is worth briefly mentioning that throughout this thesis the peak strength form of the Mohr-Coulomb failure criteria is used rather than the residual strength form used by Iverson (1998). This reflects a focus on slower glaciers such as Skalafellsjökull rather than an ice stream analogue. Whereas an ice stream may continually be moving and so many areas may consistently be in the residual state, on a smaller slower glacier regular periods of quiescence will result the peak shear strength being more applicable. This is perhaps particularly relevant to stick-slip motion (see section 2.2.3.2) involving rapid changes in strain rate from a low or zero value.

2.2.1.1.1 Effective pressure and the role of hydrology

The dependence of till rheology on the Mohr-Coulomb relationship makes water central to deformation within the subglacial zone. The final term in Equation 1, *N*, can be expressed as:

$$\sigma'_n = \sigma_n - u$$

Equation 2

Where σ'_n is the total normal stress (kPa) and *u* is the pore water pressure and total normal stress is a function of the thickness and unit mass of overlying ice and till. This is referred to as 'effective pressure' throughout the glacial literature but here 'normal effective stress' is used as it is the standard term in geotechnical literature. Equation 1 simply states that increasing the pressure on the slip plane makes it harder to induce a failure. As σ'_n is dependent on overlying ice and pore pressure within the till, the pore pressure alone can be considered the governing factor as ice thickness can be considered constant or at least negligibly dynamic over the timescales under consideration.

This leads to the occurrence of deformation being highly dependent on subglacial water pressure. Potentially deformation is not actually impossible without high water pressure as the overburden weight of ice (σ_n) means till yield strengths may exceed any feasible driving stress applied by the ice in the absence of a balancing water pressure (Brown, 1987). Using Equation 1 and taking typical values of 30 for *f*, a driving stress of 100 kPa, and an ice depth of 100 m, then deformation would require a normal effective stress of <170 kPa which equates to water pressure exceeding 83% of ice overburden (Cuffey and Patterson, 2010). However, as deformation is observed in Echelmeyer and Wang's (1987) study where the till is frozen this is a nuanced issue.

Despite this fairly simple governing relationship, the influence of hydrology on deformation is exceedingly complicated due largely to four factors: 1) the spatial and temporal heterogeneity of water supply to the subglacial environment, 2) the role of dilatancy during deformation, 3) the hydraulic conductivity of the till and 4) the influence of ploughing clasts through till on local water pressures. These are discussed in turn below before we turn to other aspects of subglacial deformation.

These factors can be broadly separated by scale. Subglacial drainage patterns exist on a scale of km^2, although the precise variability fluctuates through a season. Similarly, their evolution over time is relatively slow, generally cycling over a season, although state changes can be rapid. Conversely, the impacts of dilatancy and ploughing of clasts through the till are more often micro in scale, operating on a grain scale level. Till permeability bridges the two and appears to operate on a macro scale, e.g. sticky spots (Alley, 1993) as well as a micro scale in the regulation of till dilatancy.

2.2.1.1.2 Subglacial drainage

Subglacial drainage system dynamics have a profound impact on the location and extent of subglacial deformation due to their control of local and macro subglacial water pressures. Their development over time, sometimes in a seasonal manner, adds a macro temporal aspect to glacial movement. This is very much a 4-dimensional problem with water inputs varying vertically within the till (i.e. from the ice-bed interface and from aquifers below (Boulton & Hindmarsh, 1987) as well as across the area covered by ice and with time.

Subglacial drainage systems are generally categorised at any one time as either discrete or distributed (see Figure 2) (Benn and Evans, 2010). A glacier may be predisposed to either due to its basal thermal regime, underlying geology and topography. Generally, water supply will determine the systems state at any given time. Water supply to the bed is overwhelmingly dependant on surface melt and precipitation and as these are self-evidently dependant on seasonality so often is the hydrological system. At the most simplistic level the change in system state is driven by either a surplus of water that forces a channelized discrete system to develop or a deficit of water that results in the closure of the channelized system via ice creep closing empty channels (Röthlisberger, 1972).

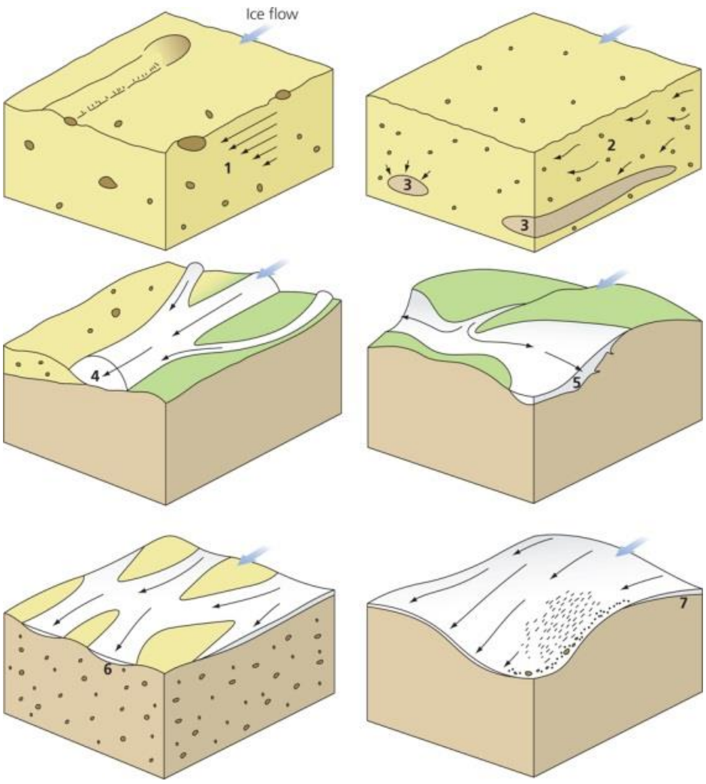


Figure 2: Different subglacial drainage systems split into distributed (1, 2, 5, 6, and 7) and channelized (3 and 4). 1. Inter pore movement through the till, arrows show flow magnitude, 2. Darcian porewater flow 3. pipe flow, 4. dendritic network, 5. linked cavity, 6. braided network, 7. flow via film at ice-bed interface (Reproduced from Benn & Evans, 2010).

Because topography and geology have a role in the subglacial hydrology system, not all research is applicable to this thesis. The most relevant study is Boulton's on Breiðamerkurjökull (Boulton et al., 2007a, b) as it demonstrates the possible evolution of a soft bedded glacier with similar till to the field site used in this thesis. The subglacial hydrology at this site was found to be highly dependent on well drained sands and gravels below the deforming till which acted as an aquifer. Darcian flow within this layer was capable of providing the majority of water discharge. During the summer when melt inputs are highest channels developed at the ice-till interface to deal with the excess capacity.

Boulton argued that this system was efficient enough to prevent water pressures from ever matching or exceeding over burden pressures. Whilst the presence of a subglacial aquifer is most probably particular to Breiðamerkurjökull and its local glacial history, if this is the case at similar glaciers, it may have a significant influence on the relative roles of deformation and sliding. Further to the basic hypothesis of channel formation, Boulton also argued that if pressure never exceeds overburden pressure then channel spacing would be defined by the rate of basal water supply and the permeability of the deforming layer and underlying aquifer. This highlights another key element in our understanding of subglacial deformation, the hydraulic conductivity of till (see section 2.2.1.1.4).

2.2.1.1.3 Till dilatancy

Till's granular nature complicates deformation through the provision of a feedback loop. As an over-consolidated till shears it also dilates and pore space increases. This results in a localised drop in pore pressures, an increase in normal effective stress and consequentially an increase in shear strength. It is suggested that this prevents till from failing in a perfect plastic manner (Cuffey & Paterson, 2010).

Some explanation of the term 'over-consolidated' is required to make sense of the phenomenon. This is provided in more detail in section 2.3.2.2.2. In brief, granular material with pore spacing similar to that expected of it if in a state where normal effective stress is negligible, can be deemed to be in a state of normal consolidation. If the normal effective stress is increased, the material will become consolidated and pore space decreases within it. If then the normal effective stress is then lowered the material will remain in a state of consolidation that does not reflect the current normal effective stress applied to it. This is a state of over-consolidation. Till is presumed to often be over-consolidated before deforming as deformation tends to occur as pore water pressures rise. Therefore, at the onset of deformation the normal effective stress is lower than it has been previously.

The potential for till dilation during deformation has a few implications. Firstly, it may predispose deformation to occur at varying depths due to the variation in pore pressure during deformation (see section 2.2.1.1.6). Secondly, in some situations it appears to allow sub-critical-state creep where the till can deform via creep for a longer period than initially imagined. This interesting situation has been explored by Moore & Iverson (2002) in the laboratory. They found that the feedback loop allowed water pressures to be lowered repeatedly during creep before eventually a critical state was reached as strain rose above 1 and unrestrained failure occurred within the sediment. The proportion of deformation that can be attributed to this is unknown and is presumably seasonal. This is further discussed in section 2.3.2.2.3.

2.2.1.1.4 Hydraulic conductivity of till

Hydraulic conductivity of till has a significant impact on subglacial system evolution, and less obviously on the role of till dilatancy and clast ploughing. Our understanding of its influence is relatively good. However, our ability to include it in models is hindered by the frequently significant disparity between laboratory measured hydraulic conductivity and reality in the field (Truffer *et al.*, 2001).

Hydraulic conductivity is determined by the void space density of a material and the connectivity of those spaces. In essence this means that hydraulic conductivity of till is a product of grain size and consolidation. Consolidation is a product of ice overburden and local pore water pressures so does vary a lot but compared to grain size which can vary by an order of several magnitudes it is relatively insignificant. This is due largely to fluvial action under the glacier and in front of it that result in coherent areas of clay, sand, gravel etc. Therefore, in most situations hydraulic conductivity is determined by till granulometry.

Till with a high hydraulic conductivity e.g. well drained sands and gravels dissipate inputs of water relatively rapidly. As shear strength is highly dependent on high pore pressures and consequent low normal effective stress, this makes them relatively stiff in the subglacial environment. Coherent areas of well drained sediments are postulated to be the cause of some 'sticky spots' (Alley, 1993). Conversely, till with a low hydraulic conductivity e.g. clay or silt based tills less readily absorb or dissipate inputs of water. This means that once they reach high pore pressure they may remain weak and highly deformable. Because of the low rates of absorption, pore pressures can also be particularly high at the boundaries of inclusions of low conductivity till (aquaclines) (Roberts & Hart, 2005).

2.2.1.1.5 Clast ploughing

Clast ploughing is a difficult subject invoked in a number of discussions about glacial movement. From the perspective of hydrology though, here a very simple perspective is taken on it. Deformation may occur, at times, in a thin relative discrete zone due to its plastic nature e.g. Echelmeyer and Wang's (1987) 0.02-0.04 m 'shear bands'. Due to the heterogeneity of grain size in many tills, it is feasible that larger clasts may partially or completely span the area deforming. Due to their emplacement in till travelling at variable speeds, it is possible that the clast is 'ploughed' through the slower or faster areas, or perhaps both to a more limited degree.

The literature on ploughing (Brown et al., 1987; Iverson, 1999; Thomason & Iverson, 2008) is focused on ploughing during soft-bed sliding. This appears to be common and potentially provides the most extreme ploughing situations. However, it is not the only occurrence of ploughing and it is highly likely that it has some relevance to most subglacial deformation. For instance, sedimentary evidence from the foreland of Skalafellsjökull (Evans, 2000) suggests that ploughing behaviour from large clasts may span the a-horizon of the deforming till, resulting in lodgement and complex dynamics within otherwise freely deforming till.

Thomason & Iverson (2008) demonstrated that although till appears not to rate weaken (Cuffey & Paterson, 2010) localised pore pressure build up in front of impermeable clasts during ploughing may result in a rate weakening effect. In their experimentation, they demonstrated this at velocities of 15-400 ma^{-1}, rates that are potentially feasible in stick-slip deformation. However, how exactly this occurs in a deformation rather than soft bed sliding situation, and how it interacts with the presumably often strengthening presence of ploughing clasts on deforming sediment, is as yet undetermined.

2.2.1.1.6 Profile of deformation

Where deformation occurs within the subglacial zone is of interest in a number of situations. For instance, large scale calculations of till transport require good estimates of the quantity of till deforming under glaciers. On a smaller scale, this thesis and other *in situ* work requires consideration of where deformation is occurring to establish how well the sensors are measuring it.

If we are to expand on equation 1 and consider where deformation occurs, we are left with quite a discrete zone. Presuming an even distribution of pore pressure within the till below a glacier and a homogenous lithology, till shear strength should increase downwards due to the rising mass on potential shear surfaces and consequential increase in normal effective stress. Shear stress also increases, but not commensurately due to the basal slope. Therefore under this model plastic deformation should be focused at the upper part of the till and ice till interface as plastic failures will always focus at the weakest horizon within the till (Boulton & Hindmarsh, 1987; Alley, 1989a).

This simple numerical model is supported by some observations but not others. It holds well for ice streams where pore pressures seem to be maintained consistently close to overburden pressures, and much of the movement can be attributed to soft bed sliding (see section 2.2.1.2). Here deforming layers are perhaps only a couple of decimetres in depth. However, under continental glaciers the model and in quaternary sediments (e.g. Benn, 1995) it does not appear to hold true.

Table 1: Measured deformation depths in existing glaciers (adapted from Cuffey and Paterson, 2010).

Glacier	Deformation depth (m)	References
Trapridge	0.3	Blake, 1992; Fischer and Clarke, 1994
Storglaciären	0.3	Hooke *et al*., 1997
Urumqi	0.35	Echelmeyer and Wang, 1987
Breiðamerkurjökull	0.5	Boulton and Dobbie 1993; Boulton *et al*., 2001
Columbia	0.65	Humphrey *et al*., 1993
Black Rapids	>2	Truffer *et al*., 2000; Truffer *et al*., 2006
Bindschadler	5	Kamb, 2001
Whillans	5	Alley *et al*., 1986; Engelhardt *et al*., 1990; Engelhardt & Kamb, 1998
Bakaninbreen	>0.2	Murray & Porter, 2001

2.2.1.1.6.1 Water distribution

Iverson *et al*. (1998) and later Tulaczyk *et al*. (2000) proposed that as it is implausible for the till to fail at a location other than the weakest point, the weakest point within the till must migrate to match observations of deformation at depth. Their suggestion was that with inputs of water into the subglacial bed, a pressure head would diffuse downwards through the till. As the pore pressure would be highest at this pressure head, and so normal effective stress the lowest, deformation would occur there.

Dilation (see section 2.3.2.2.3) due to shear may also transfer shear to depth (Cuffey & Patterson, 2010). As dilation lowers the water pressure locally and strengthens the till, presumably shear stress is transferred through that till so deformation is moved elsewhere.

As well as dynamic water movements throughout the till, concentrations of water at depth due to an aquacline, or upwelling of water from subglacial aquifers, are both feasible causes of deformation below the top few decimetres. As described above in section 2.2.1.1.2, Boulton et al. (2007a, b) suggested that an aquifer was present below the till at Breiðamerkurjökull. This meant there was a persistent upwelling present and so deformation could occur at depth. Truffer et al. (2000) noted deformation at depths exceeding 2 m at Black Rapids glaciers due to similarly consistent water dynamics. He suggested that over the season a point of minimum effective pressure could be determined within the till (see Figure 3). This relationship was determined by modelling diffusion of water down through the till and compaction due to ice/till overburden weight. This point would be the least over-consolidated part of the till and so the weakest, focussing deformation around that point.

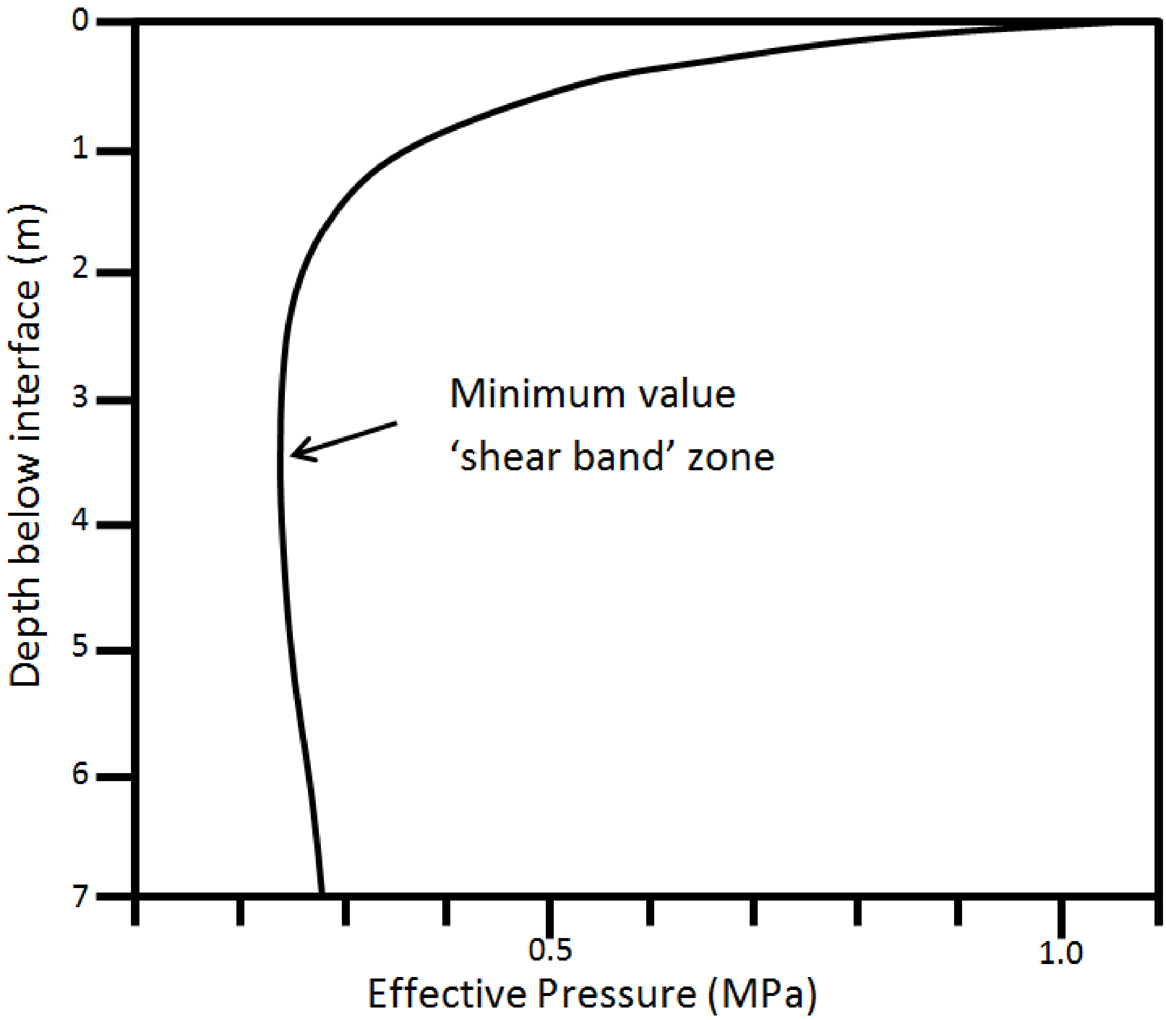


Figure 3: Consideration of normal stress due to overburden of ice and till which increases linearly with depth, and water pressure which also decreases with depth provides an estimate of the lowest maximum effective pressure possible vs depth. The highest normal effective stress that occurs during the year is presumed to have an impact on the degree of over-consolidation of the till and so peak shear strengths (reproduced from Truffer et al., 2000).

2.2.1.1.6.2 Heterogeneity of till lithology

These models seeking to explain the role of water pressure dynamics within the till exclude the role of lithology heterogeneity for simplicity. Clearly, this is not representative of many actual deforming beds and the importance of this factor should be considered outside simplified models. Similarly, the role of granularity is also largely excluded, although this is more to do with the complexity of granular physics that is still relatively poorly understood.

Two situations are commonly recognised as significant, although predicting exactly how they affect deformation is still beyond our capability. Perhaps most obviously deformation must be impacted when clasts are present that span or exceed shear zones as explored already (Brown et al., 1987). The second situation in which till sedimentary heterogeneity results in complex and potentially deep deformation is when sediments with different shear strengths are present within the till. Often this takes the form of bodies of well drained sands or gravels within poorly drained clay or silt based tills. A well-known example might be the North Norfolk coastline where boudins of stratified sand are present within highly deformed clay rich tills (Roberts and Hart, 2005). This topic is poorly covered in glacial literature, but present in geology literature.

In geology if different strength materials are present within a zone of deformation, they are referred to as having a 'competency contrast' and their ability to deform described as their 'competence'. These terms have existed for some time (Willis, 1893; van Hise, 1896), and Goodwin and Tikoff (2002) provide an excellent up to date summary of how it impacts sediment behaviour. Simply, small differences in shear strength between bodies of sediments, a competency contrast, can result in the transfer of shear stress through the stronger sediment into the weaker sediment where strain occurs. The most obvious result of this is that deformation need not always occur close to the ice-till boundary and could be transferred to a depth equal to the thickness of the competent sediment. This is essentially the argument of Truffer et al., (2000) though so not that novel in glaciology. However, interactions that are more complex are possible which result in compositional banding of competent and incompetent domains within the deformation zone (Goodwin & Tikoff, 2002). The implications for the profile of deformation within a till because of this are less clear, although presumably it would result in complex *in situ* sensing results.

2.2.1.2 Soft bed sliding

Basal sliding is a term used when ice is underlain by both hard and soft beds, but often the processes involved are quite distinct. Hard bed sliding is by no means simple, but the area of slip is relatively constrained, occurring between the ice and bed unless quarrying or similar occurs (e.g. Zoet *et al*., 2012). Comparatively soft bed sliding is poorly constrained in terms of where slip occurs, what the process involves, and how it can be defined. Cuffey and Patterson (2010, pg. 256) define it as *'deformation of a thin layer of substrate wherever ice or rock inclusions touch the bed'*.

It is difficult to discern clearly between subglacial deformation and soft bed sliding. Clearly, when deformation is used in the description of soft bed sliding, it intimates that the differences are negligible. Ideally, it would be possible to adopt a definition whereby any process of movement where deformation occurs is considered subglacial deformation. However, potentially this is misleading as ploughing of clasts held in the ice through the underlying sediments during soft bed sliding (Brown et al., 1987; Iverson, 1999; Thomason and Iverson, 2008) clearly involves some degree of deformation, but deformation of the till is not the governing factor, rather global controls are probably more significant (See section 2.2.3.1).

What could be described as pure soft bed sliding is the situation when ice becomes totally decoupled from the bed due to water pressures exceeding overburden pressures. Ice movement at this stage is presumably free from deformation, although ploughing could still occur. Boulton (2007a) disputed that this was possible, but conversely Iverson *et al.* (1995) proposed that it is must occur in order to explain observed relationships between deformation and water pressure at Storglaciären. They proposed that partial decoupling of the ice from the bed due to water pressure exceeding overburden in a patchwork fashion results in 'stress bridging' through the ice so that the areas of ice still in contact with the bed apply a higher shear stress than would be possible under an even distribution of shear stress.

2.2.2 Subglacial bedforms

Subglacial bedforms are a suite of landforms produced by glacial flow over soft beds. Subglacial bedforms span a range of scales from centimetres to kilometres and are common in deglaciated areas. As with other subglacial phenomenon the exact processes involved in their formation are often difficult to identify due to the inaccessibility of the subglacial zone. Because they are accessible in deglaciated areas and their formation is so difficult to discern they have attracted significant and continuous research interest. The prime example of this phenomenon is drumlins and these have attracted over 1,600 publications to date (Clark, 2010) but there is a high volume of research on all subglacial bedforms.

Subglacial bedforms are of interest to this thesis as their form is in some way related to the dynamics of the subglacial environment. Therefore, there may be some relationship between the *in situ* sensing and geotechnical testing conducted in the thesis and the bedforms apparent across the foreland of Skalafellsjökull. Because of their ubiquity in the foreland, the processes related to the formation of flutes are particularly relevant. It is of course feasible that the link between bedform genesis and subglacial dynamics is minimal. If we consider subglacial bedform genesis under Hart's (1997) classification of erosional, depositional and deformational then there is an obvious variance in the impact on the subglacial environment. However, in the case of flute genesis the dominant theories do not align distinctly with that tri-partite classification and analysis is increasingly focused on primarily deformational theories of genesis (Hubbard & Reid, 2006)

Flutes are elongated ridges aligned with former ice flow and ubiquitous across many deglaciated landscapes. They vary in size and are found with widths in the order of centimetres (Boulton, 1976) to hundreds of metres (Smith, 1948; Shaw and Freschauf, 1973; Clark *et al*., 1993). As with other subglacial bedforms they tend to be found in large coherent groupings (Schoof and Clarke, 2008). This intimates that they are profoundly linked to subglacial processes when present.

Theories of flute formation, as with other bedform theories, are wide ranging and contested. They can be generalised as two groups. This first hypothesises that flutes are formed by protuberances on the glacier bed creating cavities which fill with till and become flutes (e.g. Boulton, 1976; Morris & Morland, 1976; Clark *et al*., 1993; Roberson *et al*., 2011; Eyles *et al*., 2015). The other group recognises some role in protuberances but suggests that lateral instabilities in ice flow a more significant (Shaw & Freschauf, 1973; Rose, 1989; Schoof & Clarke, 2008).

The most widely covered theory of flute formation is based around protuberances/obstructions to ice flow. It is discussed in various forms by Dyson (1952), Hoppe and Schytt (1953), Lliboutry (1968), Morris and Morland (1976), Boulton (1976), Eklund and Hart (1996), Clark *et al*. (2003) and continues to produce new literature (e.g. Eyles *et al*., 2015). The basic theory is thus. An obstruction, commonly a boulder, that previously had been carried along englacially lodges against the subglacial till. As in most cases < 100% of glacial movement will be occurring due to deformation, this results in a velocity differential between the ice and obstruction. This produces a cavity in the lee of the obstruction. Till is extruded into this cavity and forms a flute.

Whilst this generalisation of the theory holds well across this large collection of literature there are, as always, a number of points of debate within it. Perhaps the clearest is as to where the till enters the flute cavity. Hoppe and Schytt (1953) argued that the length of flutes and lack of attenuation along their length suggested the till froze on to the ice after entering the cavity behind the obstruction. Frozen till then would be carried along by the ice and the flute would continue to grow via accretion at the obstruction end. As noted by Boulton (1976) this mechanism is presumably not feasible in glaciers where the snout is warm based.

The alternative to this theory is Dyson’s (1952) suggestion that till enters the flute at the distal end. There are also less distinct variations on this theory. Boulton (1976) agrees that till is accreted at the head of the flute behind the obstruction. However, he rejects the possibility that till has to be frozen to maintain a flute of significant length. Instead, he suggests that the length of flutes is due to the hydrostatic conditions in their vicinity that allows the fluid till to remain in a stable state.

As with other bedforms (e.g. drumlins, Clark, 2010) the apparent self-similarity in flutes and frequent regular spacing (Hoppe & Schytt, 1953; Shaw & Freschauf, 1973; Boulton, 1976) has raised questions as to whether a physically based mathematical theory of their formation is feasible. As well as this basic premise as to the attraction of general theory, Schoof and Clarke (2008) also raise a number of issues with the protuberance based theories. Primarily Schoof and Clarke (2008) question why till soft enough to be extruded into a cavity behind a protuberance can then manage to maintain the flute without any apparent attenuation. They suggest that attenuation noted in the immediate lee of boulders but not then further downstream (Boulton, 1976) might suggest that the boulders had a role in seeding an instability but not otherwise in the flute creation.

Their alternative modelling based theory elaborates on evidence that standard down valley flow of a glacier will always result in some lateral stress (McTigue *et al*., 1985; Man and Sun, 1987). This manifests itself in transverse flow cells of ice as envisaged by Rose (1989). The transverse movement of ice results in the movement of till from troughs to peaks and the formation of flutes. The cells, and consequentially flutes, vary in size depending on the velocity of the glacier. Schoof and Clarke (2008) suggest that the herringbone fabrics frequently noted on flutes (Shaw and Freschauf, 1973; Benn, 1994; Eklund and Hart, 1996; Hubbard and Reid, 2006) are evidence to this persistent mode of flute creation.

Unlike drumlins (e.g. Greenwood and Clark, 2008) there have been no large scale surveys of flute morphology with Spagnolo *et al.*'s (2014) work on MSGLs (Mega Scale Glacial Lineations) coming closest. This is largely due to preservation issues. Whilst larger forms like drumlins and MSGLs are well preserved in deglaciated areas, flutes are generally only visible in the forelands of modern glaciers. This makes large scale data led assessments of flute genesis theories difficult. The data that does exist is inconclusive as to whether the obstruction or instability hypotheses are correct.

As mentioned above, flute spacing as measured in small scale studies does appear to be regular (Hoppe & Schytt, 1953; Shaw & Freschauf, 1973; Boulton, 1976). This could support a theory of an underlying mechanism for flute creation as hypothesised by Schoof and Clarke (2008). However, Boulton (1976) suggests that it could also reflect random placement of boulders and so the obstruction based formation theory. Without additional evidence, discriminating between the two hypotheses is difficult and feasibly a combination of the two is viable further complicating the analysis.

2.2.3 Manner of glacial movement

2.2.3.1 Global *vs.* local controls

In section 2.2.1.1 the issue of global vs local controls on glacial movement was briefly discussed. Hindmarsh (1997) suggested that the reason glacial movement at a macro scale did not adhere to the Mohr-Coulomb model like till was due to a multitude of global factors that influence glacial movement in a variety of manners.

This issue of global *vs*. local controls is problematic for many scales of glacial study. We know about a number of issues but in many cases they are scale determinate. Is the glacial adherence to viscous flow a product of macro factors like sticky-spots (Alley, 1993; Stokes *et al*., 2007) and ice marginal drag, or is it controlled by strain heterogeneity in till during deformation (Sane *et al*., 2008)? In this thesis consideration of the factors impacting the results of the *in situ* sensing is central to linking them to geotechnical laboratory work.

If we consider glacial motion at a point location and try to deconstruct driving and resistive forces then we must consider factors present at that point (e.g. local) as well as system influences that impact the wider area (e.g. global). When conducting subglacial *in situ* sensing this clearly complicates analysis of the essentially point data collected by the instruments.

It is obviously attractive to try and find correlations between observations but it is difficult from that point data alone to deduce causality. A key example here might be efforts to deduce the impact of pore pressure on sediment deformation and so help provide a constitutive relationship for till rheology in the early 1990s. Early *in situ* experimentation by Iverson *et al*. (1995) attempted to provide further evidence as to whether till confirmed to a non-linear viscous (Boulton & Hindmarsh, 1987) or plastic (Kamb, 1991) rheology. However, a key finding of the experimentation was that as pore pressure passed a given threshold deformation decreased. The theory presented is that at this stage the ice is 'decoupled' from the till, shear stress locally is reduced, and other better drained areas with lower pore pressures where the glacier remains coupled to the bed experience higher shear stress. In this situation local factors at the site monitored clearly impact deformation at the better drained areas where they are global factors.

Winberry *et al.* (2011) is another good example of global and local factors affecting the velocity of ice movement by providing some system level insight into the movement of Whillans Ice Stream B. The subglacial till appears mostly to have a high clay content and consequently low hydraulic conductivity (Kamb, 1991). Much of the ice stream appears to have consistently high pore pressure levels allowing the ice stream to move consistently at a relatively low speed. Whilst this is a wide spread effect, at any given location these factors could be considered relatively local.

The defining point of the movement at Ice Stream B though is the influence of tidal forcing. As the tide rises elastic strain is transferred up the ice stream providing a reduction in normal stress that increases the ice velocity – a clearly global forcing. During these periods, sticky spots (Alley, 1993; Stokes *et al.*, 2007) provide resistance to the down ice component of shear stress, reducing the velocity of the ice, and from interferometry results they appear to influence the macro patterns of velocity across the ice stream. As with the Iverson *et al.* (1995) example, this demonstrates local controls with global effects.

In this thesis as much consideration as reasonably possible is given to the impact of global forcing on the area where *in situ* sensing is carried out. This will be done in the manner of Iverson *et al*. (1995) where testing aims to elucidate the significance of local factors and mismatches between predicted and observed behaviour provides evidence of global factors, rather than the approach taken by Winberry *et al*. (2011) that starts with the global aspects.

2.2.3.2 Stick-slip motion

The term stick-slip motion is referred to frequently within the glacial literature (e.g. Blake *et al*., 1994; Fischer & Clarke, 1997; Iverson *et al*., 1999a; Ekström *et al*., 2003; Rathbun & Moore, 2010; Hart *et al.,* 2011) in order to describe the episodic nature of glacial movement. Episodic release of shear stress via movement between two frictional surfaces is a common, if poorly understood situation (Peng & Gomberg, 2010). It was at one point understood that this motion occurred via two discrete mechanisms, either aseismic slip or seismic slip (earthquakes). However, it now appears that actually a continuum between the two states exists and movement occurs with a range of seismic moments over a range of durations.

Observations to date (e.g. Ekström *et al*., 2003) suggest that glacial episodic movement bridges the gap between seismic and aseismic tectonic events. As such, the term 'stick-slip' appears in a variety of literature to explain the phenomenon that appears to be aseismic slip punctuated by quiescent periods of no movement (stick) followed by near instantaneous slip seismicity (slip).

The mechanisms behind stick-slip motion in tectonic situations are poorly understood (Peng & Gomberg, 2010). However, in glaciology the term is used without strong semantic control and so has been applied to areas where there is a relatively good understanding *and* areas where there is little or no understanding. These can be broadly divided:

- General velocity variations and behaviour of the glacier surface
- Global periodic build up and release of shear stress (Bahr & Rundle, 1996; Fischer & Clarke, 1997).

- Externally influenced movement, e.g. tidally influenced movement (Bindschadler *et al*., 2003; Gudmundsson, 2007; Winberry *et al*., 2011).
- Rheologically defined episodic motion, perhaps dilation controlled (e.g. Iverson *et al*., 1999a; Hooyer & Iverson, 2000; Moore & Iverson, 2002; Roberts & Hart, 2005; Iverson *et al.,* 2007; Rathbun *et al*., 2008; Iverson, 2010; Hart *et al*., 2011) .

To date the field is not sufficiently mature to have started to define stick-slip in a particularly discrete manner. Sometimes the term is used in a genetic sense and on other occasions in a more general manner. In this thesis, the term is not used as a genetic term but rather as a descriptive term for an episodic or stochastic style of movement. It seems that if there is a continuum between aseismic and seismic releases of stress between frictional surfaces (Peng and Gomberg, 2010) then the number of areas and processes that stick-slip is applied to can only increase with time. In that situation any attempt to use stick-slip in a genetic manner can only lead to confusion. Based on that premise it is also thought that it is likely that stick-slip behaviour will be found throughout this thesis in surface velocity, *in situ* and geotechnical data.

2.3 Investigative techniques

Three investigative techniques are used in this thesis: *in situ* sensing, geotechnical testing and UAV surveying. In this section a historical perspective on their use is provided along with detail on findings and methodology particularly pertinent to this thesis.

2.3.1 In situ sensing

In situ sensing has been used in glaciology since the early 1990s. Many workers have been attracted by the possibility of studying how glacial movement occurs in the actual subglacial environment rather than the laboratory or via numerical modelling. The studies have ranged in scope but broadly have been concerned with either determining properties also studied in the laboratory, for instance till shear strength, or for improving our understanding of the role of the subglacial zone within the glacial system e.g. implications of seasonality (Rose *et al.*, 2009). *In situ* sensing perhaps remains one of the few particularly 'blue-sky' science elements of glaciology and a number of breakthroughs were not anticipated. For instance, discoveries by Boulton and others (e.g. Boulton & Jones, 1979; Boulton & Hindmarsh, 1987) are often described as a paradigm shift in glacial research, Humphrey *et al* (1993) designed ploughmeters by accident and Iverson *et al.'s* (1995) findings about the relationship between water pressure and deformation were unexpected.

There have been a limited number of *in situ s*tudies at relatively few study sites (see Table 2). This is largely due to the complexity and expense of undertaking them, and potentially also influenced by the complex data retrieved. Due to the spatial and temporal heterogeneity of any single glacier, and the vast differences in factors controlling movement between glaciers, comparison of data between projects can also be difficult. Despite this, they have frequently demonstrated their worth because so little is known about actual events in the subglacial environment.

Equipment used for *in situ* sensing can be divided into 5 categories (Benn & Evans, 2010):

- Tiltmeters
- Drag spools
- Ploughmeters
- Dragometers
- Autonomous probes

Tiltmeters are designed to address a fundamental question in studies of the subglacial environment: where does strain occur and how does it vary temporally? Commonly deployed as a series of wired cells, tiltmeters are generally deployed down a bore hole and then left until they cease to function. The depth of deployment varies with tiltmeters being used to look at ice and till deformation. Via a variety of methodologies, they measure the vertical angle of the cell over time and report it back to the surface. As with most *in situ* techniques, they are imperfect. A primary issue is the wired nature of the majority of devices used. This hinders the movement of the cells and potentially creates misleading signals. This can be particularly significant when the cells are not properly coupled to their environment, for instance, due to borehole closure being incomplete, and unfortunately it is often impossible to tell whether this has occurred or not. Further issues develop when it is considered how well the tilt cells are coupled to the environment around them when the material is relatively fluid. In a Newtonian fluid the cell is required to be at least four times as long as it is wide (Jaber *et al*., 2013) which is rarely the case, and in a Glen-type rheology it may be even further impacted.

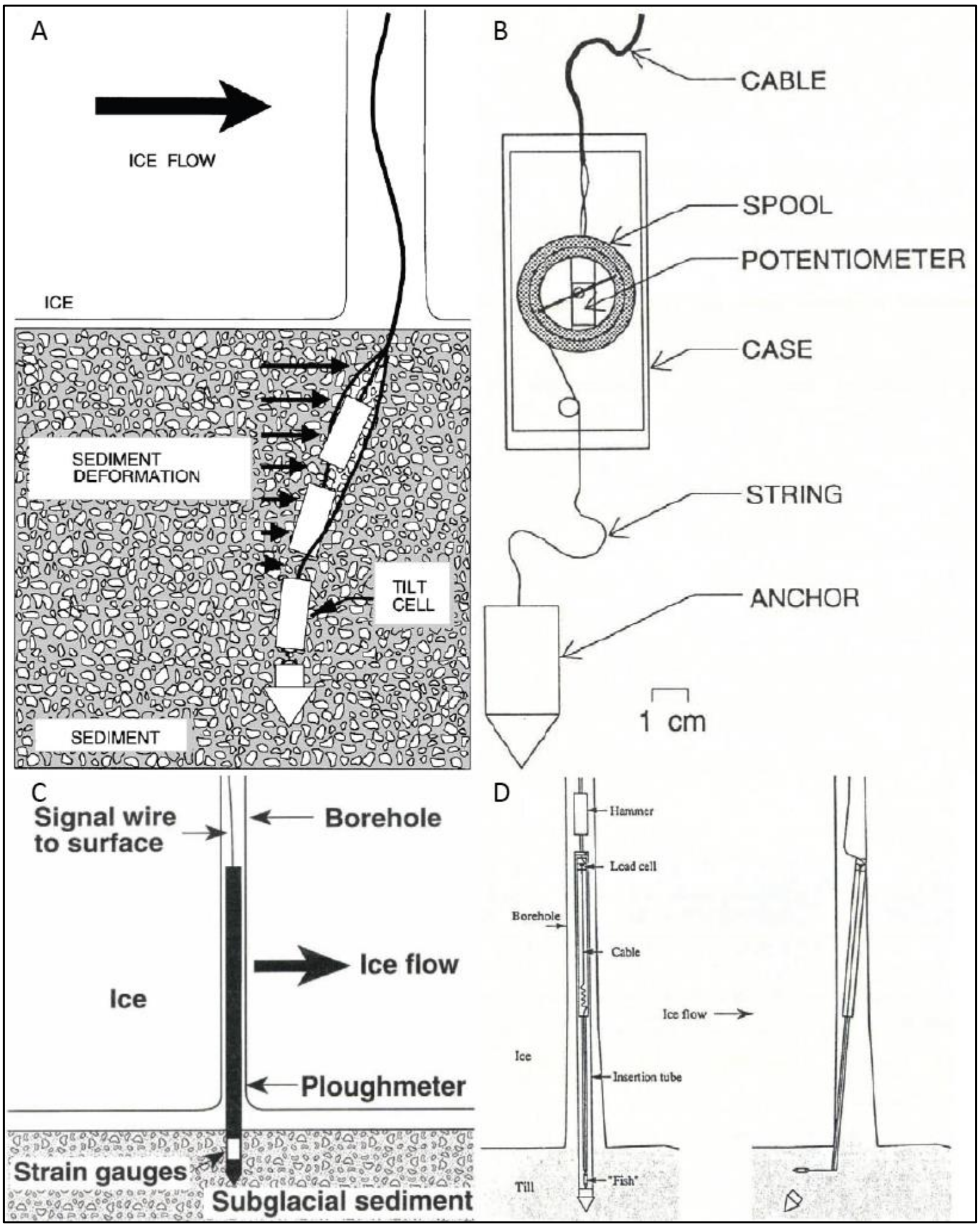


Figure 4: Illustrations of *in situ* sensing techniques. A) Tilt meter (reproduced from Fischer & Clarke, 2001). B) Drag spool (reproduced from Blake *et al*., 1994). C) Ploughmeter (reproduced and amended from Porter *et al*., 1997). D) Dragometer (reproduced from Jansson *et al*., 1995).

Fundamentally, even if the tiltmeters manage to couple to the environment and remain unfettered by their wires, the signal is complicated. The assumption is that the tilt cell behaves as a Lagrangian unit vector within the medium. This remains a difficult situation to understand and model (Keller & Blatter, 2012; Jaber *et al*., 2013). A further complication in many studies is that the sensors are very simple. One prime issue this leads to is the assumption that the dominant tilt is occurring down glacier (Blake *et al*., 1992; Iverson *et al*., 1999a)

Whereas tiltmeters are concerned with strain and deformation in ice and till, dragspools instead investigate sliding at the ice-till interface (Blake *et al*., 1994). An anchor attached to cable that extends to the surface is lodged into the till. As displacement due to sliding occurs at the ice-bed interface, the cable is drawn out and displacement quantified. Attempts are generally made to lodge the anchor at as shallow a depth as possible to limit the amount of till deformation included in the results. Aside from the difficulty of successfully lodging an anchor into the till, dragspools also struggle with the possibility of the cable cutting through the ice as sliding occurs, reducing the apparent quantity of sliding measured.

Ploughmeters are used to estimate the strength of the subglacial till. By lodging a steel rod partially into the till at the bottom of a bore hole the rod then gets bent as differential movement occurs in the till. Initially the concept of ploughmeters were discovered by accident by Humphrey *et al*. (1993) when a drill bit was inadvertently stuck at the bottom of a borehole in Columbia Glacier and then recovered 5 days later. Over that period it had been bent and abraded. Later, via determination of the strength of the drill bit, it was possible to estimate the strength of the till.

The method was improved on by Fischer and Clarke (1994) who deployed steel rods with strain gauges bonded onto them in order to measure the forces enacted on the ploughmeter in real time. There remain a number of difficulties with the methodology. Similarly to tilt meters, quantifying coupling to the environment is paramount for accurate estimates (Jaber *et al*., 2013). Other issues include determining heterogeneity in till lithology in order to establish whether variation in results is a product of the environment or experimental issues (Fischer and Clarke, 1994), but arguably that plagues all *in situ* methodologies.

Dragometers are one of the more rare tools deployed in *in situ* work. They function by measuring the forces between a piece of pipe inserted into the till and a ‘fish’ connected to it that is dragged through the till. Via measurement of the force exerted on the pipe, it is possible to make some estimation of the properties of the till (Iverson *et al*, 1994).

All of the above methods though are increasingly side-lined in favour of autonomous probes as demonstrated in this thesis (Hart *et al*., 2006, 2009, 2011; Truffer and Harrison, 2006; Smeets *et* *al*., 2012). Improvements in technology make it possible to make a subglacial probe a platform that contains a number of different sensors. It is also now feasible to use wireless communication to relay information to the surface without the use of a wire, although to date the only project to do so has been the Glacsweb project (Hart *et al.,* 2006; Hart *et al*., 2009; Hart *et al*., 2011).

Table 2: Reproduced and updated from Rose (2008)

Study	Location	Time Scale	Area	Reference	Publication Year
Conductivity and turbidity	Trapridge, Canada	1989-1991		Stone *et al.*, 1993	1993
Sediment strength, water pressure, turbidity	Columbia Glacier, Alaska		1,100 km^2 5 boreholes ~5 m apart	Humphrey *et al.*, 1993	1993
Sliding	Trapridge, Canada	1990-1992		Blake *et al.*, 1994	1994
Rheology	Trapridge, Canada	1991		Fischer and Clarke, 1994	1994
Hydrology and rheology	Trapridge, Canada	1992 (1989-1995)	70 boreholes	Murray and Clarke, 1995	1995
Water pressure, subglacial drainage	Arolla, Switzerland	1993 (from 1989)	6.33 km^2 glacier	Hubbard *et al.*, 1995	1995
Conductivity and turbidity	Trapridge, Canada	1990		Stone and Clarke, 1996	1996
Sliding (stick-slip)	Trapridge, Canada	1992		Fischer and Clarke, 1997	1997
Deformation, surge, properties of till	Bakaninbreen, Svalbard	1994-95 to 2000		Porter *et al* ., 1997	1997
Subglacial drainage, pressure, turbidity, conductivity	Arolla, Switzerland	July-August 1993	250 x 50 m 24 boreholes	Gordon *et al.*, 1998	1998
Sediment strength	Variegated Glacier, Alaska	~1981-82 (surge 82-83)		Richards, 1988	1988
Strain and hydrology	Trapridge, Canada	Jul-92	~10 m study site diameter	Fischer *et al* ., 1999	1999
Surface motion, sliding, pressure, ice and sediment deformation	Black Rapids Glacier, Alaska	1997 > 1 year of data		Truffer *et al* ., 2000	2000
Hydrology and rheology	Trapridge, Canada	1990-1995	20,000 m^2	Kavanaugh and Clark, 2001	2001
Hydro-mechanical coupling	Trapridge, Canada	Review		Fischer and Clarke, 2001	2001
Rheology, hydrology, deformation	Bakaninbreen, Svalbard	1995-2000		Porter and Murray, 2001	2001
Basal conditions	Bakaninbreen, Svalbard	1994-2000		Murray and Porter, 2001	2001
Spring events, hydrology, velocity	Arolla, Switzerland	1998-1999		Mair *et al.*, 2003	2003
Deformation and pressure	Black Rapids Glacier, Alaska	2002		Harrison *et al* ., 2004	2004
Deformation, pressure	Black Rapids Glacier, Alaska	2002		Truffer and Harrison, 2006	2006
Deformation, pressure, conductivity	Brikdalsbreen, Norway	2004-2006		Hart *et al* ., 2009 and 2011	2009
Pressure	Russel Glacier, Greenland	Summer 2010		Smeets *et al.*, 2012	2012

2.3.1.1 Glacsweb

In this thesis, data from wireless probes deployed by the Glacsweb project are used. Here some of the more relevant discoveries by *in situ* sensing on pressure variations and tilt oscillations are outlined and discussed in order to inform investigations later in the thesis.

The Glacsweb project is an interdisciplinary investigation into subglacial processes. Whereas previous *in situ* investigations have been primarily geographical ventures (e.g. Blake, 1994; Iverson, *et al.*, 1995; Truffer *et al*., 2000) the research interests in Glacsweb include glaciology, electronics and web science. Whilst the project is technologically well-resourced and works with substantially more advanced technology than previous *in situ* efforts, the pressure to innovate is ever present.

From a technological perspective Glacsweb's research significance is as a sensor network (Martinez *et al*., 2004), a concept more recently referred to as the 'Internet of things'. This avenue of research considers how an environment might be monitored by collating data from a number of different sensor nodes and communicating that in near real time to a central repository online. The crux is how an online environment is combined wirelessly with physical sensors. This only became possible in the early part of the century due to technology miniaturisation (Martinez *et al*., 2004) enabling sensors to be suitably integrated with the environments being monitored.

Glacsweb has also specialised in the development of a low power wireless network. The fundamental issue whilst sensing in the subglacial environment is accessibility. Deploying the sensors effectively is a complex task and retrieving or modifying them thereafter is impossible. Therefore, the probes have to be able to communicate wirelessly. They must also be able to do so for a suitably lengthy period, preferably in excess of 12 months, in order to capture seasonal variability fully. Realising these requirements has required developments in low power operation. These have been achieved largely through novel use of low power ARM processors that manage the probes' data collation and transfer. Improving radio communication protocols and so minimising battery intensive transmission times has also been important (Martinez & Basford, 2012).

2.3.1.1.1 Deployment and publication history

Glacsweb first deployed sensors at Briksdalsbreen in Norway. It was chosen because of evidence of deformation in the foreland, the ease of access and the coverage of mobile networks. In 2004 the latter was less ubiquitous than today and due to its importance in transferring data back to the UK it was a significant aspect in site selection.

Three field seasons were conducted at Briksdalsbreen and probes were deployed in 2004 and 2005. Survivability of the probes improved between the two probe iterations. In the first deployment four probes lasted >1 month producing 859 days of data over 2004/2005 with probe No. 8 producing the most lengthy record. In the second deployment four again survived >1 month producing 1208 days of data with probes 10, 12 and 16 all producing coherent datasets.

The deployments had a number of scientific outcomes pertaining to probe location (Hart *et al*., 2006) seasonality of the subglacial environment (Hart *et al*., 2009; Rose *et al*., 2009), and rheology (Hart *et al*., 2011).

The deforming till at Briksdalsbreen was estimated to be between 0.2 and 0.4 m deep based on proglacial flutes (Hart *et al*., 2006; Rose and Hart, 2008). During deployment, care was taken to ensure that drilling had been successful in reaching the base of the glacier and all boreholes were inspected with a custom made CCD video camera. However, it was not initially clear if probes would be incorporated into the deforming till rather than the basal ice. Data from the 2004 deployment demonstrated that temperature data clearly defines the probe position. In probes in the till positive temperatures are recorded throughout the year whilst in the ice (close to the ice-bed interface 68-75 m below the surface) temperatures drop below freezing during the winter (Hart *et al*., 2006).

The deployment in 2005 and longevity of probes 10, 12 and 16 provided valuable data on pore pressure changes (Rose *et al*., 2009). Water pressures appeared to drop dramatically through the winter months and the spring is then characterised by two events. The first is a minor increase in the till's water content presumably related to short lived early season weather events. Weather before this event was warm, with air temperatures rising to 8.6°C, and numerous precipitation events were recorded. Rose *et al*. (2009) suggest that the elevated temperatures may have led to the snowpack becoming isothermal enabling water to move freely within it (Harper *et al.,* 2005) and so access the base of the glacier. The second event is a much larger increase in pressure probably signifying the onset of ablation. Changes in the nature of the pressure behaviour after the second event suggest that it forces re-organisation of the subglacial drainage system. These discoveries would appear to confirm theories about subglacial drainage evolution (Röthlisberger, 1972).

Whilst these two findings were valuable, arguably the strength of the probe technology is the quantity of sensors carried and therefore its ability to inform on more complex characteristics of deformation. Characterising the tills rheology requires data on subglacial pore pressure, till strain rates and shear stress. Hart *et al*. (2009) attempted to determine rheology via consideration of the data from probes 10, 12 and 16 through 2005/2006.

Determining the till rheology is difficult precisely because of the range of variables that must be integrated in order to make an assessment, each with a range of uncertainties. The key difficulty in doing so is estimating the shear stress applied to the till encompassing the probe. The probes measure case stress via four strain gauges but this is complicated to relate to the deviatoric stress operating on the till. Instead, this must be calculated based on ice depth. Further difficulties are encountered when relating probe movement to strain. The assumption must be made that tilt changes mean deformation distributed over the length of the probe is occurring, i.e. the magnitude of tilt reflects strain differences within the till between the top and bottom of the probe. This discounts possibilities that ploughing of the probe through till might be occurring or that the probe may not be characterising deformation correctly due to flow around the probe (Jaber *et al*., 2013).

To estimate the rheology Hart *et al*. (2011) calculated the average shear stress applied, estimated the angle of friction of the till and then calculated the yield strength of the till over time via use of the pore pressure data. Probe tilt was then considered during occasions where pore pressure was high enough that the theoretical yield stress was exceeded. It was found that excess shear stress was linearly related to tilt magnitude therefore suggesting a linear-viscous rheology.

This is a significant finding as the rheology of till and whether it is scale dependent (Hindmarsh, 1997) is a contentious subject. The finding that deformation at the scale of the probes behaves in a linear-viscous manner therefore may suggest something about the scale at which deformation diverges from a plastic behaviour. At 0.16 m long, a probe sits within a volume of till approximately a magnitude greater than that used in geotechnical laboratory testing. Feasibly this quantity of till could be large enough that its rheology has already diverged from the plastic behaviour observed in the laboratory. If this is the case, it would significantly weaken claims of the relevance of laboratory studies to field situations.

Alternatively, the result could come due to miss-interpretation of the probes behaviour or assumptions made in the calculated values used in the analysis. Error could be present in a number of areas, although not all of them will impact the rheology estimation. The angle of friction estimate could easily introduce error into the analysis, but due to the assumption of a Mohr-Coulomb relationship, it would have minimal impact on the linear-rheology outcome. The assumption of a constant shear stress may also be problematic. The variability in probe case stress and variation with pore pressure is discussed extensively within the paper. The equation used to calculate the shear stress seems robust at a larger scale but it is difficult to know to how small a scale it can apply. The biggest difficulty may come in the interpretation of probe tilt and this is discussed in 7.4.2.2.

2.3.1.2 Seasonal pore pressure variation

Typical seasonal variance in glacier velocity is well established. Velocities tend to peak in spring, remain relatively constant through the summer and decline during autumn/winter (Benn & Evans, 2010). The seasonal variance in velocity is due to changes in the hydrological system driven by surface meltwater inputs (Iken *et al.,* 1983; Mair *et al*., 2001; MacGregor *et al*., 2005). Over the winter, the reduced inputs of water into the hydraulic system result in it shutting down and cavities closing due to ice creep (e.g. Willis, 1995; Hubbard & Nienow, 1997; Fountain & Walder, 1998). As temperatures rise during the spring and surface melt inputs to the subglacial environment increase. Glacial velocity peaks as water cannot escape quickly through the poorly developed hydrological system and so basal water pressure rises and normal effective stress on the till plummets (Kavanaugh & Clarke, 2001; MacGregor *et al*., 2005). Through the summer, the hydrological system then matures becoming increasingly efficient. As a result, pore pressures reduce, normal effective stresses on the till rise and ice velocity falls (Willis, 1995; Fountain & Walder, 1998).

Whilst the model of seasonal variance in velocity based on development of the hydrological system is well developed, *in situ* sensing was required to provide direct evidence. During the summer, fieldwork can usually be easily undertaken to monitor water levels in bore holes (e.g. Fischer *et al*., 2011) which are presumed to provide evidence of subglacial water pressures. During the winter, this is not often feasible due to snow cover and borehole closure. As discussed above, the Glacsweb project at Briksdalsbreen (Martinez *et al*., 2006; Hart *et al*., 2006; Hart *et al.,* 2009; Rose *et al*., 2009; Hart *et al*., 2011) demonstrated how *in situ* sensing can monitor seasonal changes in the subglacial zone. The wireless probes deployed by the project under Briksdalsbreen provided evidence for two reorganisations of the subglacial hydrological system termed Event 1 and Event 2 (see Figure 5) in 2005 and 2006 (Rose *et al*., 2009).

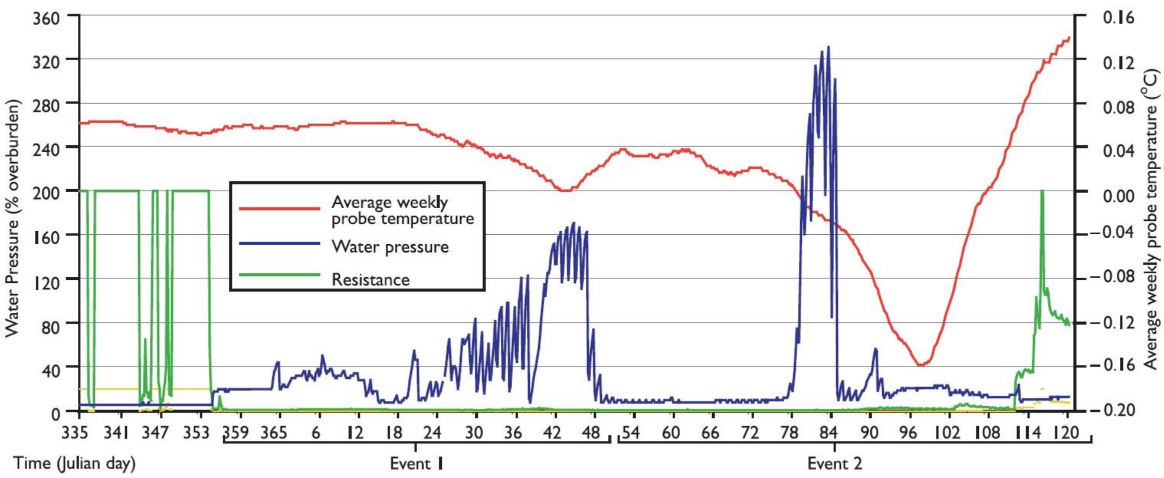


Figure 5: Glacsweb data showing the two early season water pressure events and associated relevant data. Reproduced from Rose *et al.* (2009).

The study is of interest as it demonstrates how a limited number of probes deployed *in situ* in the subglacial environment are capable of informing on macro factors effecting glacial velocity. For the 2004/5 season data from just one probe was available, and for 2005/6 data from three probes was available. Furthermore, it also demonstrates the potential longevity of wireless *in situ* experiments unhindered by wires with probes in 2004 and 2005 deployments lasting for over a year.

2.3.1.3 Tilt oscillations

Intuitively during *in situ* investigations probe movement is anticipated to reflect progress along flow. If the sensor is deployed in a deforming medium then it should behave as a Lagrangian unit vector and presuming the glacier proceeds in a relatively coherent down-ice direction so the sensor should increase in tilt in that direction. Clearly, at some stage it is possible that it may roll, but the complexity is anticipated to be low.

Intriguingly, this is not always the case and in several studies (Blake, 1992; Iverson *et al*., 1995; Hooke *et al*., 1997; Iverson *et al.,* 1999; Truffer *et al*., 2000; Tulaczyk *et al*., 2000; Hart *et al.,* 2009) sensors have been recorded moving in a periodic up-ice direction (note – Iverson *et al*., 1995; Hooke *et al*., 1997; Iverson *et al.,* 1999; Truffer *et al*., 2000; Tulaczyk *et al*., 2000 focus on the same data from field campaigns at Storglaciären from 1992-1995). Several suggestions have been given for this counterintuitive behaviour including pressure gradient driven deformation (Blake, 1992), extrusion driven deformation (Blake, 1992), behaviour as per roller bearing models (Blake, 1992), elastic recovery of vertical strain (Iverson *et al.,* 1999), compressible Coulomb plastic till (Tulaczyk *et al*., 2000), elastic recovery of horizontal strain (limited explanation) (Truffer *et al*., 2000) and lodgement (Hart *et al.,* 2009).

The situation is interesting as it is a good demonstration of 'blue sky' *in situ* work revealing unpredicted phenomenon in the subglacial zone. Whilst it has been theorised about several times there still is no compelling evidence for any particular theory due to the paucity of supporting evidence. One gratifying element about the phenomenon is that it is probably not an artificial construct of sensor design. This is not certain, but it has been recorded on sensors in four different deployments at four different glaciers. The obvious suggestion for its occurrence as an artificial trend would be the temperature variations impacting the sensors. This is plausible especially with the frequently diurnal nature of the phenomenon, but it seems unlikely as it is not consistent and the Glacsweb probes (Hart *et al*., 2009) show no change in relation to radio usage that increases the temperatures of the probe. Another clear issue is the use of wired instruments in all studies except Hart *et al*. (2009). Truffer *et al*. (2000) warn that smaller scale features of tilt data are likely to be impacted by the constraints of wired sensors. However, the presence of similar oscillations in data from wireless instruments (Hart *et al*., 2009) presumably dismisses this concern.

Blake (1992) was the first to explore the phenomenon that he encountered during his PhD. He hypothesises that the negative strain occurred either due to pore pressure driven deformation, extrusion driven deformation, behaviour as per roller bearing models. Pore pressure driven deformation was dismissed due to requirements for unfeasibly large pressure variations. Similarly extrusion related negative strain was dismissed due to requirements for unfeasibly large normal effective stress variations, although as till was assumed to be incompressible this may have been flawed. The roller bearing model though, or at least a related form of it, potentially was feasible.

In summary the perfect roller bearing model is of several rows of rollers stacked on top of each other between plates that cannot be moved vertically (see Figure 6). When the plates are moved relatively to each other in the horizontal plane the rollers move, but alternate rows of rollers will rotate in opposite manners.

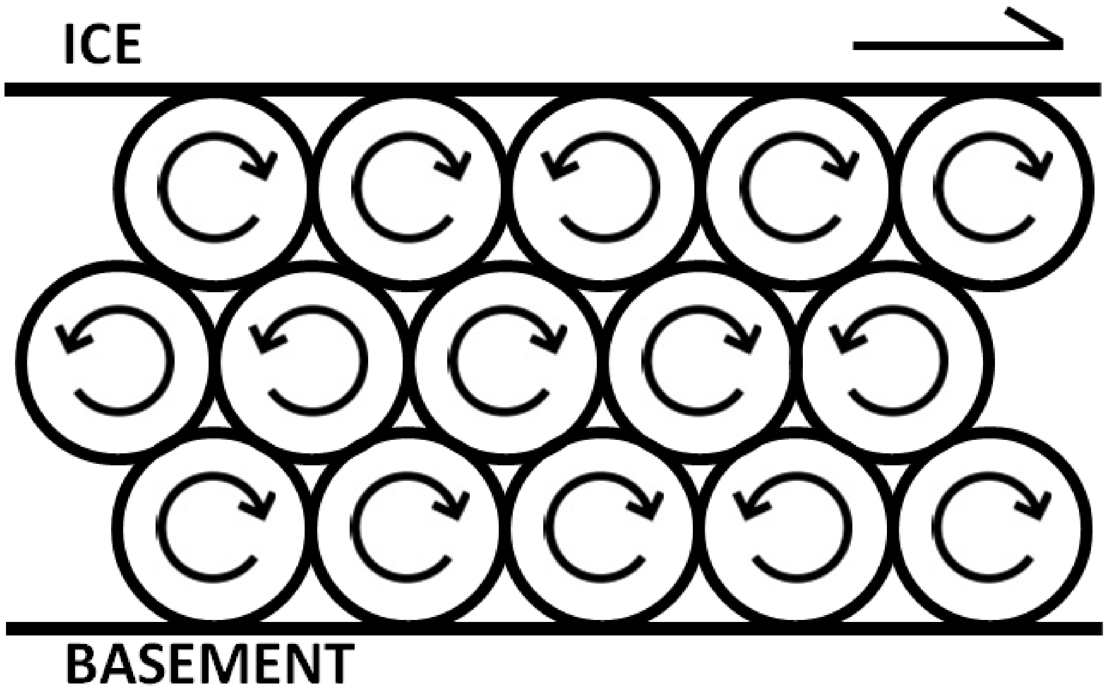


Figure 6: Roller bearing model: rows of roller bearings are stacked between plates that are immovable vertically. When relative movement is induced between the top and bottom plates, the roller bearings rotate. Up-glacier movement is produced in some bearings (Reproduced from Blake, 1992).

The model is imperfect as grain rearrangement is not possible, all particles (rollers) translate and rotate at a similar speed, it struggles with grain size variation and interstitial pore spacing is not dealt with. For these reasons, Blake (1992) did not pursue a numerical solution, but instead attempted an analogue model of the situation. With various size particles trapped between two plates, relative horizontal movement of the plates did induce both clockwise and anti-clockwise movement in the particles.

Iverson *et al*. (1999) recorded periodic up-glacier oscillations in tilt meters deployed below Storglaciären throughout July and August of 1993 (see Figure 7). The oscillations had a magnitude of up to 1 degree and an approximately diurnal frequency. The proposed explanation was oscillations are produced by the release of elastic strain in the till. As water pressure decreases normal effective stress increases but the higher coupling between the ice and till results in an increased shear stress. As a result, strain occurs in a down-ice direction. As water pressure rises again and normal effective stresses decreases the shear stress also drops. At this point, it is suggested an up ice movement occurs due to recoverable elastic strain.

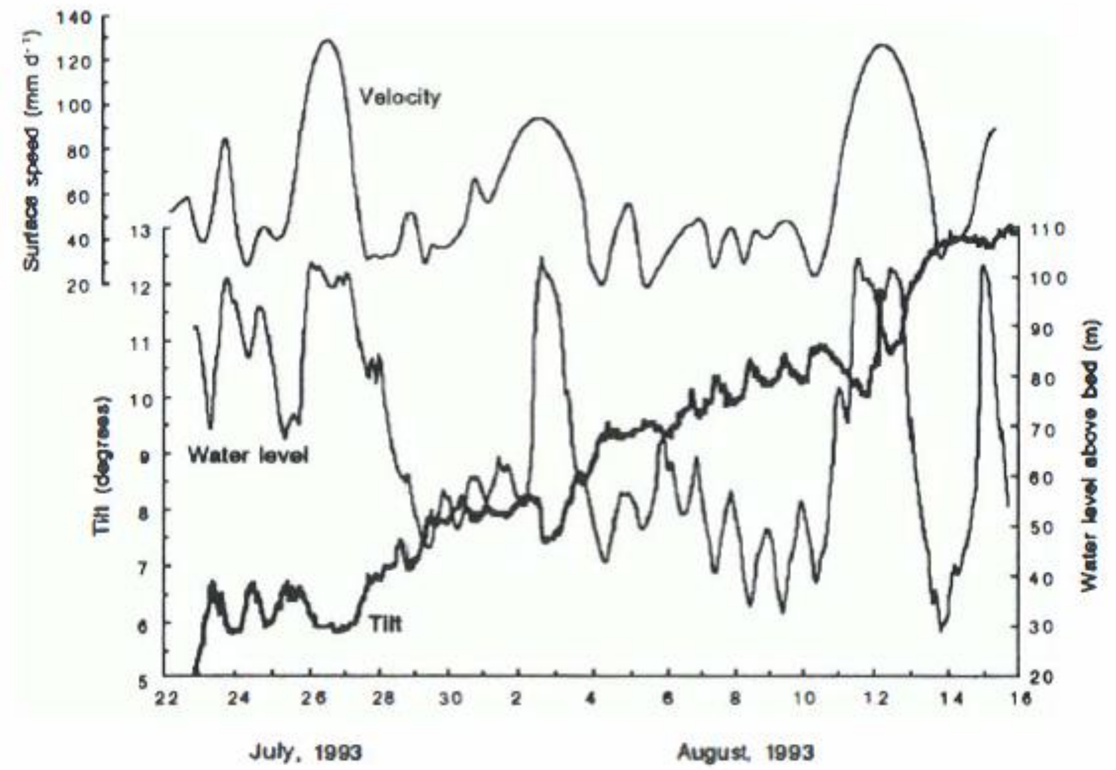


Figure 7: Ice velocity, borehole water level and tilt cell data from Storglaciären in July and August 1993 (reproduced from Iverson *et al*., 1999).

This is an improbable explanation due to the behaviour of granular material. As an over-consolidated till is subject to monotonic strain it tends to produce a distinct stress response. Initially shear stress increases rapidly until the yield point is reached, then shear stress increases at a decreasing rate until peak stress is reached (see Figure 8). At this point shear stress will drop to the residual strength where shear stress will plateau. It is presumed that the initial stress response is elastic up until the yield stress is reached and then progressively plastic thereafter.

Iverson *et al*. (1999) provide an interesting geotechnical investigation into the recoverable elastic strain in till, but use of a ring shear apparatus makes it complex methodology. The theory is elegant but there are a couple of theoretical problems with it. In granular materials a proportion of the strain is always plastic (Hardin, 1978; Altuhafi *et al.*, 2011) and the recoverable strain is relatively low (Nicot & Darve, 2006). This is particularly the case past the yield strength, which in the till at Storglaciären occurs at low strains according to data provided by Iverson *et al*. (1999). This issue is raised but dismissed by Iverson *et al.* (1999) based on the claim that shear stress rarely reaches a level high enough for deformation to occur, based on his calculations.

The data presented suggests nearly entirely recoverable strain on many occasions. This seems improbable as the tilt cell usually moves approximately 1 degree and so approximately 0.0015 m (probe size 0.085 m) of strain occurs. That estimate presumes that the tilt cell functions as perfect Lagrangian unit vector and the deforming area encompasses the entire cell (e.g. localised strain is not higher). Based on data presented in the paper from geotechnical testing this is well in excess of the yield strength. Various pieces of evidence are provided to argue that the yield stress is not exceeded but they require many assumptions about the water pressure at the site of the tilt cell, the shear stress applied and the properties of the till.

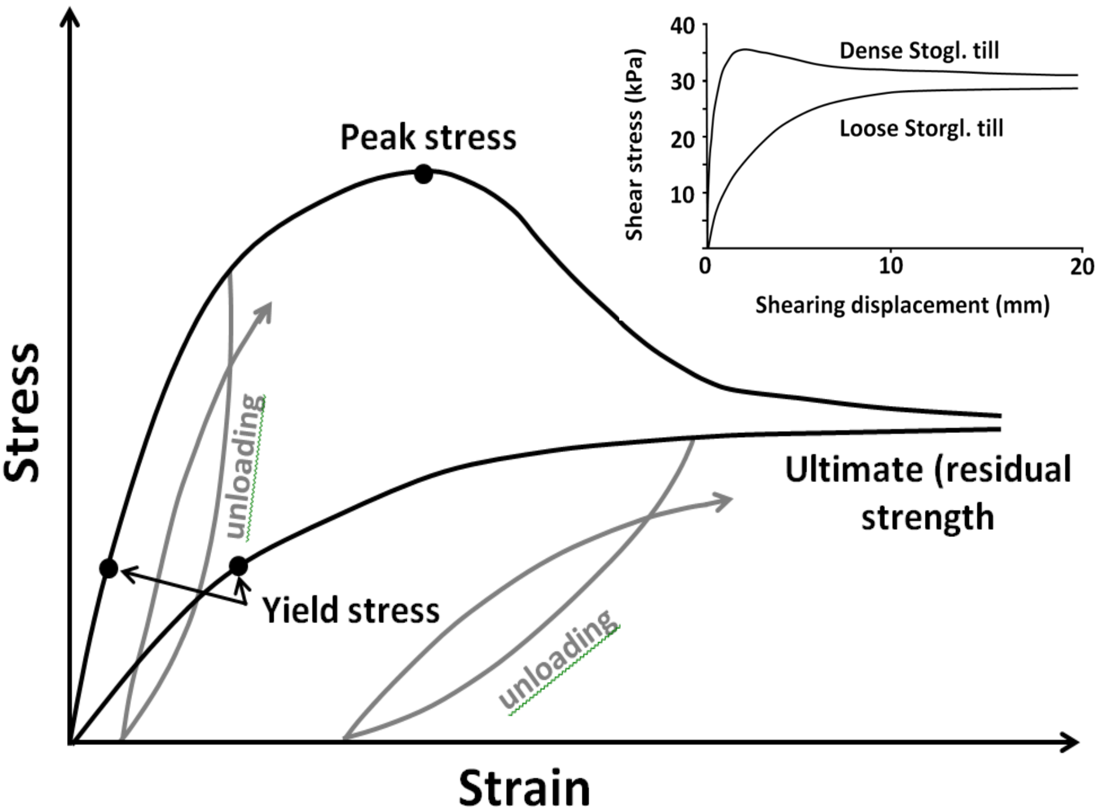


Figure 8: Idealised and actual (inset graph) stress-strain curves for Storglaciären till (reproduced from Iverson *et al*., 1999)

It is possible that the theory presented is correct but it is highly complex with a number of assumptions and appears at times to disagree with the data presented and known aspects of granular deformation from the literature.

Tulaczyk *et al.* (2000) also consider recoverable elastic strain but focus on compressibility during consolidation due to variations in normal effective stress. They assume near perfect elastic recovery that is borne out by triaxial testing where irrecoverable compression was minimal. In first order modelling of the situation, they examine the influence of oscillations of normal effective stress on tiltmeter behaviour in tills with contrasting hydraulic conductivity. Their conclusions are that at an initial inclination of 20 degrees it is feasible that compression and expansion of till could feasibly produce negative strains of the magnitude seen at Storglaciären as reported in Iverson *et al*. (1995) and Hooke *et al*. (1997). However, in a till with lower hydraulic conductivity, such as that of Ice Stream B that has a higher clay content, oscillations in normal effective stress might not result in similar tilt variations.

A more recent alternative proposal for probe oscillation is given by Hart *et al*. (2009). Data from wireless probes deployed at Briksdalsbreen, Norway, from 2004-2006 display dip oscillations periodically. The oscillations were larger than those seen in Iverson *et al*.'s (1999) study. They commonly had amplitude of approximate 5 degrees and sometimes were as high as 25 degrees, far higher than reported elsewhere. Oscillations occurred during low, high, rising and falling pore pressures, but not consistently.

Hart *et al.* (2009) hypothesise that the oscillations occur due to stick-slip movement causing a lodging (Benn & Evans, 2010) of the probe between a deforming and non-deforming area of till or between the ice and the till. Presuming the probes have an incomplete connection to any particular medium in the subglacial zone, ice or till, then this is perhaps feasible. Hart *et al.* (2009) suggest the size of the probe increases the chance of lodging occurring and shows that they occur particularly during periods of rapid pore pressure increases after sustained periods of lower pore pressures. Problematically there is no suggestion of how it should produce such regular oscillations. The brevity of the explanation and limited quantification makes it an incomplete theory, although it is interesting to note that the pressure situation is similar to studies discussed above where decoupling is suggested.

With regard to the *in situ* work undertaken in this thesis, it is important to note that the experimentation to date has been done in similar tills with high hydraulic conductivities. The behaviour of basaltic till at Breiðamerkurjökull, as reported by Boulton and Hindmarsh (1987), could be reasonably assumed to be more similar to the till at Skalafellsjökull than other tills studied. Boulton and Hindmarsh (1987) presented results that normally consolidated till from

Breiðamerkurjökull dilated by 10% under shear. This is abnormal behaviour for normally consolidated granular material that usually does not dilate under shear, and a very large amount of dilation for any granular material (Tulaczyk *et al*., 2000). If the till at Skalafellsjökull was to behave similarly and the mechanism for tilt oscillation presented by Tulaczyk *et al*. (2000) is correct then tilt oscillations of sensors under Skalafellsjökull should be pronounced.

Although the literature is limited, interestingly it appears that these oscillations are also found outside of glacial *in situ* sensing. Tilt sensors are widely used for monitoring subsurface deformation with applications such as landslide monitoring (García *et al*., 2010) and investigations into karst hydrology systems (Jacob *et al*., 2010). Landslide monitoring has many similarities to deforming subglacial till. Both involve flow under gravity dictated primarily by water pressures where a consistent vector of motion would be expected. However, oscillation and up-slope movements of sensors are often present. No firm reason for its occurrence is given but oscillations did not occur when the water table dropped and there was often a diurnal nature to the oscillations. Therefore, it was hypothesised that it could be related to evapotranspiration and consequential expansion/contraction of the soil due to water removal.

Jacob *et al*.'s (2010) study is quite different but again focuses on the ability of water inputs to produce oscillating signals in tilt cells. The tilt cells are of a different construction, water based with a longer baseline, and the study of subsurface movement of limestone requires greater precision to detect the signal. The premise remains similar though. Through experiments in variable surface loading (via placement of tractors above the test site) and numerical modelling, they demonstrated that water flow into the karst system could result in variable lateral deformation resolvable by the tilt sensors as oscillations. Unequal forcing could be caused by variable water supply to the surface, or laterally (not vertically) variable spacing of fractures and cavities within the system.

The analogues are imprecise but there are clear similarities between both situations. Glacial systems experience temporally variable water inputs, there are discrete pathways by which they can enter as per karst systems and water pressures can modulate spatially variant loading of the till by the ice. This is a similar but different mechanism to that suggested by Blake (1992) and Iverson *et* al. (1999) as it is less focused on down-ice deformation and more on the rearrangement of the system as water enters it. Whilst there are no data to refute Iverson's theory that tilt oscillations under glaciers occur due to elastic recovery of the surrounding till the more nuanced theories presented by Jacob *et al.* appear to better cope with the spatial heterogeneity of the glacial system. Equally, it seems entirely feasible that both theories could be correct.

One situation that cannot be discounted is that the up glacier movement of the sensor is actually reflective of a flow reversal. Whilst in many ways it is perhaps an obvious suggestion, presumably it is not included in earlier analyses due to questionable plausibility. However, it appears that this it is actually a feasible occurrence with flow reversals having now been observed on marine terminating glaciers (Murray *et al*., 2015) and terrestrial glaciers (Fudge *et al*., 2009). Without further evidence, it is difficult to ascribe regular oscillations to this mechanism, but for events that are more sporadic it must be viewed as an option.

Regardless of the exact mechanism though all theories are to some degree based on temporally variant inputs of water into a spatially variant hydrological system. Whilst understanding remains too imprecise to infer any particular system structure from the presence of oscillations their seemingly inherent relationship with stick-slip movement means that their presence or absence will probably inform on the manner of deformation and/or basal sliding.

2.3.1.4 Till rheology from *in situ* data

2.3.2 Geotechnical investigations

The term 'geotechnical engineering' covers a broad range of techniques, laboratory based and otherwise that aim to establish mechanical, physical or chemical properties of soils and rocks (or more specifically in this context – till). Within glaciology, the principle behaviour studied is the response of till to stress. However, this may be considered via study of other characteristics such as particle size and there have been numerous studies (not catalogued here) that have classified tills via simple tests such as Atterberg limits.

Conventional geotechnical techniques include both field and laboratory studies but here there is limited coverage of the former. They are rarely used as the attraction of assessing palaeo tills outside the laboratory is limited due to the evident differences in conditions to when it was glaciated diminishes the advantages of sampling it for laboratory study. Some of the *in situ* tests discussed in the section above could be considered geotechnical, albeit generally more esoteric than conventional techniques. Rea (2004) provides a good overview of the range of approaches employed in glacial geotechnical study.

The geotechnical study of glacial till is an interdisciplinary approach. It remains niche and comparatively few studies have employed a geotechnical approach, presumably due the paucity of geographical institutions with facilities for it and frequent requirement for custom made testing apparatus (e.g. Iverson *et al*., 1997). However, despite that it has had a significant impact on our understanding of how subglacial deformation occurs.

As noted by Rea (2004) the objectives of glacial geotechnical studies tends to differ from those of the engineer. An engineer considers specific properties of the soil in question relative to standards, for instance peak strengths, in order to construct buildings safely. In the broadest of terms, the focus is on making sure structures do not fail. Glacial geotechnical studies instead have largely concentrated on how till behaves once peak stress has been exceeded and in other dynamic contexts. This is evidently quite different and problematically there is not a great deal of cooperation between the research areas in engineering and glaciology in terms of co-authorship or integration of engineering literature. There are a number of engineering studies on till but none with much relevance to glacial study (e.g. Hoopes & Hughes, 2014).

Geotechnical techniques have been applied in glaciology for nearly 50 years. Over that time there has been a logical progression in techniques, summarised in Table 3. Initial studies to employ geotechnical techniques focused on basic characterisation of palaeo tills. These studies predominantly included simple tests such as Atterberg limits and particle size characterisations (not included in Table 3). These were superseded by studies attempting to calculate how thick ice had been in the glacial maximum (e.g. Kazi & Knill, 1969). In the absence of any widespread understanding of till deformation's role in glacial movement, they instead considered the role of the glacier in the application of normal stress to the till. By testing the extent to which *in situ* samples were over-consolidated (see section 2.3.2.2.2 for more detail), they were able to estimate the approximate normal effective stress experienced and thus approximately estimate ice thickness.

Boulton *et al.*'s work (Boulton *et al.*, 1974; Boulton *et al.*, 1979; Boulton *et al.*, 1986; Boulton *et al.*, 1987) on deformation prompted a host of new questions relating to till's response to strain. These questions can be generalised as 'what resistance does till provide to glacial movement?' (Cuffey and Paterson, 2010). Over the course of the 1990s, the main aspects of this question were addressed. Kamb (1991) provided evidence that till conformed to the Mohr-Coulomb model and so water pressure was key and till had a plastic response to applied deviatoric stresses. This was confirmed by additional studies that also demonstrated that this behaviour held even under fast flowing ice, i.e. till is largely strain invariant and slightly rate weakening in its critical state (steady strain) (Ho *et al.*, 1996; Iverson *et al.*, 1998). These studies really marked the divergence from common engineering testing into a more exploratory domain of glacial geotechnical testing.

Since the millennium, research has increasingly focused on more niche aspects of deformation. The studies in the 1980s and 1990s had established the large scale behaviour of till quite well, and in combination with Alley's (1996) work on 'sticky-spots' there was a workable model for glacial flow. However, the understanding of how the scale at which glacial flow diverges from plastic to viscous remained unclear (Hindmarsh, 1997). Consequentially there have been a number of studies examining various aspects of deformation that might lead to a better understanding of that juncture. These include attempts to determine strain behaviour of till before peak stress is reached (Moore & Iverson, 2002; Desai *et al*., 2010; Altuhafi *et al*., 2010), understand how particle size heterogeneity (and particular ploughing) influences till deformation (Rousselot & Fischer, 2007; Thomason & Iverson, 2008; Iverson, 2010), and assessing the impact of decoupling in the lee-side of obstacles on the glacier bed (Iverson& Zoet, 2015).

The latter two approaches have yielded convincing results supportive of the early experimentation. In both situations during steady deformation some degree of rate weakening occurs. In ploughing experiments, this was achieved by elevated water pressures down ice of the ploughing particles. In decoupling experiments contact between the ice and bed decreased as ice velocity increases, again producing a rate weakening effect. This encourages a view that as glaciers accelerate there must be a progressive transfer of stress to areas of stronger undeforming till or topographic obstacles (Iverson & Zoet, 2015). However, the behaviour of till at low strain rates, and how that might be combined in models with the rate weakening at rapidly deformation rates, remains more problematic.

In this section there is an attempt to establish a conceptual basis with which the reader can interpret the results presented later in chapters 4 and 5. There is also discussion of key methodological aspects of the study such as consolidation and pre-failure behaviour.

Table 3: Table of glacial geotechnical studies on till involving some form of deformation, e.g. excluding some studies of basic characteristics such as texture and studies on ice or ice/sediment mixes.

Study	Apparatus	Aims
Hoopes & Hughes (2014)	Triaxial	Shear Strength
Altuhafi et al., (2011)	Triaxial, Ring Shear	Particle Size, compressibility
Altuhafi & Baudet, (2011)	Ring Shear, Oedometer	Particle size evolution
Altuhafi et al., (2010)	Triaxial	Define CSL
Desai et al., (2010)	Triaxial	Shear Strength, Creep, model calibration
Rathbun & Marone, (2010)	Double direct shear	Stress Response
Rathbun et al., (2008)	Double direct shear	Shear Strength, Stress Response
Thomason & Iverson, (2008)	Ring Shear	Ploughing
Rousselot & Fischer, (2007)	Rotary Ploughing Device	Ploughing
Moore & Iverson, (2002)	Ring shear	Stress Response
Kamb, (2001)	Triaxial, Ring Shear, Shear Box	Shear Strength, Stress Response
Hubbard & Maltman, (2000)	Triaxial	Shear Strength, hydraulic conductivity
Truffer et al., (2000)	Triaxial, Ring Shear, Oedometer	Shear Strength
Tulaczyk et al., (2000)	Triaxial, Ring Shear, Oedometer	Shear Strength, Stress Response, Compressibility
Iverson et al., (1999)	Ring Shear	Shear Strength
Boulton & Dobbie, (1998)	Ring Shear	Shear Strength, Strain rate dependency
Evans, (1998)	Triaxial	Stress Response
Iverson et al., (1998)	Ring Shear	Shear Strength, Strain rate dependency, Stress Response
Iverson et al., (1997)	Ring Shear	Stress Response
Ho et al., (1996)	Shear Box	Strain rate dependency
Kamb, (1991)	Shear Box	Shear Strength, Stress Response
Bell & Forster, (1991)	Triaxial, Shear Box	Shear Strength, Compressibility, plasticity
Sladen & Wrigley, (1983)	Particle Size	Plasticity, Compressibility, Particle Size
Boulton & Paul, (1976)	Oedometer	Compressibility
Boulton et al., (1974)	Shear box	Shear Strength
Kazi & Knill, (1969)	Shear box	Shear Strength, Pre-consolidation loads

2.3.2.1 Calculation of theoretical variables

Before progressing to the testing details, it is important to establish the basic constitutive model used throughout chapters 4 and 5. This will provide a theoretical framework and allows basic estimation of starting values where *in situ* data are not available or sufficient.

Subglacial till will deform in response to changes in the effective stress environment ice (Cuffey and Paterson, 2010), where effective normal stress, σ'_n, is defined as:

$$\sigma'_n = \sigma_n - u$$

Equation 2

where σ_n is the total normal stress (kPa) and u is the pore water pressure (kPa). Total normal stress is a function of the depth and unit weight of overlying ice:

$$\sigma_n = \rho g h$$

Equation 3

Where ρ is the density of ice (917 kg m^{-3}), g is gravity and h= the depth of the ice. Pore-water pressure variations are driven by temperature-controlled changes in meltwater production and to a lesser degree precipitation on the glacier surface. Driving shear stress, τ_b, is a function of ice surface slope and glacier thickness that can be defined as:

$$\tau_b = F\rho g h \sin\alpha$$

Equation 4

Where *F* is a shape factor derived for a parabolic valley glacier (Nye, 1965) and α is the surface slope angle. Laboratory experimentation in a variety of apparatus (ring-shear, triaxial, double-direct shear) indicates that till exhibits Mohr-Coulomb plastic deformation behaviour (Iverson, 2010) with peak till strength being defined as follows:

$$\tau = c_O + f\sigma'_n \approx fN$$

Equation 5

Where: $\sigma'_n = \sigma_n - u$ and $f = \tan\varphi$

τ is till peak strength, C_O is the apparent cohesion, f the friction factor, and σ'_n the effective normal stress on the slip plane (equation given below), u the pore pressure within the till and φ is the angle of the slip plane.

Beyond this mathematical approach, it is worth considering the manner in which the till sample may behave during geotechnical testing which should allow for a fuller assessment later. To provide coherency this is done as per the stages of a shear box testing e.g. starting with consolidation, moving on to initial behaviour during shear and finally considering constitutive behaviours of shear.

2.3.2.2 Observed sediment behaviour and characteristics

2.3.2.2.1 Plastic deformation

As Cuffey and Paterson (2010) note, Mohr-Coulomb behaviour is found in saturated granular matter throughout soil science and so is unsurprising that glacial tills conform to it. However it was potentially difficult to reconcile with observations of glaciers that suggested power-law flow in the manner of a Bingham fluid (Boulton and Hindmarsh, 1987; Alley, 1989) but *in situ* measurements from a variety of studies (Boulton *et al.,* 2001; Truffer *et al.,* 2001; Kavanaugh and Clarke, 2006; Tulaczyk 2006) now confirm that till does deform in this manner. Plough-meters, rods placed downwards into the till that record the force applied to them, have shown shear stress has little dependency on strain rate. Deformation depth variation, initially difficult to reconcile between the laboratory and field (Iverson *et al.,* 1998) is expected to occur as a result of diffusing pressure heads through the till (Iverson *et* al., 1998; Tulaczyk *et al.,* 2000) and upwelling of water from deep below the ice – till interface (Boulton *et al.*, 2001).

Whilst the Mohr-Coulomb plastic deformation behaviour is relatively well established pre-failure behaviour is understood less. It is not well approximated by the Mohr-Coulomb model and aside from Altuhafi *et al.,* 2009 and 2010 little work has been undertaken on it with other authors instead focussing on larger scale relationships or high strain rates. Porosity (or level of consolidation) at this stage is significant, and changes in it due to grain rearrangement during shear results in internal friction and pore-water pressure changes that affect stress-strain behaviour. Lithology here also appears to be important with differences noted between sandy and clay based tills (Altuhafi *et al*., 2009, 2010) that are not totally encompassed by different friction factor values. Much of the literature has ignored the pre-failure state of till assuming a pure elastic period of deformation and so instead focusing on post-failure behaviour. As pre-failure deformation is actually mostly plastic (lithology dependant) and the strain required to reach failure is variable this is not advisable (Altuhafi *et al*., 2009).

2.3.2.2.2 Consolidation

Consolidation is the reduction in volume of saturated sediment in response to an increase in normal effective stress (Equation 2) (Craig, 2004). The type of experiment, permeability of the sediment and rate of change of normal effective stress dictate the manner in which consolidation occurs. The two possibilities are drained or undrained. If consolidation and so pore-water evacuation keeps pace with the rate at which normal effective stress is changing then the sediment is said to be in a drained state. However, if pore water evacuation cannot keep pace with the rate at which normal effective stress is changing then the sediment exists in an undrained state with excess load carried by the incompressible water. In this situation, consolidation will continue until excess pore water has been evacuated.

An undrained state can occur because the experimental set up restricts or prevents evacuation of pore water. It could also occur because the permeability of the sediment is such that it cannot keep pace with the rate of pore water evacuation required. In addition, if normal effective stress is increased at sufficient speed then it is likely that an undrained state can always be achieved.

During deformation an undrained state is significant, as with the incompressible water taking some of the normal stress the normal effective stress will diverge from the normal stress applied in the experimental set up. This will lead to experimental behaviour differing between the experiments where a drained state is maintained and those where an undrained state is produced. In a testing situation this can be either problematic and reflective of poor experimental design, or indicative of how the sediment’s permeability impacts its deformation.

Experimental design must ensure that a sample is brought to the desired normal effective stress before shearing commences. Therefore, whether the sample is in an undrained or drained state is significant. This means care must be taken over how the sediment reaches the desired normal effective stress. By increasing normal effective stress at a suitably low rate then the sediment can remain in a drained state throughout.

A useful by product of ensuring a drained state during consolidation is that the relationship of normal effective stress against void ratio becomes more meaningful as there is no lag in the relationship. The e-log σ' relationship for normally consolidated clay will be linear whereas for overconsolidated clay it will be nonlinear (Craig, 2004). Therefore, plotting these variables becomes a useful diagnostic of sediment preparation. When testing intact samples it can be used to identify prior maximal loading. This has been a technique usefully employed to investigate normal effective stresses below palaeo glaciations. Samples collected *in situ* are consolidated progressively, and the point at which the e-log σ' relationship changes from nonlinear to linear should indicate the normal stress the till was subject to during glaciation (e.g. Kazi & Knill, 1969).

An undrained state can occur during deformation due to a high rate of shearing. This results in an undrained shear strength that is distinct from the drained shear strength and cannot easily be approximated.

2.3.2.2.3 Pre-failure behaviour

The behaviour of deforming till before it reaches critical state steady deformation has been the subject of relatively little research (Moore & Iverson, 2002; Sane *et al*., 2008; Altuhafi *et al*., 2009). As mentioned in the introduction to this section its significance is due to the current appreciation that the beds of rapidly moving glaciers are likely to be a patchwork of rapidly and less rapidly deforming till with excess shear stress being born by the stronger lower strain rate areas (Iverson & Zoet, 2015). Therefore the behaviour of till as it transitions to critical state strain behaviour is likely to be a control on the manner of ice movement.

The three studies on this area to date have approached it from quite different perspectives. Moore & Iverson (2002) considered the behaviour of till under a constant deviatoric stress as normal stress was periodically reduced. Sane *et al*. (2008) modelled the deforming zone as a mix of tills of different shear strengths and consequentially different strain rates. Altuhafi *et al*. (2009) assessed the impact of temporary and permanent alterations of the strain rate on deviatoric stress. Sane *et al.* (2008) use a floating numerical model in which parameters cannot be represented in analogue experimentation, and so their work has limited relevance to this study.

Moore and Iverson's (2002) experiment used a ring shear to simulate the initiation of shear in an overconsolidated till. The till was consolidated with a normal stress of 250 kPa that was then reduced to 180-155 kPa for testing. A shear stress insufficient to shear the sample (17-25 kPa) was applied and the normal stress then was periodically reduced by 0.8-2.5 kPa. It should be noted that only one result is documented in any detail in the publication, presumably due to the brevity of the publication format, but some form of episodic behaviour was present in all experiments regardless of variations in initial setup. There are no indications as to whether normal stress was reduced in a constant manner (in terms of stress or timing) in the testing, but in every experiment once shear started normal stress was held constant.

In the documented experiment, (see Figure 9) the initiation of shear was followed by episodic increases in strain rate before a final catastrophic failure. Shear resulted in dilation sufficiently faster than the rate of pore-water diffusion resulting in a net increase in shear strength and the cessation of the episode. At that point the opposite occurred and pore-water diffusion outpaced dilation resulting in the weakening of the till and shear initiation. This process continued for 10 episodes before at 100 min the sample failed catastrophically. At failure the sample's angle of friction (24.5°) was close to that previously measured for its critical state (26°).

Moore and Iverson theorise that with typical measured diffusion and dilation speeds, shear velocities would have to exceed only 10^{-4} m/s (9 m/day) for dilation to exceed pore pressure diffusion. Therefore dilation controlled quasi-stable episodic shear should be feasible until the till reaches its critical state. At that point, no additional dilation is possible and so it will fail catastrophically. With ice velocities at the Glacsweb site <9 m/year it seems feasible that this form of quasi-stable shear could be possible.

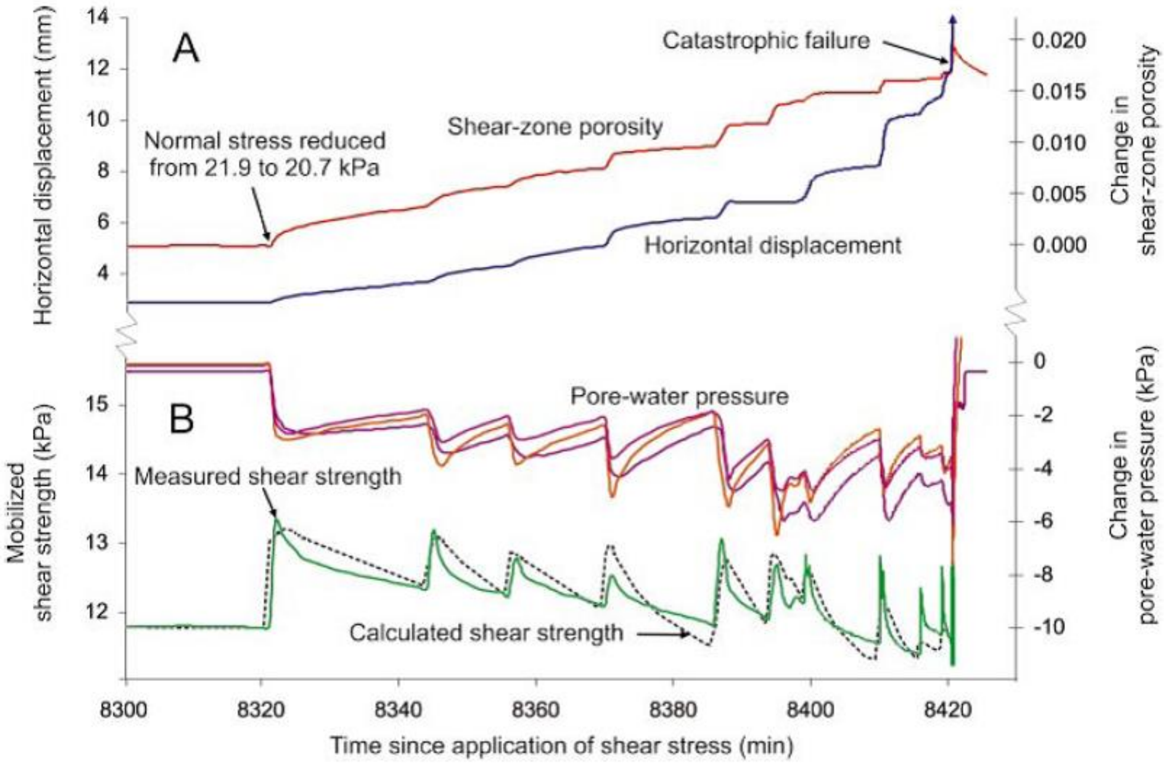


Figure 9: Reproduced from Moore and Iverson (2002). Results of a ring-shear experiment with coarse-grained sediment. Graph A shows porosity change and horizontal displacement and graph B shows pore-water pressure, measured shear strength and calculated shear strength.

Whilst Moore and Iverson (2002) considered normal stress variations, Altuhafi *et al*. (2009) considered strain variations. Whilst till has appeared to be relatively strain independent in the residual state whilst undergoing Constant Rate of Strain (CRS) testing (Hamilton and Crawford, 1959) (i.e. set strain rates within each test) this method of testing often fails to identify time dependent variations in stress response (Tatsuoka *et al.*, 2002; Altuhafi *et al*., 2009). A testing methodology where strain rate is varied within a single test (e.g. Tatsuoka *et al*., 2002) is more likely to identify variations between tills, if they are present. Whilst even in this situation the effects of strain rate on the critical and residual states are likely to be minimal, pre-failure behaviour can vary significantly. Sediments tend to display either Isotach behaviour where changes in strain rate result in stress-strain response moving to a new distinct curve, or TESRA (Temporary Effect of Strain Rate and strain Acceleration) behaviour where the change in strain rate results in only a temporary change in shear stress response.

Because of the yet minimal focus on the pre-failure behaviour of till in modelling, the significance of these behavioural variations are not known. It seems likely that with the stochastic stick-slip motion observed at many glaciers (e.g. Fischer & Clarke, 1997) it may be important. Even in the absence of evidence for field relevance, the Tatsuoka *et al*. (2002) testing methodology appears to provide a better differentiation between tills than the CRS method.

2.3.2.3 Reconciling differences between testing methodologies

A fundamental problem in geotechnical experimentation is reconciling the results produced by different methodologies. Broadly, these may include shear box, triaxial and ring shear testing, although smaller differences exist between each for instance back pressure vs normal shear boxes. Table 3 shows the methodologies used in major glacial geotechnical studies. Broadly it can be said that the largest number of studies have been done using shear boxes, presumably due to their ubiquity in laboratories. However, much of the recent important work has been carried out with ring shear apparatus, predominantly by Iverson. Triaxial cells have been less commonly used, but the work by Altuhafi (Altuhafi *et al.,* 2010; Altuhafi & Baudet, 2010; Altuhafi *et al.,* 2011) that has been done with them is clearly very relevant to this study because the till tested is very similar to that tested in this study.

Each testing methodology is different, but all can produce similar outputs. This is especially true when attempting to define large scale rheology, e.g. plastic or viscous behaviour. Comparison can be more complicated when attempting to produce failure criterions based around peak or residual stresses. Iverson *et al*. (1997) note how often the residual shear strength calculated by triaxial and shear box testing often is higher than that measured in ring shear apparatus, sometimes by 75%. This is due partially to those testing methodologies being restricted to 20% strain, but when using shear boxes there is also concern about deformation focusing towards walls at the end of the specimen.

Testing with a ring shear device removes many of these issues by allowing any strain desirable and having no end walls to focus deformation around. However, ring shear devices are not without their own issues. Confining walls still produce drag that influences results and the circular nature of the device results in unequal strain rates across the sample influencing shear strength measurements. Ring shear devices also limit the possibility for back pressure control, but this may or may not be an issue depending on the test.

Fortunately for this investigation the disparities in residual stresses achieved on shear boxes and ring shear devices are generally exaggerated by clay based sediments, unlike the till tested here. Therefore, residual strengths extracted from the testing can be faithfully compared to other results. This increases the comparative data available as often only residual or peak stresses are reported. Unfortunately, complicating matters further, whilst some authors specify whether their angle of friction is defined by peak or residual stresses, others fail to do so and there is some variation in what is considered a residual stress.

2.3.2.4 Outsize clast removal

One common theme in geotechnical laboratory testing is the need to remove outsize clasts. Due to till's frequently unsorted nature and the frequent presence of large clasts, this has been criticised as a fundamental problem with the technique. A number of issues have been raised. Boulton and Dobbie (1998) suggest that blocking of strain by outsize clasts results in localised failure events. This reduces non-linearity in deformation and so is a significant part of till deforming viscously. They argue that the removal of outsize clasts from laboratory experiments is to some extent responsible for the plastic rheologies discovered there. Elsewhere Hiemstra and van der Meer (1997) suggest that interlocked clasts can fail due to grain fracture and this may be a key reason for stick-slip behaviour within till.

These concerns are unfounded. Clast removal must be undertaken such that no clasts are larger than 10% of the sample depth. Larger clasts would distort the results (Chandler, 1972; Head, 1982). However, this does not appear to be problematic. There are multiple studies where testing has been undertaken with and without the coarser fraction of a sample (e.g. Fannin *et al.,* 2005; Chang & Phantachang, 2007) and the impact on results is shown to be negligible. Smart (1985) even provides a reassuring criteria, stating that samples are considered to be dependent on their matrix when 30% of the sample is silt or finer. Further reassurance is provided from a sedimentological perspective as in situations where outsize clasts are present in a matrix deformation is often partitioned into the weaker matrix around them (Evans *et al.*, 2006).

Chapter 3: Field Site

3.1 Introduction

The field site used for the work undertaken in this thesis was pre-designated due to the link to the Glacsweb project. The glacier was chosen in 2008 before the commencement of this PhD after the previous field site, Briksdalsbreen in Norway, became unusable due to rapid retreat of the glacier. This provided an opportunity to examine a different type of glacier and Skalafellsjökull was eventually chosen as it fulfilled a range of scientific and logistical requirements.

Skalafellsjökull is an outlet glacier of the Vatnajökull ice cap in South East Iceland (see Figure 11 and Figure 12). It provided an opportunity to study similar deforming beds to seminal studies by Boulton *et al*. (1979; 1987) and offered the possibility of progressing *in situ* probe deployment to deeper ice depth than possible at Briksdalsbreen. It was also logistically simple to access due to a well maintained gravel road running up its western margin and had extensive options for local accommodation due to tourism in the area.

3.2 Skalafellsjökull, Iceland

Located in the South East of Iceland, Skalafellsjökull is a non-surging (Chandler *et al.*, 2015) piedmont outlet from the southeast of Vatnajökull ice cap. It is topographically constrained for most of its length by a self-incised valley, bordered on its northern margin by the Hafrafell and Litlafell and on its southern margin by Skalafellshnuta and Þormóðarhnuta. Initiating on the Breiðabunga plateau the glacier flows for *c.* 25 km from *c.*1000 m to 60 m, its terminus infringing on the Hornafjördur coastal plain. The terrestrial terminus of the glacier is topographically constrained on its SW side by Hjallar, a ridge rising *c.* 40 m above the coastal plain and on its SE side the margin is bounded by a small lake that feeds the River Kolgrima.

To the north of Skalafellsjökull is Heinabergsjökull and between Hafrafell the two glaciers coalesce with two lobes of Skalafellsjökull joining Heinabergsjökull resulting in a large medial moraine. There is clear geomorphological evidence of a confluence at the margin occurring in the past and documentary evidence from the mid-20th century suggests this continued until sometime between 1929 and 1945 (Thórarinsson, 1943; Hannesdóttir *et al.*, 2014) when retreat split their margins.

The glacier, as with many in Iceland, is retreating rapidly. Detailed observations of marginal retreat are not available but surface losses measured by dGPS at the Glacsweb site at approx. 800

m altitude are in the order of 3 m annually. The firn line, or approximate ELA, witnessed in 2012 and 2013 lay somewhat higher up the glacier, approximately 1000 m in altitude, close to where it joins the ice cap.

Like most glaciers in the region the foreland is dominated by post-LIA glacial and glacio-fluvial geomorphology, including in this case an extensive series of annual push moraines behind a LIA maxima (Sharp, 1982, 1984; Chandler *et al*, 2015) overlying flutings (Evans, 2000). This LIA advance resulted in a general foreland stratigraphy of diamicton on boulder gravel, lake silt, peat, sand and diatomite (Sharp and Dugmore, 1985).

As with Brei*d*amerkjökull (Boulton, 1979; Boulton and Hindmarsh, 1987; Benn, 1995) the till at Skalafellsjökull also displays a two-tier, A-B horizon, stratigraphy within the thick 2.5 m unit of till from the last advance (see Figure 10) (Sharp, 1986; Benn and Evans, 1996; Evans, 2000). This is clearly of significance to this thesis and the focus on deformation. The two tiers of till have a fabric characteristic of the D_A – D_B tills of Boulton and Hindmarsh (1987) and there is evidence of ductile and brittle shear in both. Evans (2000) hypothesises from sedimentological evidence that although the majority of deformation occurred in the units of till in the top 2.5 m of the sediment sequence, some strain occurred down to at least 5 m moderated by rheological properties.

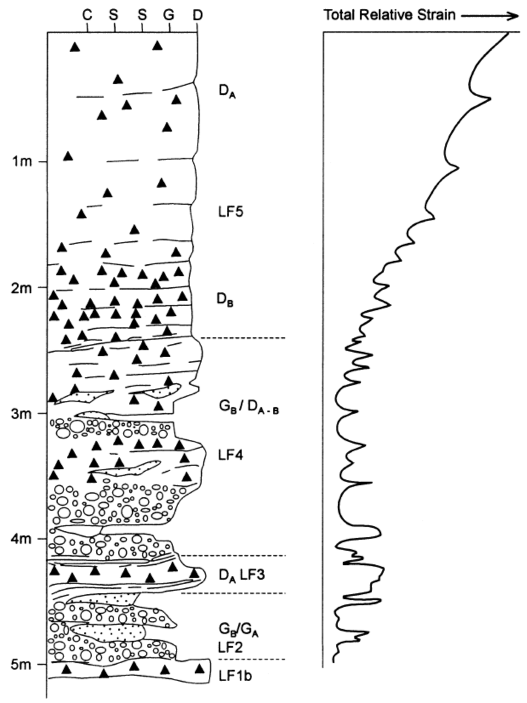


Figure 10: Composite stratigraphic log for Skalafellsjökull including hypothetical profile of strain. Reproduced from Evans (2000).

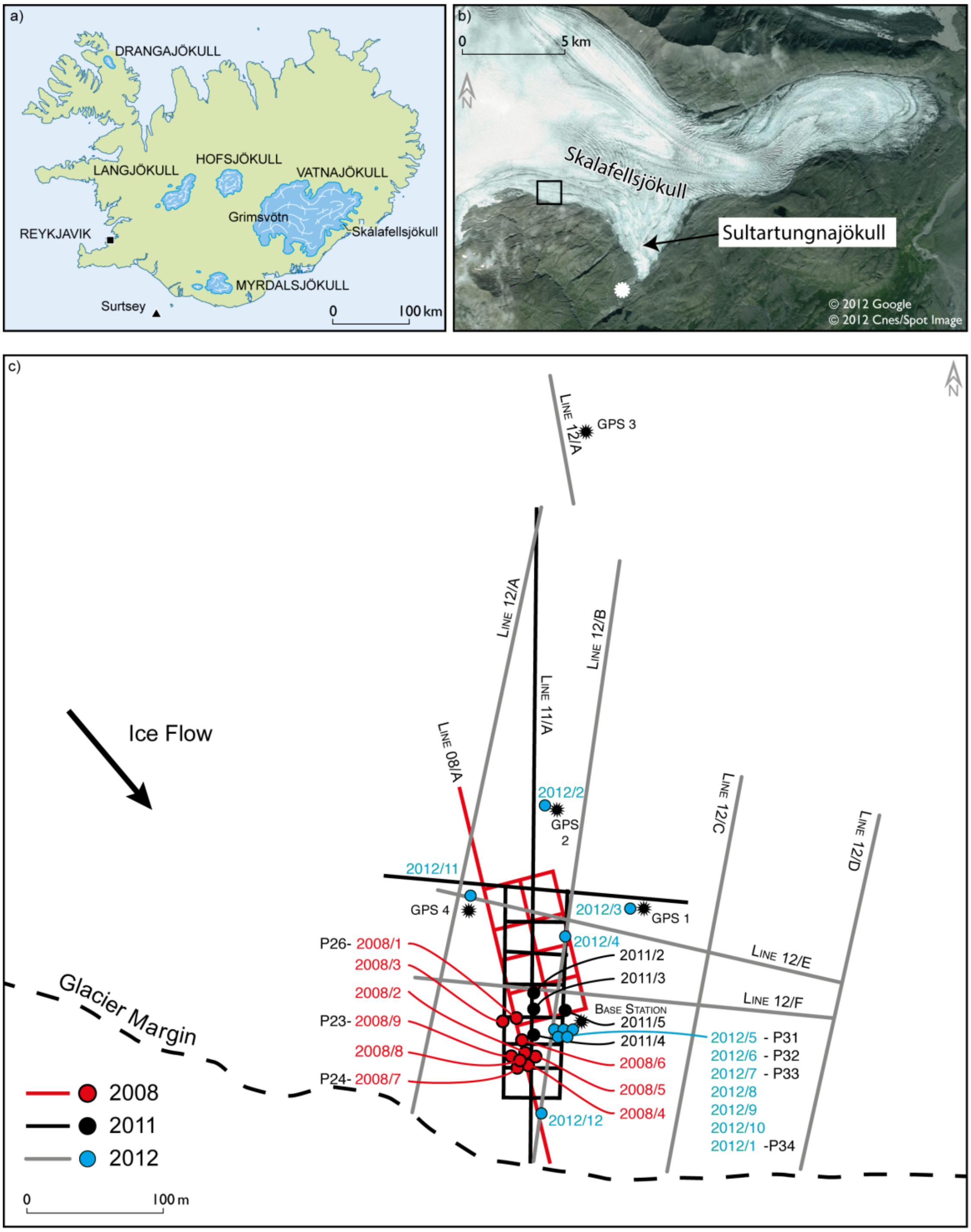


Figure 11: Location of Glacsweb site on Skalafellsjökull, amended and reproduced from Hart *et al.* (2015). A) location within Iceland, B) satellite imagery of glacier, C) GPR surveys (lines), and borehole locations (coloured circles) with probe and GPS deployments indicated by text.

Figure 12: Off-nadir visualisation of Skalafellsjökull from Google Earth [Accessed 28/05/2016]. View is to the north east with terrain exaggeration set to 1. The Glacsweb site is outlined in red and the UAV survey area outlined in yellow.

3.3 Scientific considerations

The field site selection is predominantly dependant on a few key scientific requirements, and further peripheral scientific reasons increase the suitability. The primary considerations regard in *in situ* sensing requirements and the need to build on previous Glacsweb studies (Hart *et al*., 2007; 2009; 2011). Secondary considerations include relevance to prior literature and current contemporary studies.

Glacsweb's aims (and that of this PhD) centre round the study of glacial bed deformation. Therefore, the glacier was required to sit on a deforming bed of unlithified sediments. Skalafellsjökull sits largely on a basaltic till. Quantitative use of GPR (Figure 13) (Hart *et al*., 2015) and consideration of basal reflectivity was able to suggest relative proportions of materials at the ice-bed interface. High reflectivity indicates water bodies, medium reflectivity indicates saturated till and low reflectivity indicates dry till or bedrock. This analysis suggests approximately 85% of the ice-bed interface at the Glacsweb site is till, with 10% being water and 5% bedrock. The high coverage by water bodies may reflect braided channels (Hock and Hooke, 1993) that are relatively stable on an interannual basis (Hart *et al.,* 2015).

To ensure suitable dynamism the site chosen also sits below the apparent ELA (Equilibrium Line Altitude) which should increase the possibility of water supply to the bed of the glacier and associated variations in deformation. However, it is worth noting that the site does not feature crevasses of note until close to the far GPS (GPS2 – see Figure 11). There are also only a few moulins in the locality, and supraglacial streams tend to drain off the edge of the glacier. This suggests basal water supply is probably dependent on the subglacial water bodies noted above.

As indicated in fig, ice flow is approximately towards the lateral margin with ice sloping predominately in that direction as well. Therefore, the margin presumably exerts some level of influence on the ice dynamics. At a larger scale the entire southern side of the glacier is somewhat restricted by the marginal bulge down flow from the site (Sultartungnajokull – see Figure 11). These factors may combine to restrict the local site influences and increase the significance of events further up and towards the centre of the glacier from the site.

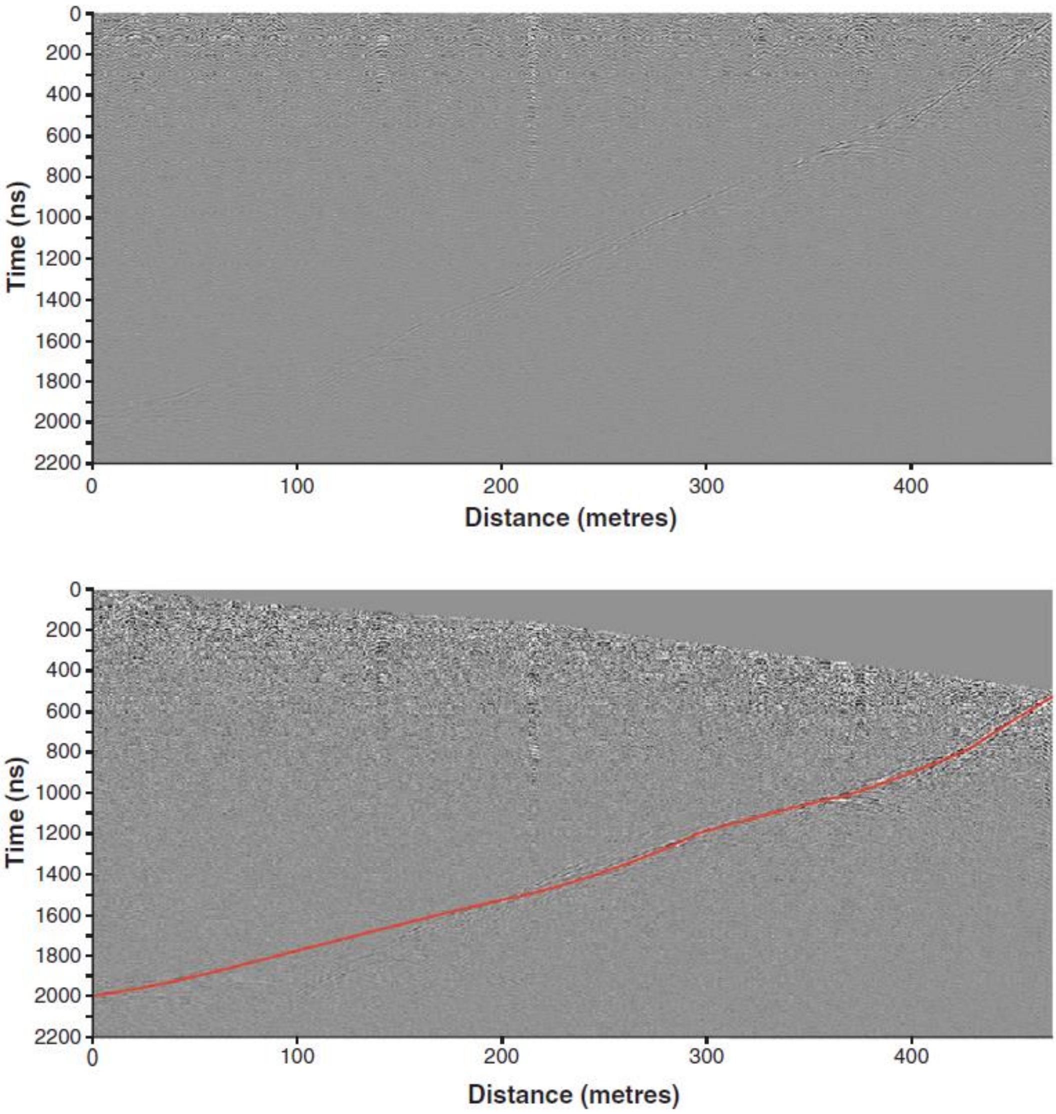


Figure 13: Radar echograms from the Glacsweb site. Both echograms are transect 11/A (see Figure 11). The top echogram is unprocessed data, the bottom echogram is after topographic correction and differential stack migration and the glacier bed has been indicated by the red line.

A significant technical difficulty in the Glacsweb project is the wireless nature of the probes. Whilst it is scientifically advantageous to use wireless probes the transmission of the data presents a number of issues. A significant issue is that liquid water attenuates radio waves and the glacial environment can contain a large amount of water. This limits the depth under the ice the probes can be deployed, however, with future improvements it is feasible that far greater depths could be managed. Skalafellsjökull is an ideal site as whilst in marginal areas probes can be deployed under <100 m of ice there is scope to easily reach much deeper areas in excess of 300 m due to the size of the valley.

3.4 Comparison to Briksdalsbreen, Norway

The move of the Glacsweb project from Briksdalsbreen to Skalafellsjökull was an enforced move caused by the collapse of the lower part of the glacier into the lake. Briksdalsbreen had advanced rapidly in the early 1990s and then made a staged retreat from 1996, culminating in the collapse (Hart *et al*., 2011). The collapse made the glacier inaccessible for the Glacsweb project forcing the move.

However, Briksdalsbreen was a very suitable location for the project. Its retreat from the 1996 maxima revealed a subglacial surface of flutes and lineations disturbed by a sequence of push moraines (Winkler and Nesje, 1999; Hart, 2006). This combined with thin section and SEM analysis of the till (Hart, 2006; Hart and Rose, 2008) demonstrate pervasive subglacial deformation throughout a relatively thin 0.3 m deforming layer.

The most obvious difference at Skalafellsjökull is the size of the glacier and position of the field site. Using a location much further up the glacier where it is over 10 times the width of Briksdalsbreen provides more security in the face of rapid retreat. It also provides further options for project progression as greater ice depths are available.

Despite both glaciers lying on unlithified and deforming sediments the results from *in situ* sensing may be quite different. The principal factor here is the depth of the till. Whereas Briksdalsbreen lies on a thin 0.3 m deforming bed, Skalafellsjökull is underlain by much thicker sediment and at the margin there is evidence of deformation occurring to depths of 5 m (Evans, 2000). If, and this is a presumption, deformation as a proportion of total ice velocity is similar at both glaciers, the signal measured by similar sized probes at each glacier is likely to differ as the strain will be distributed over a greater depth.

3.5 Summary

With the demise of Briksdalsbreen as a suitable site for the Glacsweb project the relocation to Skalafellsjökull yields logistical and scientific advantages. The glacier is more accessible, reducing costs and increasing the research feasible. It is also larger, reducing the chance of site loss to ice retreat and presenting opportunities to progress the project via progression to deeper ice. The presence of a deep deforming bed and similarities to glaciers like Breiðamerkurjökull studied in seminal papers on deformation (Boulton and Hindmarsh, 1987) presents an ideal opportunity to progress glacial knowledge of deformation.

Disadvantages of the site primarily focus around the potential for lower than ideal dynamism due to the presence of a downstream bulge of ice, the predominant flow direction into the lateral moraine and the absence of significant crevassing and moulins. However, these are unavoidable difficulties presented by technical limitations and deeper areas of ice close to the site provide the opportunity to investigate areas that are more dynamic in future projects.

Chapter 4: Geotechnical characterisation of Skalafellsjökull's till

4.1 Introduction

Geotechnical laboratory study provides an opportunity to collect data on till from Skalafellsjökull in a standardised manner. This enables robust comparison to the wider literature and theorising about subglacial bed deformation more generally. In this sense, it is very different to the *in situ* data collected at Skalafellsjökull (Chapter 7). There the lack of concurrent pore pressure and tilt data fundamentally inhibits attempts to understand the controls on deformation. Furthermore, as *In situ* data may lack the spatial coverage required to understand fully the role of pore pressure across the Glacsweb site the findings can be more difficult to apply outside of that location. By accepting some simplifications, undertaking a geotechnical laboratory study provides an underpinning of reliable data collated in idealised conditions. The results can then be used to help understand the more chaotic and less complete field data, at Skalafellsjökull and elsewhere.

The primary objective in this study is to use a back pressure shear box (BPS) to undertake experiments that are novel within glaciology and will constrain the behaviour of till during subglacial deformation. These will examine how deformation responds to NES (normal effective pressure) reductions that are forced by increases in pore pressure. This will enable comparison to trends seen in the probe data. The study bears comparison to Moore & Iverson (2002) but the experimental design better represents pore pressure drive NES variations in the subglacial environment.

The first stage in understanding the controls on subglacial deformation of till involves defining and appropriately constraining the subglacial stress environment experienced by the till. Our understanding is guided by a mix of *in situ* experimentation (e.g. Iverson *et al.,* 1999, 2007; Truffer *et al.,* 1999, 2000; Boulton *et al.,* 2001; Hart *et al*., 2007, 2011), analogue laboratory experimentation (e.g. Kamb, 1991, 2001; Iverson *et al.,* 1997, 1998; Tulaczyk *et al.,* 2000; Rathbun *et al.,* 2008; Altuhafi *et al.,* 2009, 2010) and numerical modelling (e.g. Hindmarsh, 1997; Iverson *et al.,* 1999; Tulaczyk *et al.,* 2000). This has been presented in chapter 2.

The second stage is to define the material and physical properties of the till sampled from Skalafellsjökull. Work by Altuhafi *et al* (2009, 2010, 2011a, 2011b) has helped progress glacial geotechnics by introducing a more standardised approach to the field. This chapter will follow a similar approach and develop an understanding of the characteristics of the till and assesses the key variables of the subglacial stress environment. These are determined by laboratory investigation, including a series of geotechnical tests using BPS. Once this basic understanding is reached, further tests documented in Chapter 5 try to replicate some of the scenarios that *in situ* sensing in the Glacsweb project has recorded via pore pressure reinflation (PPR) tests.

Some field data from the Glacsweb project, *in situ* or otherwise, is required for the set-up of this work. This is taken from the 2008 deployment as detailed in Chapter 7 and includes annual and ice velocities, rates of water pressure change through the year, ice-bed geometry and ice thickness.

4.2 Aims

The aims relevant to the geotechnical work presented in this thesis are:

1. To establish the rheology of the till at Skalafellsjökull.
3. To assess how pore pressure variations impact the behaviour of till samples in geotechnical experimentation and to what extent the variations and behaviour is replicated at Skalafellsjökull (as observed by the *in situ* study).

Re-phrased as research questions and more directly aimed at geotechnical experimentation:

1. Does till from Skalafellsjökull adhere to the Mohr-Coulomb model of plastic deformation?
2. What is the effect of pore pressure-driven variations in normal effective stress on till deformation, manifest as shear displacement in the BPS?

The second question will be directly tackled by experimentation presented in Chapter 5. Before that, initial laboratory geotechnical tests are presented to characterise the shear behaviour of the till and answer the first question. This will address two initial research questions:

Testing will include the following stages:

1. Remove existing sedimentary structures resulting from stress history in the sediment by mixing thoroughly with distilled water to create reconstituted, remoulded samples.
2. Undertake particle size analysis and loss on ignition tests.
3. Complete monotonic shear tests in the BPS using five different normal effective stresses; these will be selected to cover broadly the range observed in the field. This will involve consolidating each sample to a fixed normal effective stress, which will remain constant throughout the subsequent shear stage. Monotonic shear under displacement control will then be conducted at a displacement rate similar to field conditions to 20 % strain, monitoring the shear stress required to effect displacement.

4. Create stress-strain curves of shear behaviour at the five normal effective stresses. These stress-strain curves will provide information on basic sample rheology (e.g. brittle vs ductile, dilatant vs contractive) and peak stress values can be used to define the Mohr-Coulomb failure envelope for the sample, characterising its shear strength behaviour using the effective cohesion, c', and effective friction angle, φ'.

4.3 Methodology

Characterising the till tested in this thesis involves providing a range of benchmarks that will allow better comparison with future work. Material properties including grain size distribution, moisture contents and organic content have been included alongside mechanical properties such as the angle of friction. For each metric there is a range of techniques available to the methodology and this often impacts the results.

4.3.1 Till sampling methodology

Till samples were taken from an ice marginal site located close to the Glacsweb deployment. Two samples were taken where care was made to preserve *in situ* structure via use of large (0.15 x 0.15 x 0.15 m) steel tins (see Figure 16). Due to the requirement to sieve and re-mould samples to prevent grainsizes >2 mm being used in the BPS, only bulk samples were used for testing and the other samples have been preserved in case of a future need for tests where *in situ* structure is required.

All the testing uses the same batch of sediment (ACSAM2B) sieved down to ≤2 mm. This is in accordance with standard operating procedure for shear box testing where particles are limited to an a-axis < 10 % of the depth of the sample tested. This limits their influence on the matrix supported sediment and makes the test more representative of the environment (see section 2.3.2.4). After sieving, the sediment was dried, disaggregated with a soft rubber bung and mixed thoroughly. This produced approximately 2 kg of suitable sediment for testing which was used repeatedly for all tests conducted. The sample was dried overnight in a 60°C oven after each test, disaggregated with a bung, and mixed thoroughly into the existing sample (see.

Figure 14: post-test disaggregation procedure. Top right shows the sample after drying overnight in the oven, top left shows the final disaggregated sample, top centre and bottom row shows the progression in disaggregation. Disaggregation usually took approximately 20 minutes per sample due to the need to avoid undue force.

Figure 15: Imagery of the ice marginal site where samples were taken (see Figure 11 in Chapter 3 for wider situation) (Imagery: http://atlas.lmi.is)

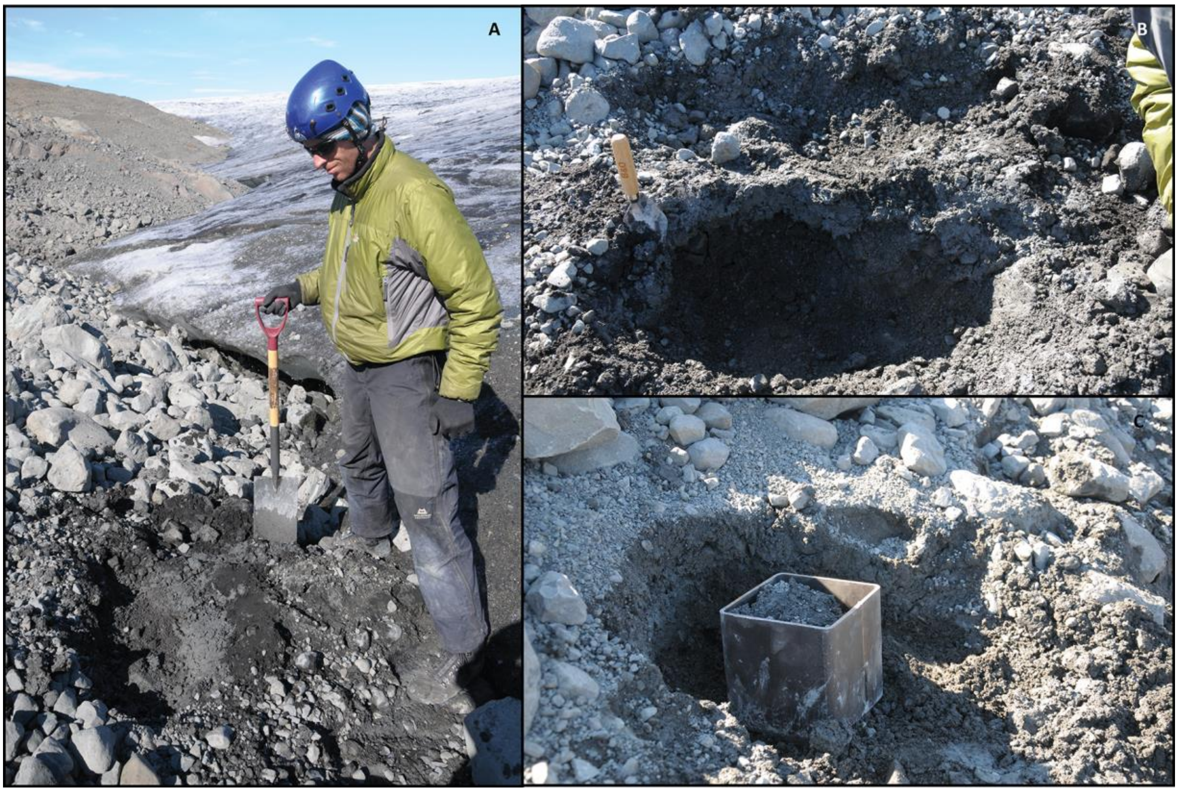


Figure 16: Illustration of sample collection. This site was used for the collection of bulk sample ACSAM2B and sample ACSAM2A where *in situ* structure was maintained via use of a tin. Image *A* shows the proximity of the site to the glacial margin, within the area uncovered by melt during spring/summer 2012. Image *B* shows ACSAM2B sample location, above and to the right of the trowel. Image *C* shows the collection of ACSAM2A. The site demonstrated a clear horizon within the till above which the till had a substantially higher water content. ACSAM2B was solely taken from the upper horizon whereas ACSAM2A includes sediment from both above and below the horizon.

4.3.2 Grain size distribution

Grain size distribution is an important sediment metric. It has not been used as a diagnostic criterion of deformation, but is a fundamental property of any sediment (Evans & Benn, 2004). It is also a property that has been recorded in a large number of glacial sedimentary studies and is near ubiquitous in glacial geotechnical studies. Therefore, it is valuable as one of the few comparable statistics available

The closest the property gets to a diagnostic nature of deformation is via estimation of the clay fraction present in a sample (Cuffey & Paterson, 2010). Clay content is related to strain rate dependency and plasticity. This is due to platey particles aligning during shear resulting in a varied response. Often it means that there is more strain rate dependency than seen in sandy sediments. Clay content will also have an impact on the hydraulic conductivity of the sediment. This is measured in some triaxial experiments e.g. Hubbard & Matlman (2000) and also has an implicit role in others such as Kamb (1991) where it resulted in the test being conducted in an undrained state (although this could have been avoided with different experimental design). Clearly though, whether laboratory testing is influenced or not the hydraulic conductivity of the sediment will have an impact on the subglacial environment.

Whilst particle size analysis can determine the presence of clay sized particles, it cannot determine whether they are actual clay particles or just clay sized grains. Unlike clay particles these are relatively inert with respect to strain dependency etc. (Evans & Benn, 2004). Geochemical analysis is required to determine between the two. The methodology employed in particle size analysis also varies significantly across the literature but a broad comparison of clay fraction is feasible.

4.3.2.1 Particle size analysis

In this study all particle size analyses was carried out with a LS13320 Coulter laser granulometer. The analysis was carried out twice. As well as hopefully providing a general characterisation of how the sediment had altered through testing it also doubles as a check on whether pre-test mixing and settling of particles during the test had resulted in a heterogeneous distribution of grain sizes through the tested sediment. Firstly four samples were taken for analysis from the sediment after it had been sieved down to <2 mm for testing in the BPS and remixed. Another round of testing was then conducted after all testing in the BPS had finished. This testing involved 21 samples from a BPS sample after it had been testing.

4.3.3 Moisture and organic content (Loss On Ignition)

To assess the efficacy of mixing during sample preparation and so establish testing consistency, on one occasion 9 moisture contents were taken once a sample had been prepared and put in the shear box cradle. The samples were weighed immediately after sampling and then again after 12 hrs in an oven at 110°C. In addition, to establish organic content, they were weighed a further time after 6 hrs in a furnace at 600°C.

4.3.4 Back Pressure Shear box (BPS)

The BPS provides an opportunity to test sediment in more realistic conditions than allowed by standard shear boxes. The BSP allows control of porewater pressures within the sample during direct shear testing and can conduct standard saturated and unsaturated tests. This enables replication of site specific conditions.

The BPS is similar to a standard shear box (see Selby, 2005 for a broader description) and takes 100 x 100 x 20 mm samples that are subjected to direct shear on a defined shear surface. The sample is contained within a split vessel comprising upper and lower sections 10 mm deep. The bottom half of the vessel is attached to the base of the shear box and immobile throughout testing. The top half is controlled by a hydraulic ram. In a standard shear box, the entire sample would sit within a flooded container that is at atmospheric pressure. The difference in the BPS is that the pressure within the flooded container is controlled (back pressure) and a high-air-entry porous disk at the sample bottom allows pore pressure to be controlled within the sample. This enables NES to be accurately calculated and controlled throughout experimentation whereas this is impossible in a normal shear box.

This is a more realistic situation than conventional shear boxes, as used in previous studies (Kamb, 1991; Tulaczyk *et al.,* 2000 etc.). The use of back pressure more accurately reflects the subglacial situation where normal effective stress is controlled by subglacial water pressure rather than just by normal stress variation. Back pressure also ensures that the sediment remains saturated throughout testing. To date the BPS has been applied to landslides (e.g. Brain, 2015) but not glacial deformation.

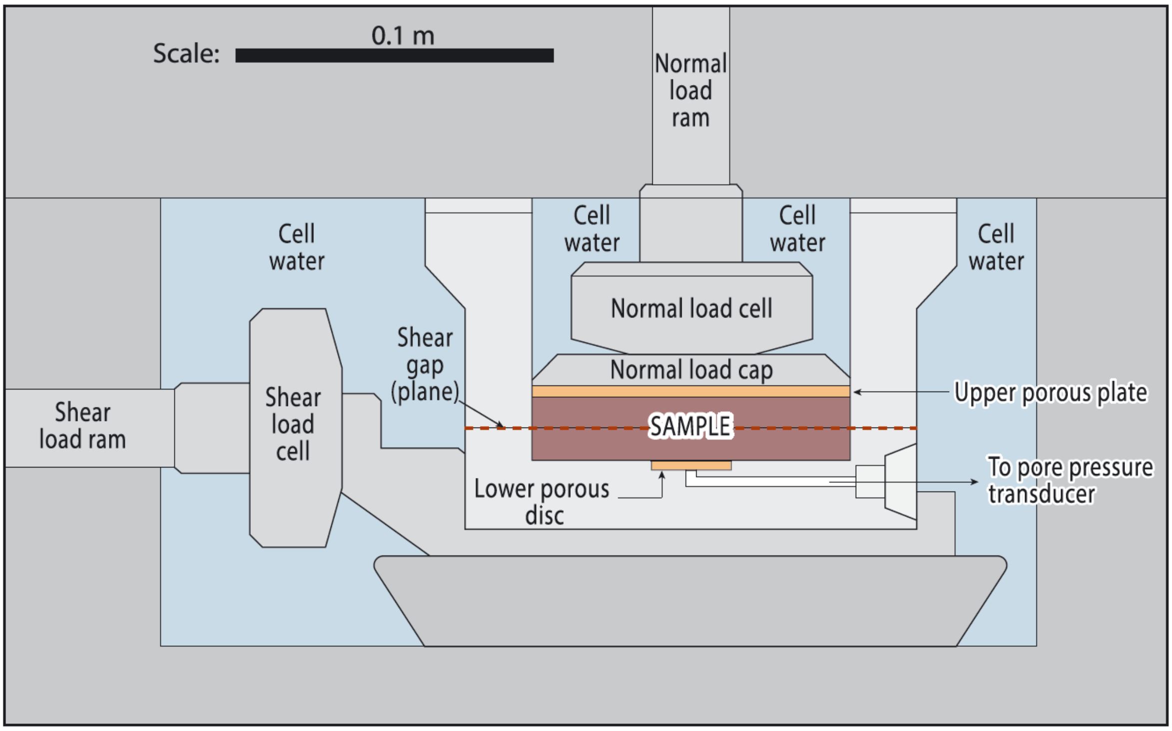


Figure 17: Cross-sectional visualisation of the DynBPS. The BPS is mechanically similar but with different control mechanisms (reproduced from Brain *et al.,* 2015).

4.3.4.1 BPS Sample Preparation

420 g of ACSAM2B was weighed out with a balance and mixed with 15% de-ionised water by weight to pre-saturate it. Pre-saturation ensures better control of water pressures during the test. 420 g was used in each experiment to achieve sufficient sample depth in the shear box, usually approximately 22 mm before consolidation. Once the water is added to the sediment, it is mixed

thoroughly by hand for 5 minutes and then placed in the carriage. Filter paper is then placed on the sediment followed by a porous plate with the coarse side of the plate facing upwards away from the sediment. The sediment is then tamped down lightly by hand with a wooden block. The pressure applied here is far below that used in testing but helps to minimise the chance of the sediment liquefying inside the shear box during the initial stages of the test. The sample depth within the carriage is measured with callipers and the carriage is then placed in the shear box and secured.

4.3.4.2 BPS test setup

Following the approach of Brain *et al*. (2015) The BPS is filled initially with carbon dioxide, and then with deionised and de-aired water. Displacing air with carbon dioxide helps to limit air bubbles being present during testing. Whereas air would remain in the cell and potentially unpredictably impact the testing, the carbon dioxide dissolves into the water within the cell before it reaches test pressures. The test is then initialised by raising normal stress to 15 kPa and pore pressure to 5 kPa at a rate of 2 kPa/min. At this stage the test often takes longer than 5 mins to reach the target pressures. This may be due to a number of reasons including possibly the control logic of the BPS at low pressures, but primarily it seems to occur due to unsteady compaction of the sediment under the 10 kPa normal effective stress. To ensure this has no impact on the test it is not progressed until target pressures are reached.

Once the 10 kPa differential between axial and back pressures is achieved, both are ramped up to the pressures required for the testing. This is done at 2 kPa/min to allow any consolidation of the sediment to occur steadily and finish before the shearing is commenced. Both axial and back pressure are then ramped up to the desired axial pressure whilst maintaining the 10 kPa differential. Back pressure is then ramped down again whilst axial pressure remains constant to provide the desired normal effective stress for the test.

4.3.4.3 Test conditions

Test conditions were selected to represent the subglacial environment at Skalafellsjökull. Due to the simplifications required for the testing, they can also be seen more widely as a good representation of a temperate valley glacier. For the initial monotonic testing there are two key parameters. The test involves shearing the sediment at a constant strain rate and at a constant normal effective stress (NES) whilst measuring shear strength. Therefore, the appropriate NES and strain rates must be determined.

The NES for the experiments is determined from data collected during the 2008 Glacsweb deployment of subglacial probes (see Chapter 6 for more details). The ice thickness above probes at Glacsweb site in 2008 varied between 57-73 m. Assuming an ice density of 0.917 this gives a normal stress of 480-660 kPa.

The observations of *in situ* pore pressures recorded by Glacsweb probes were highly variable. It appears that largely pressures were around 60% overburden but extensive periods in excess of 80% and very low pressures were also recorded. Therefore, NESs selected for the initial monotonic testing are 50, 100, 200, 300 and 400 kPa (see Table 4). These should encompass the range of conditions that occur in the subglacial environment at Skalafellsjökull, and in all but the fastest flowing ice streams. They also provide a suitable range of values for calculating a Mohr-Coulomb shear envelope.

When defining strain rates for testing there are two elements that must be considered; what strain rates are representative of field conditions, and whether the strain rate used in testing has any impact on the results e.g. is the sediment strain rate invariant.

For this testing an initial rate was established from field data (see Glacsweb review - 2.3.1.1) and used for the large majority of monotonic testing. Average ice surface velocities recorded by dGPS are approximately 3-5 m per annum above where the Glacsweb probes are deployed. Therefore, initial testing was carried out at a 5 m/a displacement rate, which in the shear box context is 20 mm over 2102 minutes (35 hrs). This also happens to be a similar velocity to the minima recorded at Storglaciären by Iverson *et al.* (1999), as shown in Figure 7. As with the NES selection, although values are nominally based on Skalafellsjökull, they are more broadly applicable to other similar glaciers.

The tests involve a scaling down of the deformation occurring at Skalafellsjökull and a number of assumptions have to be made. The central assumption made is that 100% of ice surface velocity is due to strain in a discrete zone similar in size to the shear box sample (~18 mm with strain focused on around 3 mm). Taking the model of Boulton *et al.* (1987) it may be more sensible to suggest that this velocity is due to deformation across an *A* horizon in the order of 0.1-0.5 m thick, although there is no evidence to suggest whether this is true over short time steps. Therefore, this can be assumed to be a scaling of the actual deformation rather than a replication. Velocity must be scaled too as there will be deformation within the ice mass and potentially sliding. There have been a number of estimates for the proportion of ice surface velocity that occurs due to subglacial deformation, and as they vary from 0-100% this remains an area of uncertainty in the experimental design.

As ice velocities encompass such a range of factors they are not an ideal manner in which to estimate appropriate strain rates. The ideal methodology would be to use strain rates recorded by the Glacsweb probes. This was not pursued due to complications with *in situ* sensing discussed in section 7.5.1.3 but would be an ideal methodology in future work. Therefore, it is possible that the value of 5 m is unrealistic.

Fortunately testing suggests that the choice of strain rate is not significant. After the initial round of test had been run at 20 mm over 2102 minutes (5 m/a) further testing was done a magnitude faster at 20 mm over 210 minutes (50 m/a). The magnitude shift in strain rate appeared to have limited impact on the results. It may also reflect actual conditions at Skalafellsjökull, as the 3-5 m/a annual average is likely to obscure higher velocities. Again, comparison to Storglaciären is merited and Figure 7 shows velocity varying from around 7-50 m/a.

This strain rate change was undertaken for two reasons. Firstly, to establish whether the till's stress response was strain rate dependant and enable comparison to other work. Secondly, it is more practical to run tests at a higher rate enabling a great number of tests to be run within the laboratory time available. Subsequent to the completion of these tests, further testing was continued at the higher rate for all PPR tests bar one (results in chapter 5).

4.4 Results

4.4.1 Grain size distribution

The grain size distribution of the till was measured after the sample ACSAM2B had been prepared from its initial state but before testing had commenced. It was then tested again after all BPS testing, including that presented in Chapter 5, had been completed.

4.4.1.1 Pre-testing results

After the bulk sample had been sieved to <2 mm, 4 pseudo-random samples were taken for particle size analysis. The average of these samples was a Coarse Sandy Very Coarse Silt that was Polymodal and Very Poorly Sorted.

4.4.1.2 Post-testing results

After all testing was concluded 17 samples were taken from a single shear box sample after testing to examine particle size variation (Figure 19). 5 samples were taken from the bottom surface (Figure 19G and Post-Test 1-5 in Figure 18), 5 from the top surface (Figure 19B and Post-Test 10-14 in Figure 18), 1 from each edge at approximately the shear plane (Figure 19C-F and Post-Test 6-9 in Figure 18) and three from the centre of the sample at approximately the shear plane (Figure 19H and Post-Test 15-17 in Figure 18).

The average of those samples was a Very Fine Sandy Medium Silt that was Trimodal and Very Poorly Sorted. Compared to pre-testing results there is a similar distribution but a slight loss of particles around 100 µm. More significantly, the post-test results have a much broader range than the pre-test results.

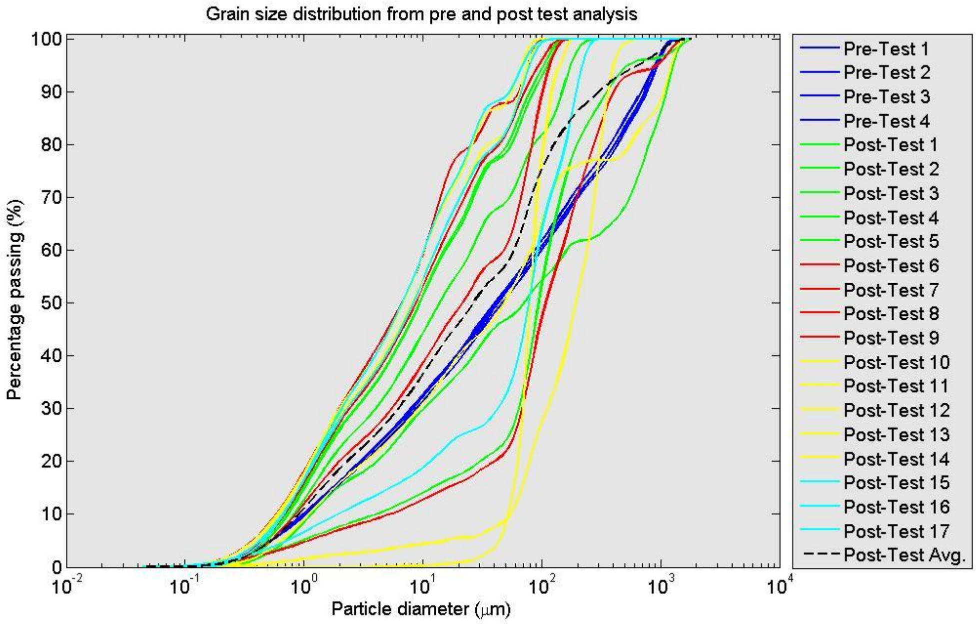


Figure 18: Particle size analysis results for all testing conducted pre and post shear box testing. 'Post-Test' samples are taken from a single sample (see Figure 19).

Figure 19: Sampling locations for post-testing particle size analysis.

4.4.2 Moistures and Loss On Ignition

Moisture contents were broadly similar with two outliers and a general trend that may reflect the time taken over sampling and relatively high hydraulic conductivity in an unconsolidated state. It appears that results may lie within error and there is no obvious systematic bias that might reflect issues with sample preparation. The average value was 21%, suggesting that there may be a general focus of moisture towards the top of the shear box as this is higher than expected based on the volume of water added to the dry sample during preparation. Loss on ignition testing shows low organic content as might be expected with a subglacial till.

Figure 20: Shear box filled in pre-test state, after samples for moisture and LOI have been removed.

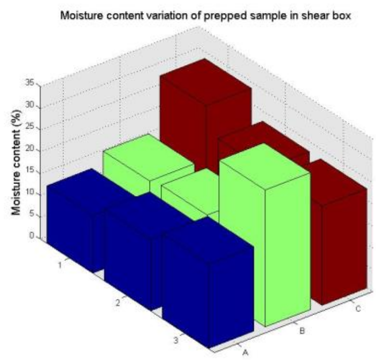


Figure 21: Bar Chart showing moisture results for pre-test shear box samples.

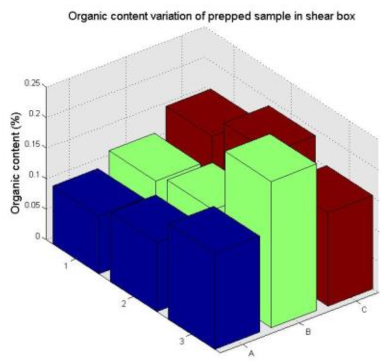


Figure 22: Loss on Ignition results for pre-test shear box sample.

4.4.3 BPS Monotonic testing

19 monotonic tests were carried out across 6 normal effective pressures (see Table 4). 11 ran successfully to full horizontal displacement, 3 ran to partial but sufficient horizontal displacements and 5 tests failed for a variety of reasons.

Table 4: Summary of the 19 monotonic tests conducted, including failed tests highlighted in darker grey.

Test Rig	Technician	Sediment Sample	Normal Effective Stress (kPa)	Full Name	Strain rate (m/a)	Successful Overall?
BPS	AIC	ACSAM2B	50	ACSAM2B-Mono-50-1	50	Yes
BPS	AIC	ACSAM2B	100	ACSAM2B-Mono-100-1	5	No
BPS	AIC	ACSAM2B	100	ACSAM2B-Mono-100-2	5	No
BPS	AIC	ACSAM2B	100	ACSAM2B-Mono-100-3	5	No
BPS	AIC	ACSAM2B	100	ACSAM2B-Mono-100-4	50	Yes
BPS	AIC	ACSAM2B	100	ACSAM2B-Mono-100-5	50	Yes
BPS	AIC	ACSAM2B	100	ACSAM2B-Mono-100-6	50	Yes
BPS	AIC	ACSAM2B	100	ACSAM2B-Mono-100-7	50	Yes
BPS	AIC	ACSAM2B	200	ACSAM2B-Mono-200-1	5	Yes
BPS	AIC	ACSAM2B	200	ACSAM2B-Mono-200-2	50	Yes
BPS	AIC	ACSAM2B	200	ACSAM2B-Mono-200-3	50	No
BPS	AIC	ACSAM2B	200	ACSAM2B-Mono-200-4	5	Partial, 15 mm displacement
BPS	AIC	ACSAM2B	200	ACSAM2B-Mono-200-5	5	Partial, 15 mm displacement
BPS	AIC	ACSAM2B	300	ACSAM2B-Mono-300-1	5	No
BPS	AIC	ACSAM2B	300	ACSAM2B-Mono-300-2	5	Yes
BPS	AIC	ACSAM2B	300	ACSAM2B-Mono-300-3	5	No
BPS	AIC	ACSAM2B	300	ACSAM2B-Mono-300-4	5	Yes
BPS	AIC	ACSAM2B	400	ACSAM2B-Mono-400-1	5	Yes
BPS	AIC	ACSAM2B	500	ACSAM2B-Mono-500-1	5	No

Before testing began, all tests were consolidated to the NES required. After initial fluctuations, all tests settle onto a log-linear response (Figure 23). This indicates consolidation at a normal effective stress higher than the sediment has experienced before (Craig, 2004). Consistency in the slope of this line indicates consistency in the sediment characteristics. The exact offset changes between tests as part of the initial set-up requires manual control of the axial ram leading to small but unmeasured consolidation. In some tests axial displacement appears to have not kept pace with increasing normal effective stress. As a result, axial displacement continues to occur after the desired normal effective stress has been reached, until it reaches equilibrium.

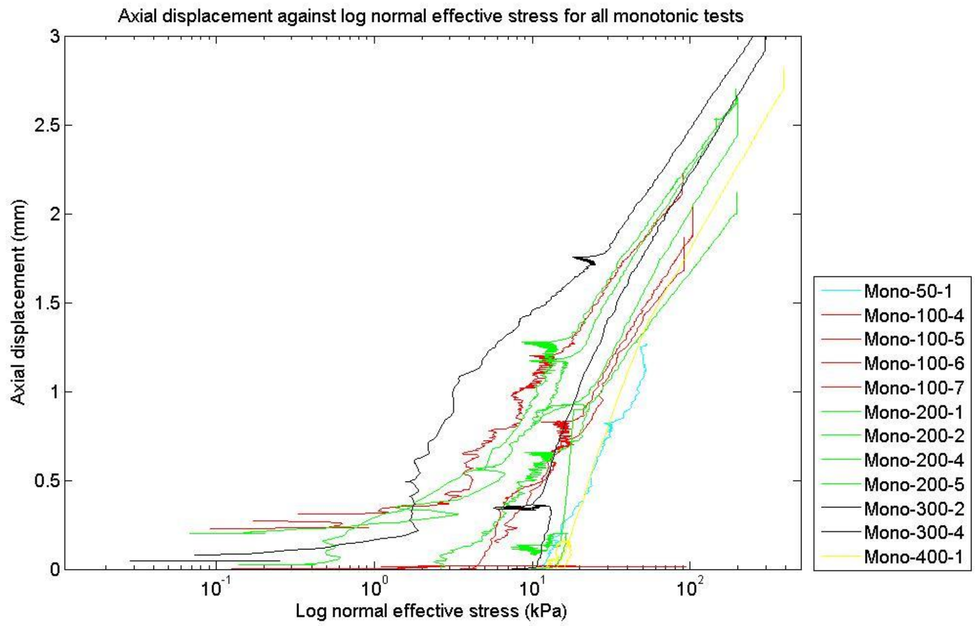


Figure 23: Axial deformation against the log of normal effective stress for all initial stages of all monotonic tests before shearing begins.

Monotonic shear testing was conducted at five NESs (

Figure 24). Tests cluster closely around each NES. There is a general increase in the strain at which peak stress is achieved as the test NES increases and an increasingly large difference between peak and residual stresses.

Figure 24 includes some 200 kPa normal effective stress tests where the test failed to reach full displacement (20 mm). These have been included as, despite not running to 20% strain, they still reached peak stresses. It is also noteworthy that some other tests appear to reach peak strain in the late stages of the test. These values have been disregarded, as the later stages of tests are unreliable due to the increasingly sizeable interface between the sediment and the steel of the BPS.

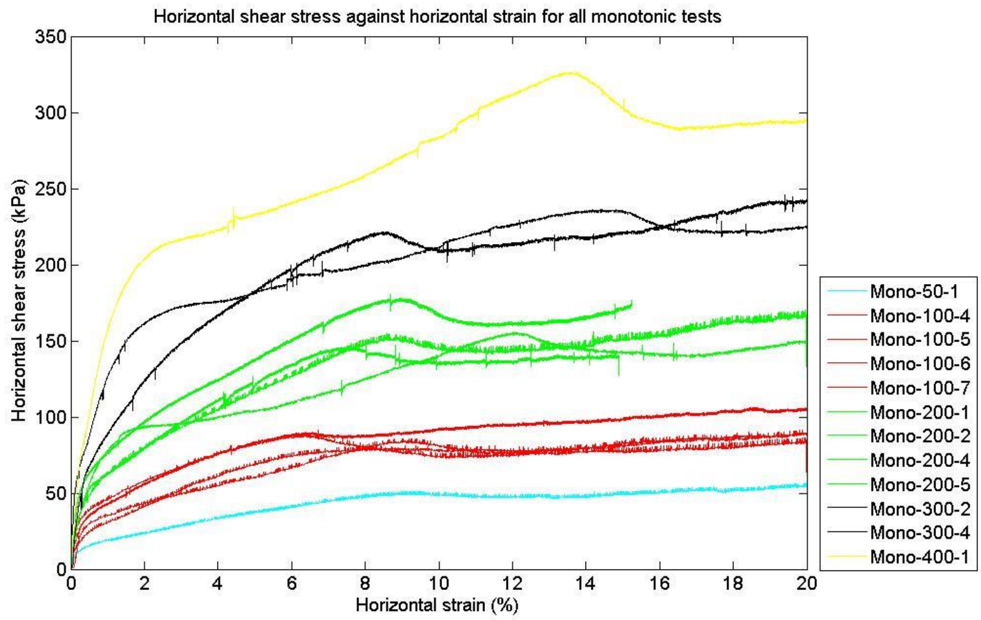


Figure 24: Stress-strain relationship for all successful shear tests across 5 different normal effective stresses.

The angle of friction has been calculated from peak stress for all tests (

Figure 25). A linear line of best fit is shown for each strain rate and for the entire data set. There is a slight different between the angle of friction for different strain rate tests. Angles of friction and cohesion are 39° (5 m/a), 35.2° (50 m/a) and 37.6° with cohesion 6.6 kPa (all tests). The NES used to calculate each angle of friction is not consistent and this will impact the results in addition to the strain rate variation.

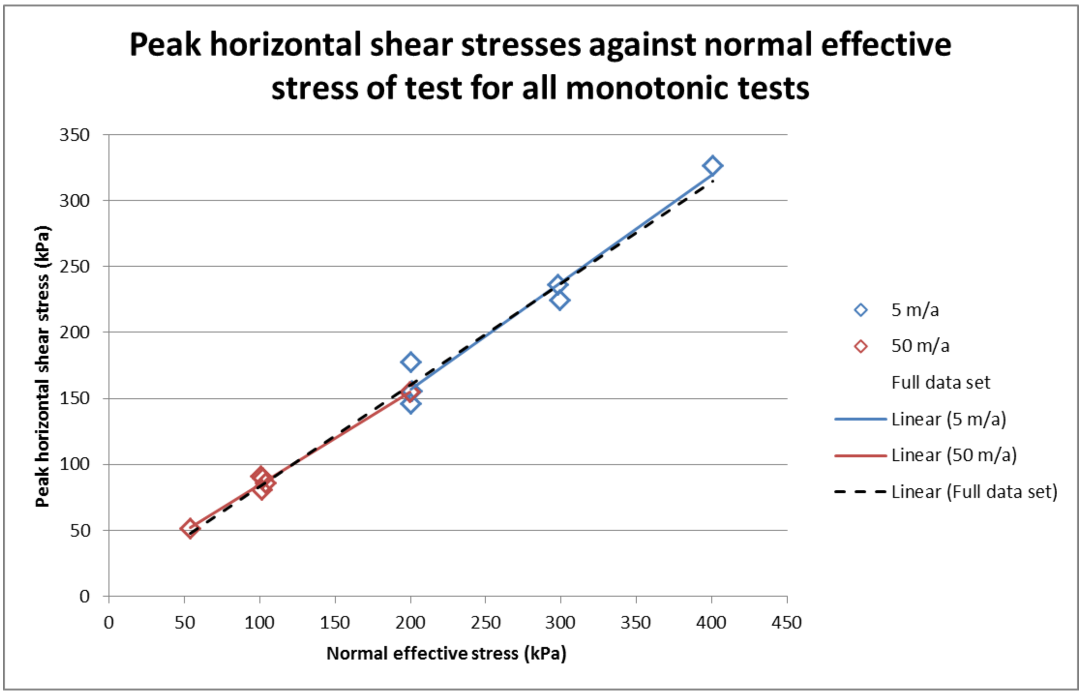


Figure 25: Peak shear stresses recorded across all monotonic testing against the normal effective stress of the test. Data has been differentiated by strain rate, either 5 m/a or 50 m/a. R^2 for all the full data set is 0.9866 and cohesion is 6.6.

Plotting shear stress normalised by NES against strain is a standard check on the consistency of results of testing conducted at a variety of NESs. Each curve should plot similarly due to the underlying sediment properties remaining the same throughout testing. Doing so here produces stress strain curves with broad, if imperfect, similarity in peak and residual stresses (

Figure 26). This is reassuring considering the time period over which testing was conducted and the alongside the particle size data suggests there is not a systematic error due to using the same sediment.

The data in

Figure 26 has been smoothed with the MATLAB ‘rlowess’ function. This is a robust smoothing algorithm that uses local regression using weighted linear least squares and a 1st degree polynomial model. The ‘r’ version assigns zero weight to data outside of six mean absolute deviations. This was required due to numerous normal stress outliers from readings spanning just a few seconds that appear to have negligible impact on testing and may be data artefacts.

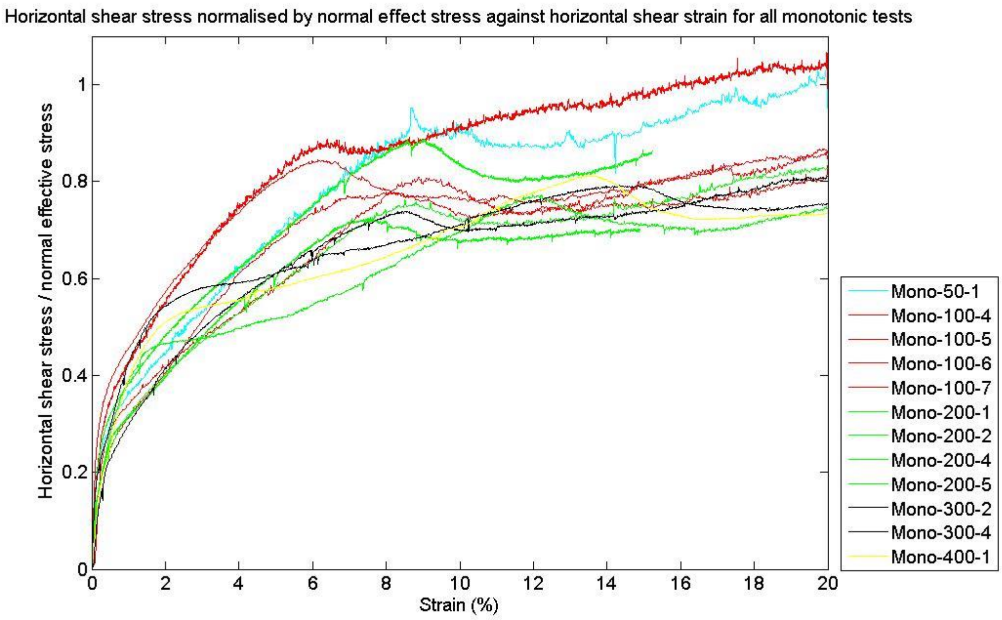


Figure 26: Stress-strain relationships where horizontal shear stress has been normalised by normal effective stress.

All tests demonstrate initial axial (vertical) contraction followed by dilation (

Figure 27). The dilation often coincides with the drop from peak stress towards residual stress. Note, axial displacement for test Mono-100-6 is recorded as 0 throughout due to axial transducer issues, but this did not appear impact the rest of the test as test was controlled by axial stress rather than displacement.

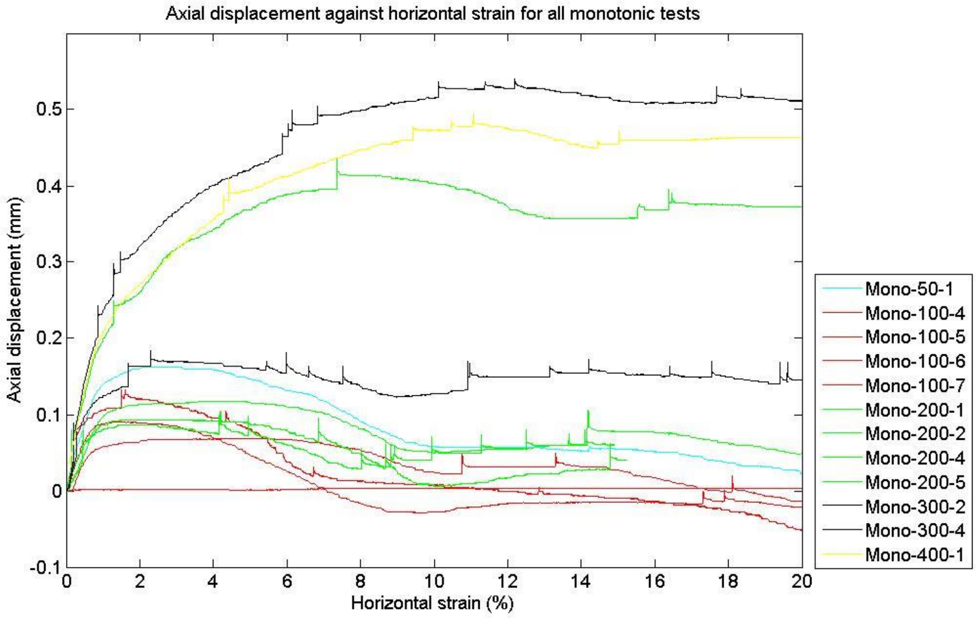


Figure 27: Axial deformation against horizontal strain. Increased axial displacement means increased contraction.

4.5 Discussion

4.5.1 Grain size distribution

Particle size analysis pre and post-testing shows a slight change in the coarser range of the sediment (Figure 18). In the post-testing results there are fewer larger grains than in pre-testing results. The fraction classed as fine sand or larger (>125 µm) fell from 37.5% of the sample to 18.3% of the sample, with the largest drop occurring in coarse sand which fell from 12.8% to 1.9%.

The variability in the post-test results is much larger than the pre-test results. This suggests that the testing methodology may be responsible for the difference in the average grain size distribution. Even within similar samples, i.e. those taken from the shear surface, there is a lot of variability. Pre-testing samples were taken from dry sediment that had just been sieved to <2 mm and remixed thoroughly. Post-testing samples were from the last BPS test and taken from the till tested after testing had been completed. Therefore, it is a reasonable assumption that this is more revealing of test sample heterogeneity than a change in the batch of sediment used for the tests.

There is no suggestion from the monotonic testing results that there has been a progressive impact on them due to a sample alteration so the difference between pre-test and post-test grain size distributions is not adjudged to be significant. However, the variation within the sample is interesting and feasibly that level of heterogeneity could be responsible for some of the test to test variability. In future testing it would be sensible to undertake regular particle size analysis on post-test samples to track the variability of samples and any development in the batch of sediment used for testing.

4.5.2 Moisture and organic content (Loss On Ignition)

Moisture content testing shows relatively low variability across the shear box sample. After being loaded into the box the sample subsequently during preparation has de-aired and de-ionised water dripped through it. The amount of water dripped through varied as saturation was the aim and the flow was stopped as soon as it was evident that this had been achieved. Usually this meant around 100 mm of water was dripped through. Therefore, it seems unlikely that variability on this scale is a significant issue in testing.

Loss on ignition testing demonstrates that the till has a low organic content. Unfortunately, this was not also performed at the start of testing but it matches expectations of a subglacial till.

4.5.3 BPS Testing

The testing in the BPS has produced a large number of metrics. Firstly, some attempt is made to discuss these individually in the perspective of wider geotechnical literature. Then the results are compared to those obtained across glacial literature.

4.5.3.1 Consolidation results

During test set up initially back pressure and normal stress were increased incrementally with the back pressure slightly below (10 kPa) normal stress. Once the normal stress required for the test has been reached, back pressure is gradually reduced at a rate of 2 kPa/min. During this stage, normal effective stress gradually increases. The 2 kPa/min was used as it is the laboratory standard.

The expectation was that 2 kPa/min is a slow enough rate that pore pressure should fall broadly in line with back pressure e.g. the sample should remain in a drained state throughout consolidation. If it is too fast and induces an undrained state then this may impact the shear phase of the experiment. Usually there was a gap between consolidation finishing and shear starting as some mechanical adjustment of the shear box is required before shearing can commence. It is feasible that this gap is long enough to allow consolidation to finish and the sample reach a drained state again, but clearly worth assessing due to the impact of undrained shear on the results.

Figure 23 demonstrates that most tests adhere to similar gradients of consolidation towards the end of the stage. The more erratic behaviour initially can be assigned to machine control issues exaggerated by the log scaling. The similarity in gradient is tempting to label as a virgin compression line (VCL). However, this is unlikely to be the case as in all tests consolidation continues after back pressure reduction stops, so the consistency in the line just signifies consistency in the test procedure. In future experimentation it may be worth reducing the consolidation rate during test set up such that the VCL can be obtained.

If testing was commenced immediately after back pressure reduction stopped, tests would have been run before the sample had finished consolidating. Due to practicalities of the testing this did not occur and at least 1 hour would elapse between the stages, often more. The lack of anomalous outliers in peak stress values (Figure 25) provides additional confidence that this has not been an issue. Furthermore, this issue would have a larger impact at higher NES testing, and as the testing in the following chapter is focused on lower NES values (50, 100, 200 kPa) the significance of the problem is further diminished.

4.5.3.2 Stress-strain results

The monotonic testing has produced results that demonstrate some variation in terms of the manner of how and when peak stresses are reached, but some consistency is present. Peak stresses demonstrate the till adheres well to the Mohr-Coulomb model and there is a strong linear relationship between them.

There is some evidence to suggest that despite this there is a degree of strain rate variability. Testing was carried out at two different strain rates, 5 m/a and 50 m/a, and there is some difference in the angle of friction calculated with each suite of tests. The angles are 39° (5 m/a), 35.2° (50 m/a) and 37.6° for the full data set. However, some caution should be taken in interpreting them as the shear envelopes were calculated for different NES, 200-400 kPa for 5 m/a and 50-200 kPa for 50 m/a. This may have impacted the results. It is also not of much significance when comparing to the literature. Either value, or the average, is helpful positioning the result amongst previous work where the range of angles spans 20-49°.

Whilst peak stresses at similar normal effective stresses remain consistent across all tests (R^2 = 0.9866) there is some variation in the manner in which peak stress is achieved. There is variation in the nature of the curve, e.g. concave or convex, and the strain at which peak stress occurs. This may be a product of the grain size heterogeneity within samples, as noted above.

4.5.3.3 Axial displacement results

Most tests display behaviour coherent with being a loose sand and contract during shear (Figure 27). There is some variation with test NES. Lower NES tests tend to demonstrate contraction with horizontal shear and higher NES tests tend to demonstrate dilation with horizontal shear, but this is not perfectly reflected in the results.

4.5.3.4 Comparison of BPS monotonic results to literature

A range of geotechnical work has been carried out by a number of different authors, as summarised earlier in Table 5. However, not all of this work is particularly comparable. The simplest summary statistic is perhaps the angle of friction (ϕ). This, fortunately, has been measured for quite a number of different tills as shown in Table 5. This gives a useful, albeit superficial, comparison and shows the till tested here is in the upper range of values from the literature, as expected from a sandy till.

As with most metrics, angle of friction is subject to testing procedure. A number of factors will impact the value including whether the sediment is remoulded or not, what apparatus is used, the strain rate testing is conducted at and whether it is calculated from peak or residual stresses. All of the above will be influenced by the type of till being tested, although neither cohesion or angle of friction are unique material properties (Selby, 1993). The differences between using residual and peak stresses are illuminated by Sladen and Wrigley's (1983) study where helpfully they reported angles of friction derived from both values.

The most relevant comparison is to work done by Altuhafi during her PhD (Altuhafi, 2007) as it was also carried out on basaltic Icelandic till. Altuhafi *et al.* (2009) demonstrated that for her sample from Langjökull the failure points lie on a unique line despite variations in strain and whether a ring shear or triaxial rig was used for testing. This coherence to the Mohr-Coulomb failure model is mirrored in the till tested in the ACSAM2B sample tested here. Altuhafi's work and this study have also produced a similar angle of friction, 36° and 37.6° respectively, which is the most similar result of all other tills tested. Considering the variance in this value in Figure 25 this is a remarkable level of consistency.

Table 5: Table of measured angles of friction for a wide variety of tills – updated and amended from Cuffey & Patterson (2010). Peak (p) and residual (r) nature of the angle of friction value calculation indicated where known.

Glacier or till	ϕ (reported to accuracy in literature)	Apparatus	Study
Langjökull	36°	Triaxial, Ring Shear	Altuhafi et al., 2009
Caesar till	31.4°	Double direct shear	Rathbun et al., 2008
Matanuska till	29.4°, 28°	Double direct shear	Rathbun et al., 2008
Whillans Ice Stream	23.9°	Triaxial, Ring Shear, Shear Box	Kamb, 2001
Traeth y Mwnt, Wales	24°	Triaxial, particle size	Hubbard & Maltman, 2000
Haut Glacier d'Arolla	49°	Triaxial, particle size	Hubbard & Maltman, 2000
Black Rapids	40°, 45°	Triaxial, Ring Shear	Truffer et al., 2000
Whillans Ice Stream	24°	Triaxial, Ring Shear	Tulaczyk et al., 2000
Storglaciären	26.3°, 18.6°	Ring shear	Iverson et al., 1998
Lake Michigan	21.8°, 24.1°	Shear Box	Ho et al., 1996
Hessle	24° (p), 20° (r)	Shear Box	Sladen & Wrigley, 1983
Withernsea	24° (p), 21° (r)	Shear Box	Sladen & Wrigley, 1983
Skipsea	26° (p), 25° (r)	Shear Box	Sladen & Wrigley, 1983
Basement	24° (p), 23° (r)	Shear Box	Sladen & Wrigley, 1983
Manicouagan River	30-35°	Triaxial	Loiselle & Hurtubise, 1976
Breiðamerkurjökull	27.06° (top 50 cm), 28.16° (bottom 50 cm)	Shear Box	Boulton et al., 1974
Manicouagan-Riviere	40-45°	Shear Box	Kazi & Knill, 1969
Little Long Rapids	31-37°	Triaxial, Shear Box	Bazett and Bell, 1963
Otter Brook	31-33°	Shear Box	Linell & Shea, 1960
Hopkinton	32-39°	Shear Box	Linell & Shea, 1960
Thomaston Dam	33-35°	Shear Box	Linell & Shea, 1960
New England	31-39°	Shear Box	Linell & Shea, 1960

4.6 Conclusions

In conclusion, the work presented in this chapter has provided an understanding of the basic characteristics of the till tested in this study. It has also provided an understanding of the suitability of the methodology employed.

The till's behaviour conforms to the Mohr-Coulomb model with peak shear stresses plotting approximately linearly with NES. The angle of friction (37.6°) derived from this relationship shows that the till is similar to that tested by Altuhafi *et al*., (2009; 2010; 2011a; 2011b) (36°). This is relatively large for a glacial till and amongst the top 1/3rd of values reported (see Table 5). It is similar to a number of other mountain tills but larger than clay based tills such as the Whillans Ice Stream (Kamb, 2001). The data suggests a slight rate weakening with the angle of friction falling by 3.8° between testing run at 5 m/a and 50 m/a. This is possibly similar to findings by Iverson *et al*. (1998) but as the peak stress data for 5 m/a and 50 m/a was obtained at different NESs, the difference may be within the experimental error of this study.

The particle size of the till sample changed through the testing with a slight reduction in the coarser fraction and minimal change in the finer fraction. Monotonic results appear to be consistent despite this suggesting it is insignificant, but heterogeneity within samples may have contributed to test variability. In future, it would be prudent to conduct regular particle size analysis after testing to ascertain how much variability is present and if it has any correlation with test variability.

The sample was shown to have a negligible organic content and minimal variation in moisture content after sample preparation suggesting a low dependence on those factors within the results. Sample set up was also examined to determine if the rate of consolidation was suitable. There was limited evidence to suggest that consolidation was not quite complete at the end of the consolidation stage. However, this is unlikely to have impacted testing due to the time elapsed before the shearing stage was initiated, and will have even less relevance for the PPR testing presented below that focuses on NESs at or below 200 kPa. In future, a lower rate of consolidation, 1.5 kPa/min or slower, would still be advisable.

4.6.1 Considerations for further work

Repeats of this work should consider three changes, two pertinent to experimental quality and one significant logistically.

Tests here were undertaken at two different strain rates, 5 and 50 m/a. A substantial number of 5 m/a tests were undertaken before the higher strain rate was tested. In future testing the strain rate dependency should be established as a priority. There is some variability in the results and so multiple repeats are required. Testing at a higher strain rate enables this and so establishing this as a possibility early on would improve the quality of the data set.

The variability within the results should be tackled in two further ways. The consolidation procedure here does not appear to be optimal. Whilst it has not been a significant issue, a slower consolidation rate would be advisable. 1.5 kPa/min and 1 kPa/min would both be worth testing. Again, as above, it would be prudent to find the fastest possible rate in order to maximise the number of tests that can be conducted.

Finally, the variability within the grain size data is intriguing, but without comparable sampling procedures before and after testing it is difficult to draw any conclusions.Sampling throughout testing would be advisable so that trends can be established and BPS behaviour can be compared to the sample's grain size results. Taking 5 samples for PSA from the shear surface of the sample and then 3 samples for PSA once the shear box sample has been disaggregated may capture any trends. This sampling methodology should also be able to track changes in the bulk sample and also changes in sample heterogeneity and any pre-test mixing issues.

Chapter 5: Geotechnical PPR experimentation

5.1 Introduction

Having established the main geotechnical characteristics of the till sampled at Skalafellsjökull this Chapter details experimentation designed to replicate conditions experienced in the deforming bed. Principally the series of tests documented here make use of the novel use of a BPS by replicating increases in pore pressure. Pore pressure increases are significant in within the subglacial deformation during drainage system alteration due to seasonal change (Rose *et al.*, 2009), short term movements and consequential stick slip motion, and quasi-stable shear where pore pressure increases are balanced by dilatancy (Moore & Iverson, 2002).

Despite their clear significance within subglacial bed deformation, no previous geotechnical experimentation has replicated pore pressure increases. The use of a Back Pressure Shear Box (BPS) enables tests to be conducted that involve a gradual decrease in Normal Effective Stress (NES) via an increase in back and pore pressures. This means the conditions experienced subglacially can be replicated relatively well in the laboratory environment. The closest comparable replication is that of Moore & Iverson (2002) but there reductions in NES are achieved via reductions in normal stress (further discussed in 8.3.3.1).

Before continuing to the detail of this chapter, it is worth considering how pore pressure sits within a theoretical perspective of the drivers of subglacial deformation. This allows for a more circumspect analysis of the results presented. At its simplest level, deformation can be considered to be controlled by three factors: driving stress, total normal stress and subglacial pore pressures. In this chapter I consider the particular dynamic situation involving variable subglacial pressures based on field observations whilst controlling the other two variables.

As stated above, there are three situations where pore pressure increases are thought to be significant. In all situations, geotechnical experimentation without back pressure control fundamentally does not replicate the subglacial environment, as pore pressure forced dilation is not present and dilation is solely a response to strain. To what extent this is significant in the glacial context is unknown.

This experimentation focuses on the last two situations. Stick-slip movement, or diurnal or sub-diurnal fluctuations in velocity, is fundamentally interesting as it is characteristic of glacial movement (see section 2.2.3.2). Pore pressure fluctuations are seen subglacially but have not been replicated in geotechnical laboratory testing. If pore pressure variations are not a control then, as normal stress is not variable on that time scale, the obvious candidate is the driving stress. Propagation of elastic stress down glacier may result in dynamism in surface velocity on the time scales observed (Bahr & Rundle, 1996).

Pseudo-stable shear moderated by till dilatancy is significant as it is an alternative outcome from pore pressure increases to stick-slip motion. It is also of interest as it has been suggested that the occurrence of dilatancy moderated deformation might account for a transition between small scale plastic and large scale viscous behaviour.

Both of these situations occur on approximately diurnal time scales. Here we replicate gradual increases in pore pressure reflective of a progressive surface input into the glacial system and consider the consequential increases in strain rate and role of dilatancy in controlling them.

5.2 Aims and objectives

As outlined in Chapter 4 this Chapter tackles the following question:

2. What is the effect of pore pressure-driven variations in normal effective stress on till deformation, manifest as shear displacement in the BPS?

On the basis of the work presented in Chapter 4, the aim is addressed by undertaking standard Pore Pressure Reinflation (PPR) experiments. For these tests an assumption is made that total normal stress and driving shear stress are effectively constant in field situations over the timeframe of interest (approximately diurnal). Effective stress is controlled by increasing pore water pressure. PPR tests will be conducted normal stresses tested in the monotonic shear tests.

5.3 Methodology

The sample (ACSAM2B) and BPS used for the tests presented in Chapter 4 is used throughout testing so sampling and core methodology is not repeated here. For one test, a different BPS is used (referred to as DynBPS throughout). This is a newer version that is capable of producing dynamic inputs, but otherwise unchanged from the model described in the previous chapter (see Brain *et al.* 2015 for more details).

5.3.1 PPR Testing

The PPR testing was based on the laboratory standard methodology and uses results from the monotonic testing and a range of NESs derived from field observations. The laboratory standard method involves four stages:

1. Test initialisation: as detailed already in section 4.3.4.
2. Consolidation: Each remoulded sample is consolidated to a normal effective stress level investigated in the monotonic shear experiments. The required NES is reached by raising back pressures and normal stress together and then reducing back pressure until the desired NES is achieved. This is carried out at a 2 kPa/min rate.
3. Shear initialisation: Monotonic shear is carried out at the strain rate used in the monotonic tests until shear stress reaches 80% of the peak value derived during monotonic testing.
4. PPR: Shear stress is held constant and back pressure is increased (decreasing normal effective stress) at a constant rate until 20% strain achieved.

Initial testing was carried out as above, with a strain rate of 5 m/a in stage 3 and a PPR rate of 2 kPa/hr. After the initial 4 tests, the methodology was changed slightly. Shear was initiated at a higher rate of 50 m/a and PPR initiated when 80% of peak stress was achieved. NESs selected for testing were 50, 100, 200 and 300 kPa. The field observations of pore pressure (Hart *et al.*, 2011) suggest that the subglacial zone experiences pore pressures usually in the range of 70-90% of overburden (normal) stress. Therefore, a range of 50-300 kPa for NES covers all likely conditions, and makes comparison to other glacial contexts more feasible.

5.4 Results

Presentation of results is complicated due to the testing producing a large number of results (see Table 6) which are non-standard and occasionally difficult to interpret. To add clarity this section focuses on the series 200 kPa NES tests, with other testing presented via summary tables and figures highlighting key similarities and differences. To help the reader understand these figures a series of simplified figures are presented before the actual test data.

5.4.1 BPS PPR Results

20 PPR tests have been conducted across four different NES of 50, 100, 200, 300 kPa. During the monotonic initiation of tests, strain rates of 5 m/a and 50 m/a were used. During the PPR stage of tests (where strain rate was uncontrolled), back pressure was raised at rates of 2 kPa/hr or 0.25

kPa/hr. Three of the early tests failed due to test set up issues resulting in a failure to initiate the PPR stage of the test.

Table 6 includes all the tests and their main parameters. The majority of tests run displayed episodic increases in horizontal strain rate with runaway failure only occurring in three tests (see Table 6 and Figure 28). The angle of friction remained similar throughout testing with the end of most tests falling on the established (see Chapter 4) envelope (Figure 29). PPR-300-1 was a clear outlier to that trend.

Table 6: Summary table of PPR testing conducted.

Test Rig	Technician	Sediment Sample	Normal Effective Stress (kPa)	Full Name	Initial Strain rate (m/a)	PPR rate (kPa/hr)	Successful?
BPS	AIC	ACSAM2B	50	ACSAM2B-PPR-50-1	50	2	Yes
BPS	AIC	ACSAM2B	50	ACSAM2B-PPR-50-2	50	2	Yes
BPS	AIC	ACSAM2B	50	ACSAM2B-PPR-50-3	50	2	Yes
BPS	AIC	ACSAM2B	50	ACSAM2B-PPR-50-4	50	2	Yes
BPS	AIC	ACSAM2B	50	ACSAM2B-PPR-50-5	50	0.25	Yes
BPS	AIC	ACSAM2B	100	ACSAM2B-PPR-100-1	50	2	Yes
BPS	AIC	ACSAM2B	100	ACSAM2B-PPR-100-2	50	2	Yes
BPS	AIC	ACSAM2B	100	ACSAM2B-PPR-100-3	50	2	Yes
BPS	NT	ACSAM2B	100	ACSAM2B-PPR-100-4	50	2	Yes
Dyn BPS	NT	ACSAM2B	100	ACSAM2B-PPR-100-DynBPS	50	2	Yes
BPS	AIC	ACSAM2B	200	ACSAM2B-PPR-200-1	5	2	No
BPS	AIC	ACSAM2B	200	ACSAM2B-PPR-200-2	5	2	Yes
BPS	AIC	ACSAM2B	200	ACSAM2B-PPR-200-3	5	2	No
BPS	AIC	ACSAM2B	200	ACSAM2B-PPR-200-4	5	2	No
BPS	AIC	ACSAM2B	200	ACSAM2B-PPR-200-5	50	2	Yes
BPS	AIC	ACSAM2B	200	ACSAM2B-PPR-200-6	50	2	Yes
BPS	AIC	ACSAM2B	200	ACSAM2B-PPR-200-7	50	2	Yes
BPS	AIC	ACSAM2B	200	ACSAM2B-PPR-200-8	50	2	Yes
BPS	AIC	ACSAM2B 10 % sand	200	ACSAM2B-PPR-200-9	50	2	Yes
BPS	AIC	ACSAM2B	300	ACSAM2B-Mono-300-1	5	2	Yes

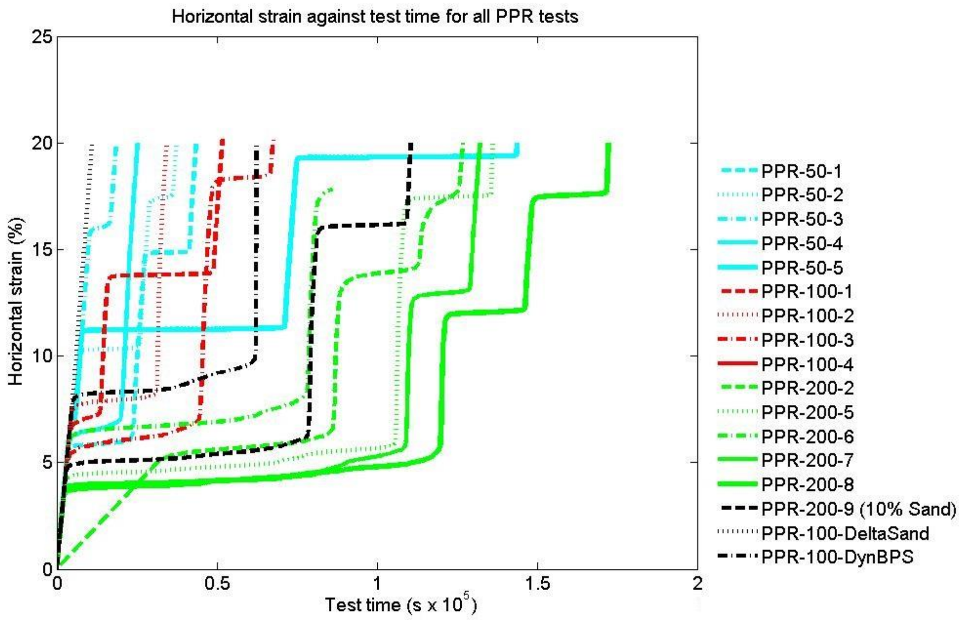


Figure 28: Summary figure of horizontal strain against test time for all PPR tests conducted.

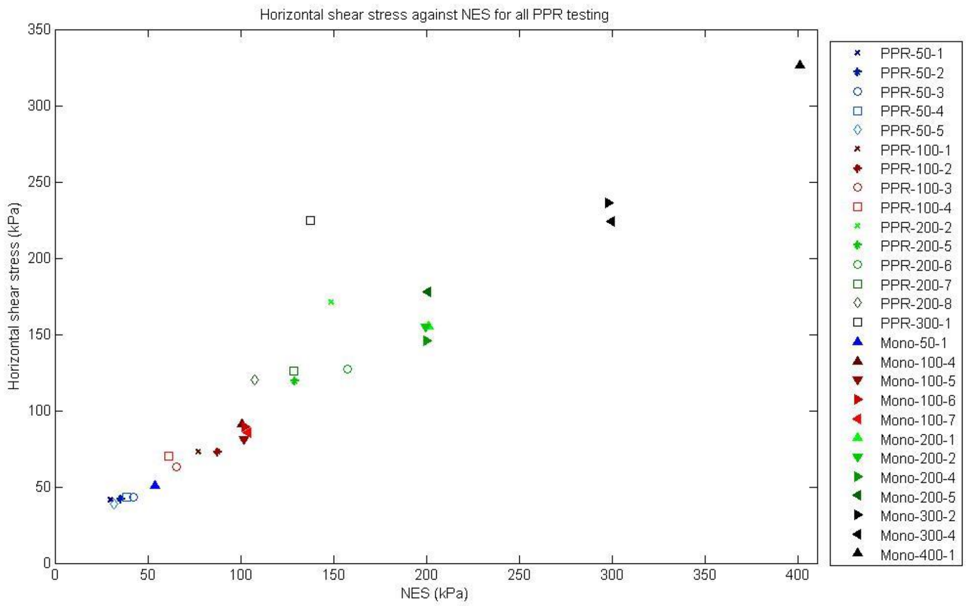


Figure 29: Normal effective stress against horizontal shear stress at the end of the test (20% strain) for all PPR testing and monotonic testing.

5.4.1.1 Simplified results

The graphical representation of the PPR results can initially be confusing. The confusion usually arises from the use of different x-axis, a requirement for exploring the data. Starting initially with showing simply strain against time, the series of simplified plots progresses through the various axes used most commonly in figures throughout the rest of the chapter.

Figure 30 is the basic plot of strain *vs.* time that is used frequently to illustrate the episodic nature of the tests. The test varies between periods of negligible strain rate (low angle lines) and periods of high strain rate (high angle lines). These have been annotated on the figure to add clarity. In overview plots several datasets may be plotted at once for comparison. The key aspect to consider is usually the number of high strain rate episodes required before 20% strain is achieved. Frequently test data will be plotted from 0% strain rather than just the PPR phase of the test. As a result, the first part of the plot is linear. This period of the test has been demarcated on the plot with a dashed black line. The gradient of this line varies between two values as two monotonic strain rates were used in the experimentation.

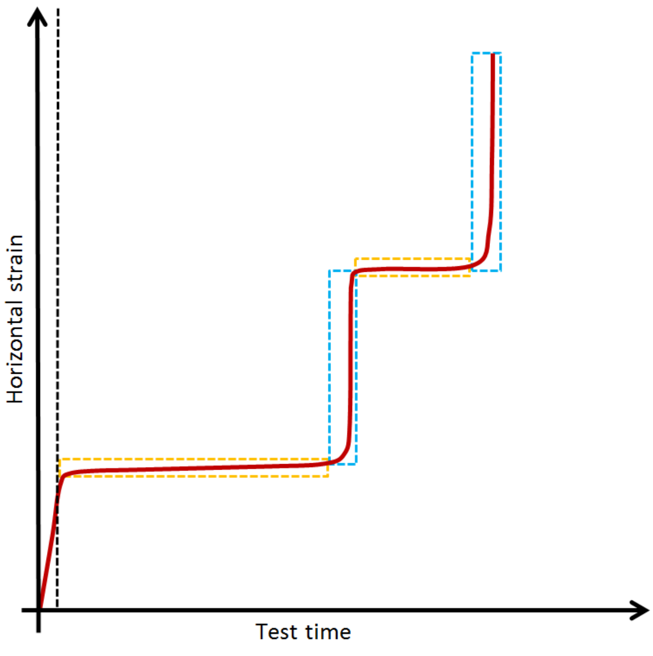


Figure 30: Horizontal strain against test time. Black dashed line indicates the transition from monotonic stage initialisation to the PPR stage. Orange dashed lines outline areas of low strain rate. Light blue areas outline areas of high strain rate commonly referred to as episodic increases in strain rate.

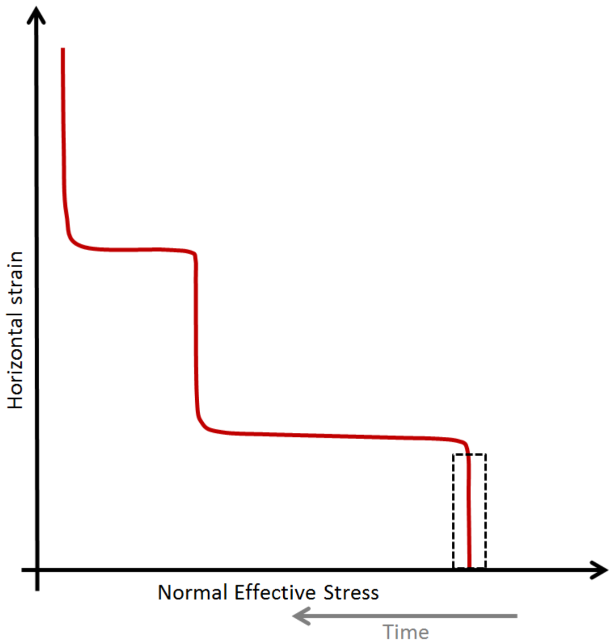


Figure 31: Horizontal strain against NES. Black dashed line outlines the monotonic initialisation of the test. Strain rates not outlined.

Sometimes instead of plotting data against time, it is plotted against NES. During the PPR phase of testing NES decreases linearly from the starting value. As a result, if we plot strain against NES (Figure 31) the graph is the mirror image of strain against time. Whilst NES is supposedly decreasing linearly, the BPS cannot always control this perfectly when the sediment is rapidly dilating or contracting. As a result the plot may look a little noisier (see Figure 35) than when data is plotted against time (note, this noise is not included in Figure 31).

Often it is useful to examine the role of axial displacement during the experiment. Positive axial displacement represents the sample contracting whereas negative axial displacement represents dilation. Axial displacement varies with NES changes and strain. Therefore, to best interpret why changes are occurring axial displacement is plotted against both of these variable. When plotted against NES it provides a good overview of the test (Figure 32), but because most of the strain in the experiment occurs during the rapid increases in strain rate, these plots do not provide much insight into these periods. By plotting axial displacement against strain (Figure 33), this issue is overcome. As the strain is taken up mostly during the increases in strain rate, the plot provides a very good insight into these periods.

The majority of plots use either time, NES or strain on the x-axis so by understanding how the data appears when plotted against each of these variables the data presented throughout the chapter will be relatively simple to interpret.

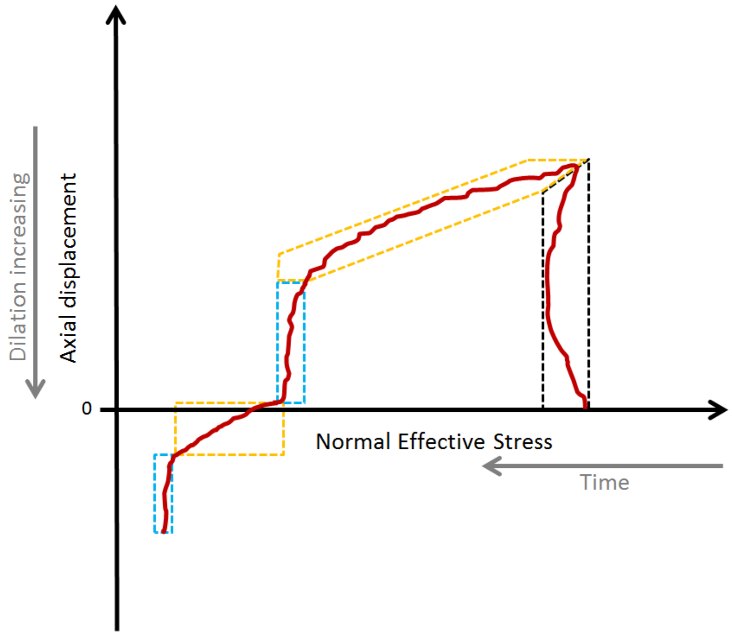


Figure 32: Axial displacement against NES. Black dashed line outlines the monotonic initialisation of the test. Orange dashed lines outline areas of low strain rate. Light blue areas outline areas of high strain rate commonly referred to as episodic increases in strain rate.

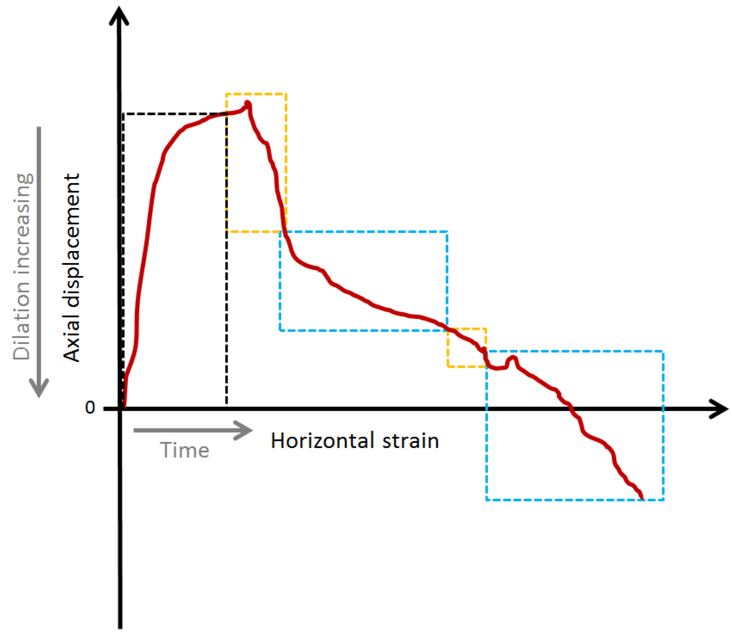


Figure 33: Axial displacement against horizontal strain. Black dashed line outlines the monotonic initialisation of the test. Orange dashed lines outline areas of low strain rate. Light blue areas outline areas of high strain rate commonly referred to as episodic increases in strain rate.

5.4.1.2 200 kPa Normal Effective Stress PPR testing

5 tests were conducted at 200 kPa with ACSAM2B (see Table 6). Four of the tests were conducted using the standard protocol, e.g. test initialisation at 50 m/a strain rate, PPR initialisation at 80% peak shear strength and PPR rate of 2 kPa/hr. The first test was run under a slightly different protocol with a slower strain rate during initialisation (5 m/a), hence the lower gradient initially in Figure 34, and PPR initialisation at a higher proportion of shear strength (90%).

As can be seen clearly in Figure 34 all testing displayed episodic increases in strain rates. Whilst there is some variation in the timing and number of strain rate increases before failure, no tests experience a simple runaway increase in strain rate despite the progressively decreasing NES due to the PPR.

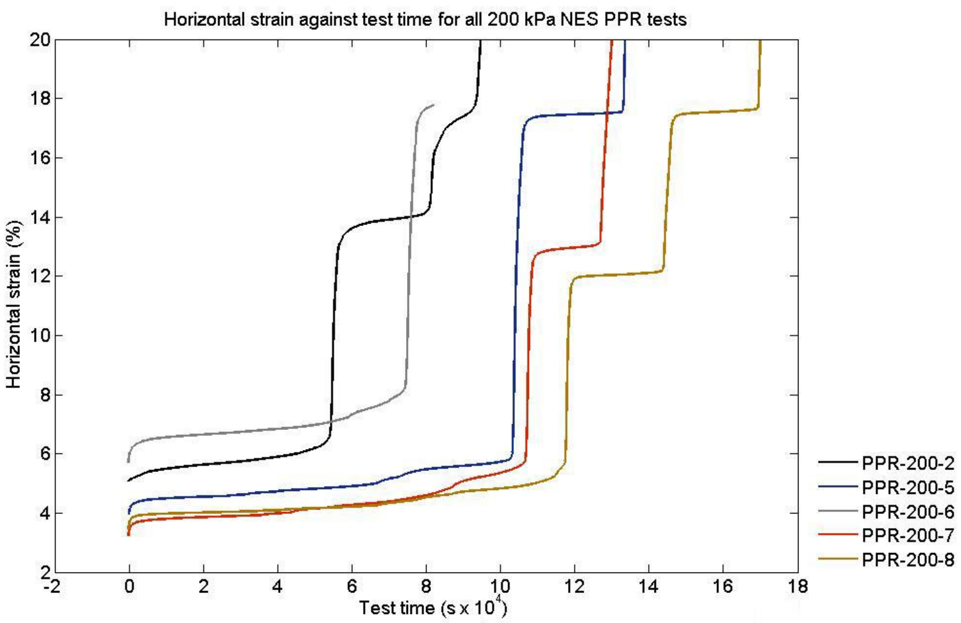


Figure 34: Horizontal strain against test time for all 200 kPa NES testing on ACSAM2B.

Plotting strain against NES (Figure 35) provides a better comparison of when failure occurs and clearly demonstrates variability in the manner in which tests proceed to 20% strain. This plot also illustrates an aspect of the test, as the data is notably noisier than when strain is plotted against time. This is because it includes a number of NES data points that are possibly outliers and on occasion NES varies rapidly. These data points appear to be real data and seem to be caused by grain re-arrangement occurring more quickly than the axial ram can respond to, resulting in brief fluctuations in NES.

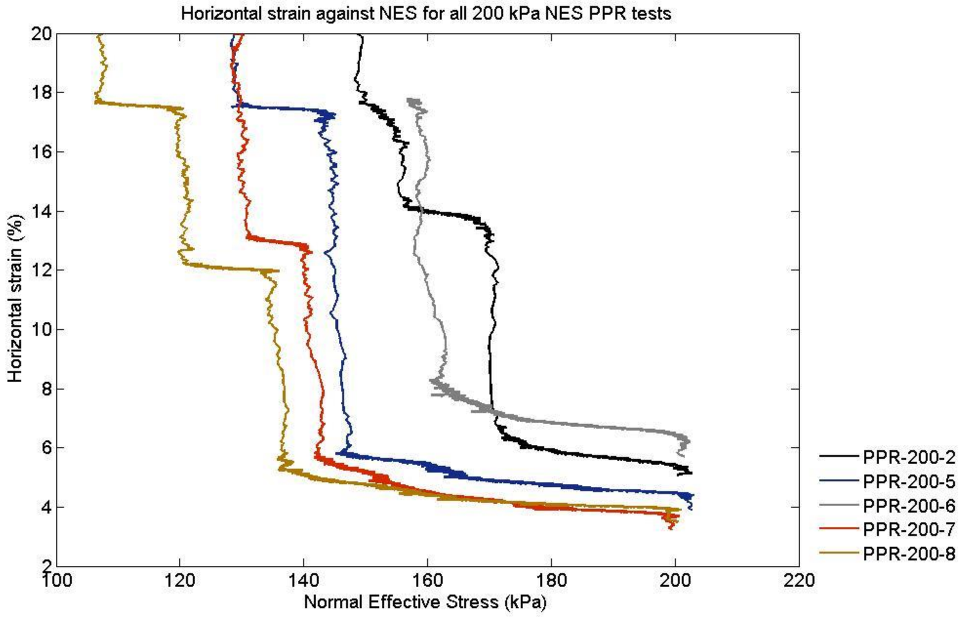


Figure 35: Horizontal strain against NES for all 200 kPa NES tests (no data for PPR-200-6 due to axial transponder issue).

Establishing the role of dilation within these tests is central to understanding them. As shown by Figure 36 all tests, aside from PPR-200-6, demonstrate initial contraction followed by dilation. Dilation was fastest approximately between 4-7% strain.

Figure 37 demonstrates that whilst dilation does seem to occur due to PPR related NES reduction, as would be expected, it is highest during high strain periods. Therefore, both these plots suggest that it is feasible that dilation is involved in the cessation of high strain rates.

The lack of data for PPR-200-6 is due to an issue with the axial transducer on the shear box. As this is not involved in the control of the test, other metrics fortunately are not impaired.

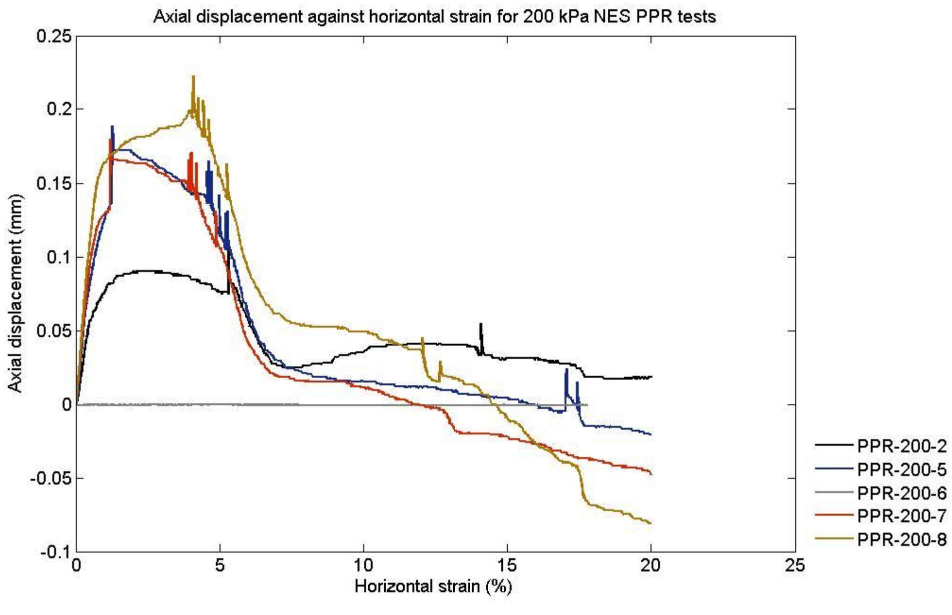


Figure 36: Axial displacement against horizontal strain (no data for PPR-200-6 due to axial transponder issue).

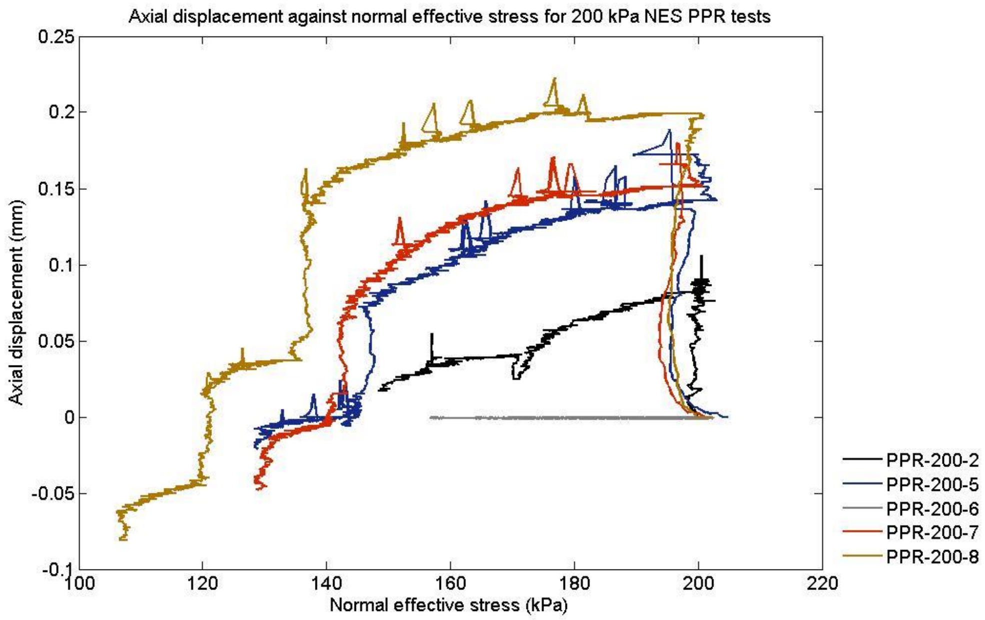


Figure 37: Axial displacement against NES.

Establishing the significance of dilation and relation to other metrics can be attempted by establishing its relative timing. PPR-200-8 appears to be representative of the 200 kPa NES tests so is used as an example in Figure 39-Figure 41. During the test there were three distinct increases and decreases in strain rate.

If dilation is related to the cessation of strain rate increases, then a relationship would be expected between horizontal and axial acceleration. Figure 38 shows that there is some suggestion that contraction of the sediment correlates with deceleration of horizontal shear, and vice versa. However, the majority of points show little influence of axial acceleration and there is no significant trend. The suggestive points are outliers or noise. The figure interestingly also demonstrates how increases in strain rate tended to be faster than decreases

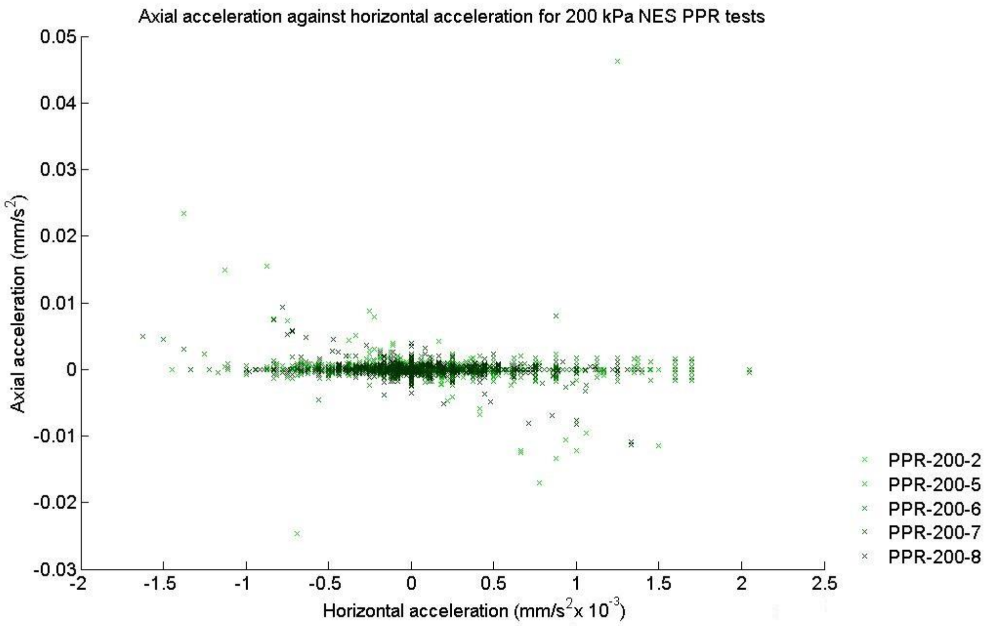


Figure 38: Scatter plot of axial acceleration against horizontal acceleration for PPR-200 testing.

Figure 39 shows axial displacement and horizontal velocity variations through the test. Before each of the three distinct increases in horizontal strain rate, dilation appears to occur. At no point though is there evidence of substantial contraction that might be responsible for decreases in strain rate. This again appears to suggest there is no link between dilation and cessation of high strain rate episode.

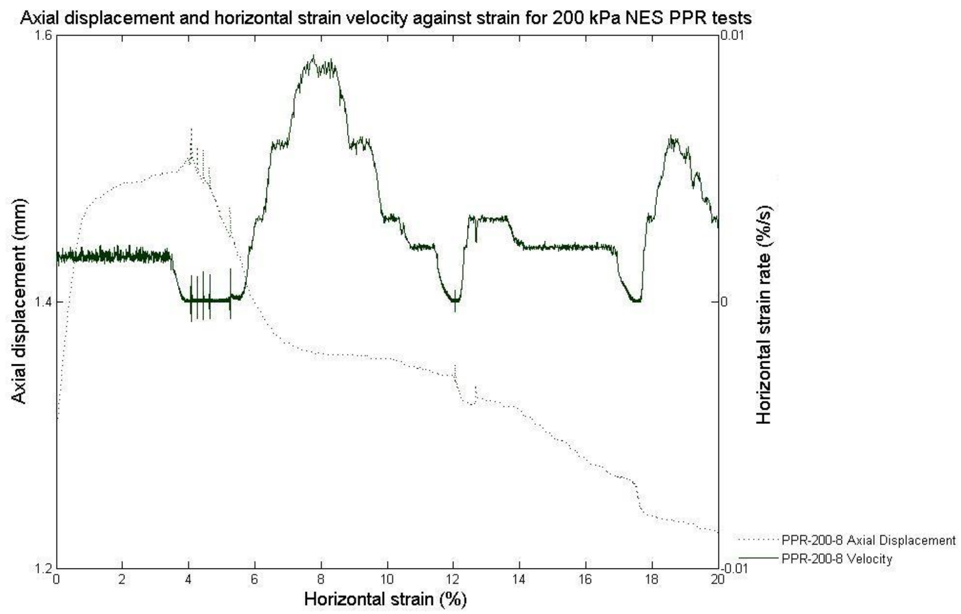


Figure 39: Axial displacement and horizontal rate against horizontal strain for PPR-200-8.

Dilation results in a reduction in internal friction weakening the material. However, it can also strengthen materials due to increasing pore spacing resulting in lower pore pressures and consequentially higher normal effective stresses (Reynolds, 1886). Figure 40 and Figure 41 demonstrate that this does not appear to have been the case here. Figure 40 shows how pore pressure consistently lagged behind back pressure but did not appear to be impacted by periodic increases in dilation rate and/or be associated with variations in velocity. Figure 41 demonstrates good coherence between the two data sets whereas if dilation was reducing pore pressure there would be periodic deviations.

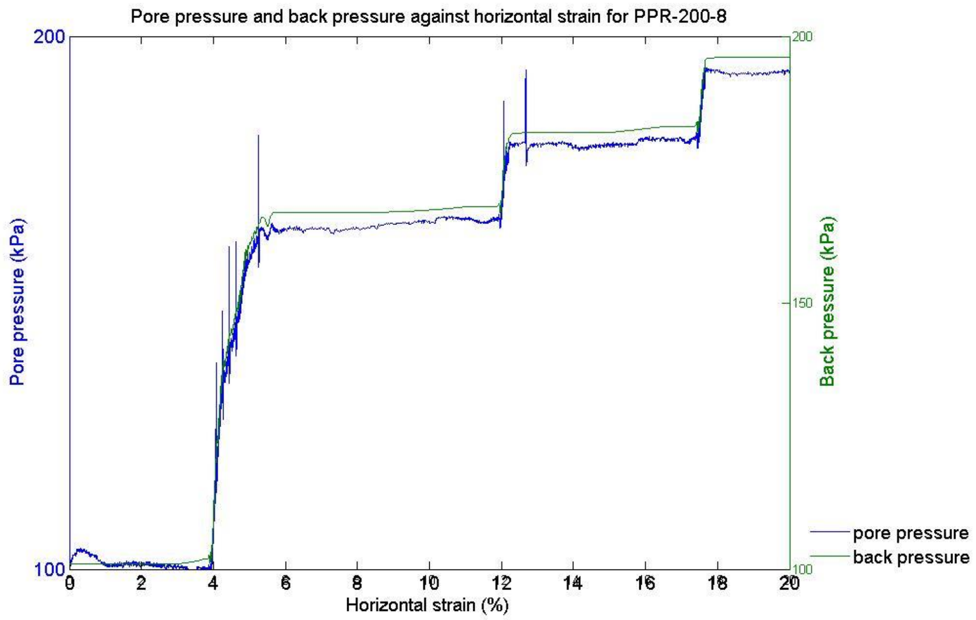


Figure 40: Pore and back pressure against horizontal strain for PPR-200-8.

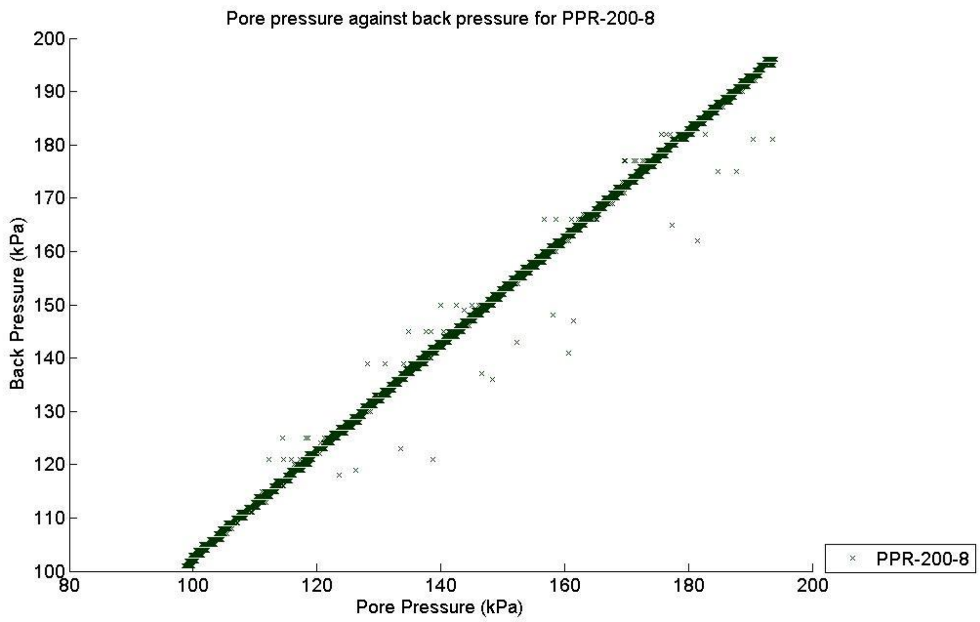


Figure 41: Scatter of pore pressure against back pressure for PPR-200-8.

5.4.1.3 Comparison to other testing (100 and 50 kPa NES)

Testing at other NES performed, on the whole, similarly to testing at 200 kPa NES. Testing largely results in episodic increases in strain rates and dilation throughout. However, the single test run at 300 kPa is viewed as somewhat anomalous based on its test end NES plotting as a clear outlier in Figure 29. Table 7 includes a summary of the manner in which tests failed for all PPR testing.

Table 7: Failure manner of all PPR tests. Tests varied in how they failed with some displaying runaway failure and others displaying several episodic increases in strain rate terminated by deceleration.

Test Name	Episodic strain rate increases?	Number of phases?	Strain rate (m/a)	PPR rate (kPa/hr)
ACSAM2B-PPR-50-1	Yes	2	50	2
ACSAM2B-PPR-50-2	Yes	2	50	2
ACSAM2B-PPR-50-3	Yes	2	50	2
ACSAM2B-PPR-50-4	No	N/A	50	2
ACSAM2B-PPR-50-5	Yes	2	50	0.25
ACSAM2B-PPR-100-1	Yes	3	50	2
ACSAM2B-PPR-100-2	No	N/A	50	2
ACSAM2B-PPR-100-3	Yes	2	50	2
ACSAM2B-PPR-100-4	Yes	3	50	2
ACSAM2B-PPR-100-5	No	N/A	50	2
ACSAM2B-PPR-200-1	N/A	N/A	5	2
ACSAM2B-PPR-200-2	Yes	3	5	2
ACSAM2B-PPR-200-3	N/A	N/A	5	2
ACSAM2B-PPR-200-4	N/A	N/A	5	2
ACSAM2B-PPR-200-5	Yes	2	50	2
ACSAM2B-PPR-200-6	Yes	1	50	2
ACSAM2B-PPR-200-7	Yes	2	50	2
ACSAM2B-PPR-200-8	Yes	3	50	2
ACSAM2B-PPR-200-9	Yes	2	50	2
ACSAM2B-PPR-300-1	Yes	5	50	2

One difference between testing at different NESs is in the velocity achieved during the test Figure 42. The greater the NES of the test the greater the velocity achieved. On average, the number of episodic strain increases is also proportional to NES of the test. Therefore, the higher velocities do not just relate to the length of the failure. However, there is also a somewhat poorer correlation between NES and acceleration than NES and velocity (see Figure 43). This suggests it is more the consistency and duration of acceleration that is related to the velocities achieved.

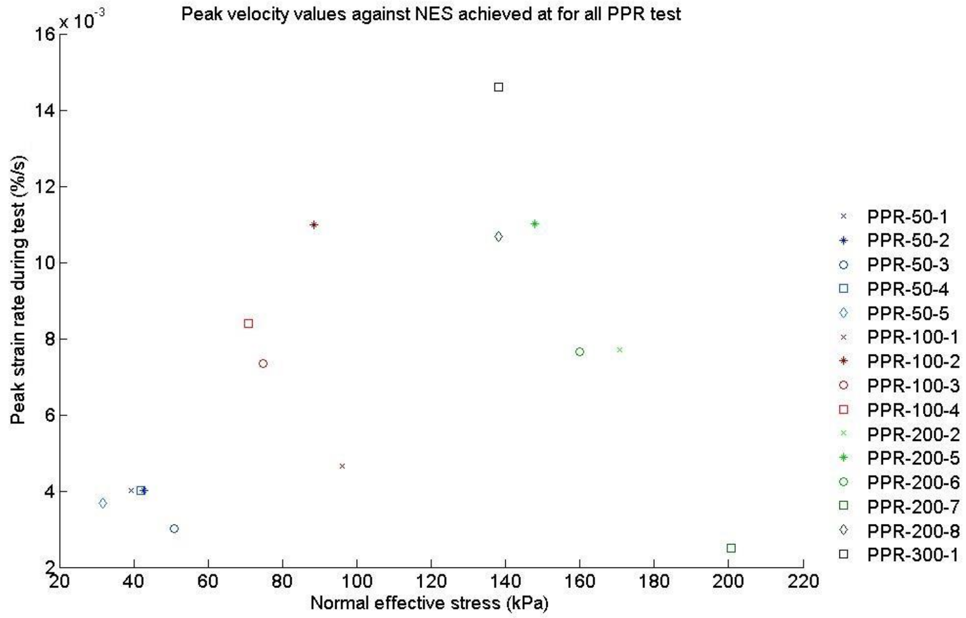


Figure 42: Summary graph of peak velocities achieved during PPR testing.

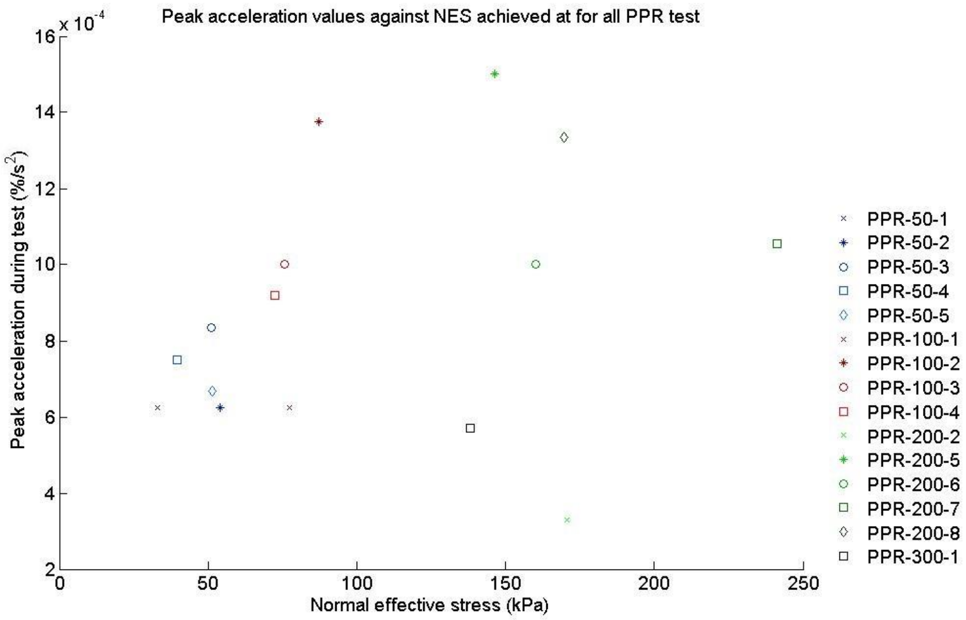


Figure 43: Summary graph of peak acceleration values achieved during PPR testing.

5.5 Discussion

The PPR testing conducted has presented a variety of interesting findings. Most significant is the prevalence of episodic increases in strain rate but there are also relationships between dilation and strain rate, peak velocities and NES and other factors. Here an attempt to expand on these is made and then some consideration is given to how they relate to the subglacial environment.

5.5.1 Test behaviour

The vast majority of tests demonstrate episodic increases in strain rate. Understanding the mechanism for this is key to linking it to the glacial environment, or alternatively, dismissing it as an artefact of testing. Episodic increases in strain rate was also been seen in testing conducted by Moore and Iverson (2002) and so initial comparison between the two tests is worthwhile.

Moore and Iverson (2002) tested till in a related but different manner. Rather than use a BPS they used a ring shear that enabled larger strains. They too periodically reduced NES but this was achieved by periodically reducing normal stress.

Their tests were marked by periodic increases in strain rate and they demonstrated that these were moderated by dilation strengthening of the till. Dilation of sediment has two potential consequences. The magnitude of inter-grain forces decrease resulting in a fall in apparent angle of friction and weakening of the sediment. However, pore spacing may increase sufficiently to result in a reduction in pore pressure and so an increase in normal effective stress which strengthens the sediment. In their testing, Moore and Iverson (2002) demonstrated that increases in strain rate were followed by dilation and a reduction in pore pressure. Therefore, consequential reductions in strain rate are likely to have been caused by dilation strengthening. This dilative behaviour was due to the over-consolidated state of the till, so when critical state porosity was finally reached the sediment could not dilate further and so failed catastrophically, strain rate increasing until 20% strain was achieved.

This has not been the case in this experiment. Whereas dilation followed strain rate increases in Moore and Iverson's (2002) tests, here it precedes it. Dilation in this testing is not accompanied by a reduction in pore pressure, which would be signified by pore pressure decoupling from back pressure.

This presents a number of questions. Focussing on the initial link between increases in strain rate and dilation; why is this the opposite of Moore and Iverson's testing and can some methodological difference explain this? Why does strain rate drop again when there is no apparent link to dilation or pore pressure, and is this related to the sediment or the shear box? Finally, how likely is it that this reflects processes occurring in the subglacial environment.

5.5.1.1 Dilation

Whilst the behaviour of the experiments here is ostensibly similar to Moore and Iverson's (2002) in terms of the episodic increases in strain rate, the experimental set up is very different and really it is a case of equifinality rather than a replication of their results. Whilst dilation is central in both experiments, the reason it occurs is fundamentally different and this is significant in how the experiments behave.

Dilation in the experiments presented here occurs for two reasons, back pressure control and shear in an over-consolidated state. As can be seen in

Figure 37 dilation occurs throughout the PPR stages (step 4 on page 87) of the experiment. This is because as the back pressure increases it forces apart the particles in the till resulting in dilation, and back pressure is steadily increasing at 2 kPa/hr. Dilation also occurs due to shearing if the till is any more consolidated than the critical state porosity as grains have to ride over each other during shear. Despite the constant dilation due to back pressure, this appears not to be sufficient to keep the till in a normally consolidated state. As a result, the till is always over-consolidated, albeit to a variable extent depending on the rate of dilation up to that point. Therefore periodic increases in strain rate result in the till dilating rapidly towards its critical state porosity.

Dilation in Moore and Iverson's (2002) experiments is fundamentally different due to the absence of back pressure control. In their experiments, normal effective stress is reduced by periodic reductions in normal stress. This weakens the till but does not directly result in dilation occurring, rather it provides an opportunity for shear to result in more dilation. As a result, when strain rate increases the till should be further away from its critical state porosity. This enables dilation to play a greater role in the stabilisation of shear as it is more likely to outpace the till's hydraulic conductivity. As the water pressures within the till cannot be maintained the dilation results in a drop in pore pressure, an increase in normal effective stress and so it strengthens the till.

These differences in experimental setup are clearly significant and explain why the BPS experiments do not experience dilation control. The steady dilation means that dilation is never as high during periods of elevated strain rate. However, the episodic increases in strain rate do cease and the full difference between the experimental setup cannot be explained without a satisfying reason for that.

5.5.1.2 Episodic increases in strain rate

As there is no evidence of pore pressure decoupling from back pressure with dilation, and so no sign of dilation strengthening, it is worth considering why most of the episodic increases in strain rate eventually decelerate. In the absence of any other evidence, it is likely that this reduction in strain is related to the inability of the BPS to maintain a constant shear stress at higher strain rates.

Following the methodology of Brain *et al.* (2015) a relatively simple assessment of the factors involved in decelerations can be conducted by plotting the theoretical distance from the failure envelope (*Nf*) throughout the test. If one considers the graph depicting the peak stress failure envelope (shear stress vs normal effective stress) then *Nf* is the distance perpendicular on the graph from the line of best fit through the peak stress values. *Nf* = 0 when the shear stress and normal effective stress during a test is the same as the failure envelope. If the sample is in a state where it should not yet fail, i.e. shear stress or normal effective stress are suitably low, then *Nf* < 0. If shear stress and NES are such that the sample should have failed, then *Nf* > 0.

Following Brain *et al*. (2015) *Nf* has been calculated as:

$$N_f = \frac{\tau_1 - m\sigma'_{n1} - c'}{\sqrt{m^2 + 1}}$$

Equation 6

Where τ_1 is instantaneous shear stress (kPa), σ'_{n1} is instantaneous normal effective stress (kPa), *m* is the tangent of the friction angle (radians) and *c'* the effective cohesion (kPa).

For this analysis the 100 kPa testing has been used. This is because whilst 3 of the 4 tests conducted on the BPS at this NES exhibited episodic increases in strain rate, an additional test run on the DynBPS exhibited a single runaway increase in strain rate. Whilst no replications of that result were undertaken this contrasting result suggests that the cause of the episodic increases in strain rate may be particular to the BPS. Therefore, analysis of results from both testing rigs may clarify their cause.

Figure 44 shows the 100 kPa tests undertaken on the BPS and Figure 45 the test undertaken on the DynBPS. Both are plots are of *Nf* against strain rate. Positive values of *Nf* indicate unstable stress states above the failure envelope, and so it is unsurprising that all but one episodic increase in strain rate occurs at a positive *Nf* (PPR-100-1 in Figure 44). More significantly, in all cases once an episodic increase in strain rate has begun, *Nf* decreases as strain rate increases. This indicates that the shear boxes are to some degree unable to maintain the conditions that initiated the strain rate increase, and as strain rate increases the stress state moves closer to the area below the failure envelope and more stable conditions. This, it would appear, must result in the cessation of the episodic increases in strain rate.

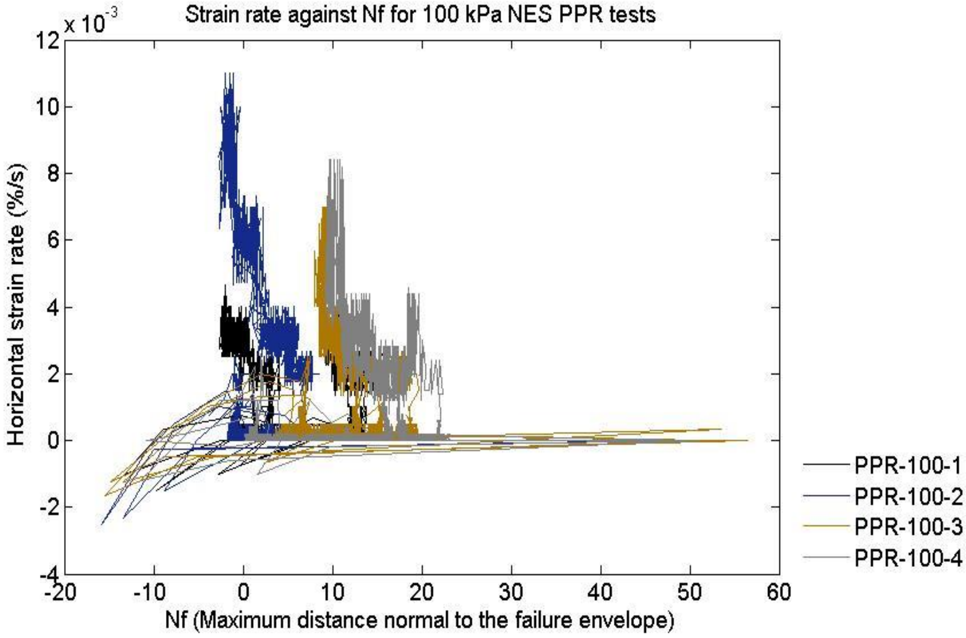


Figure 44: *Nf* against strain rate for 100 kPa NES PPR tests.

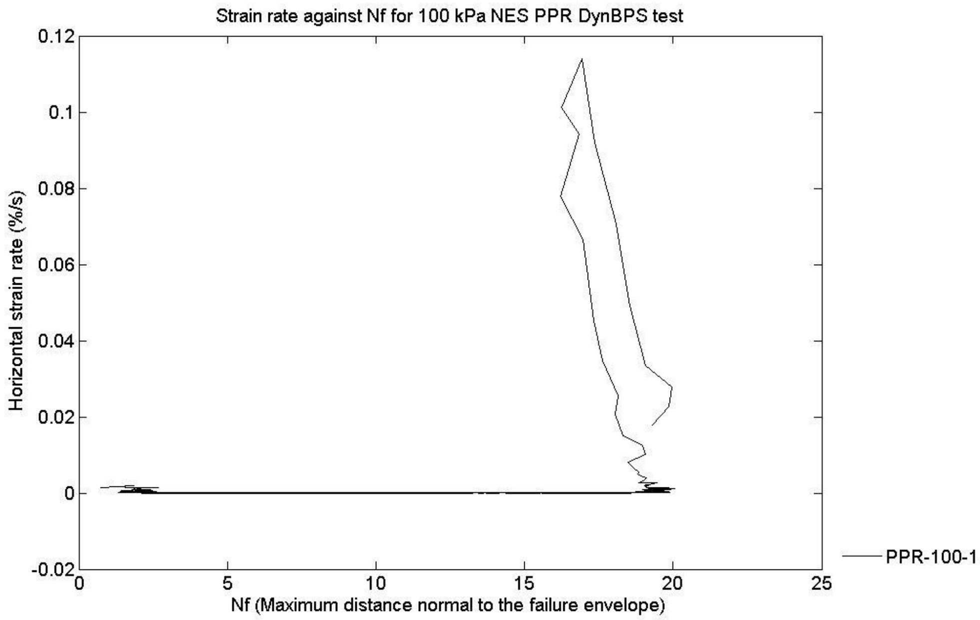


Figure 45: *Nf* against strain rate for 100 kPa DynBPS test.

The *Nf* is combination of pore pressure data and shear stress data and so examining the data for those individually helps identify the likely causal factor in the cessation of episodic increases in strain rate. Figure 46 and Figure 47 show that in both tests NES decreases slightly, resulting in a small strengthening of the sample, but this is minor. This means that dilation is not significant in controlling the increases in strain rate.

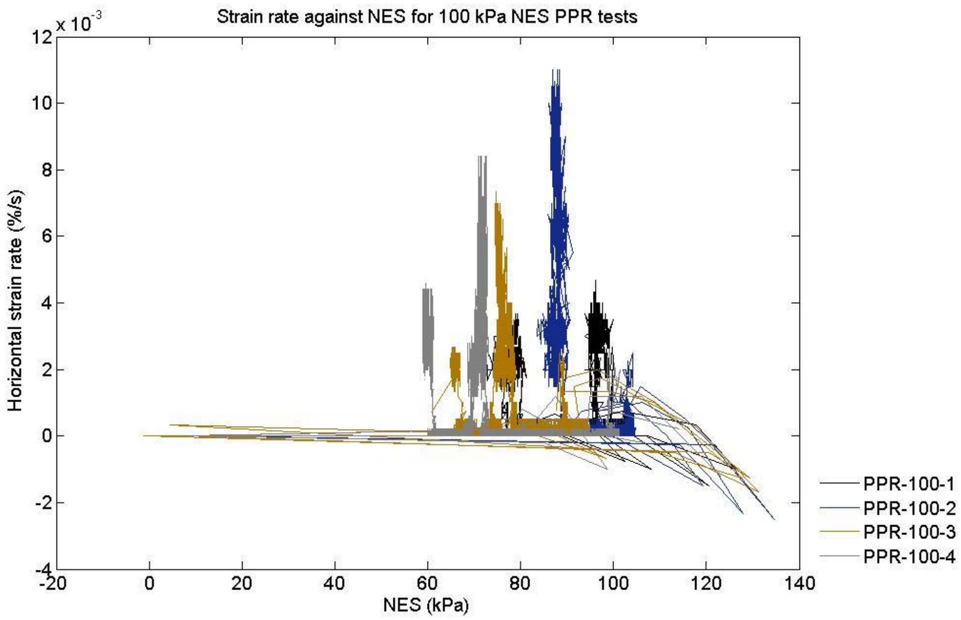


Figure 46: 100 kPa PPR testing on the BPS demonstrating the impact on NES of increasing strain rate.

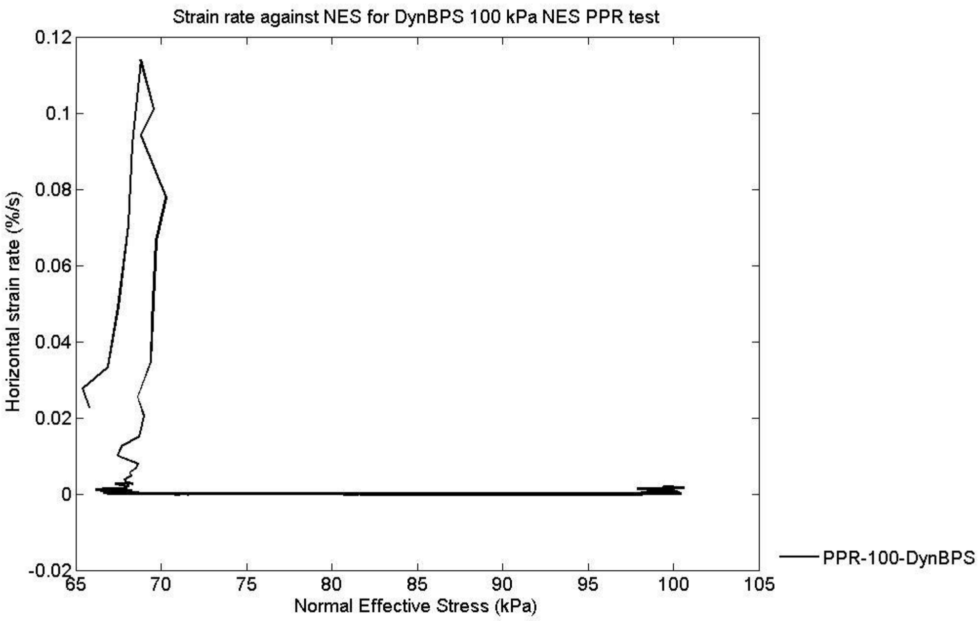


Figure 47: 100 kPa PPR testing on the DynBPS demonstrating the impact on NES of increasing strain rate.

Conversely, Figure 48 and Figure 49 show that shear stress falls as strain rate increases, and that this happens to a greater extent in the BPS than DynBPS test. Both testing rigs appear to struggle slightly to maintain the exact shear stress as strain rate increases, with some degree of hysteresis as the tests decelerate. This is likely to be a software issue. To maintain a given shear stress in a dynamic situation with increasing strain rates requires complex forward prediction of the displacement required, and it appears that neither shear box is quite able to manage this.

The BPS testing is impacted by this more than the DynBPS testing. On the DynBPS, an increase in strain rate to 0.1 %/s results in a 2 kPa reduction in shear stress. However, on the BPS the same increase in strain rate results in a 14 kPa reduction in shear stress. The trend is almost perfectly replicated by all four tests. Considering the variability in non-controlled aspects of other tests, seemingly inherent in the till, this suggests it is a machine controlled factor. For both pieces of equipment, the decrease in shear stress is approximately linear with strain rate.

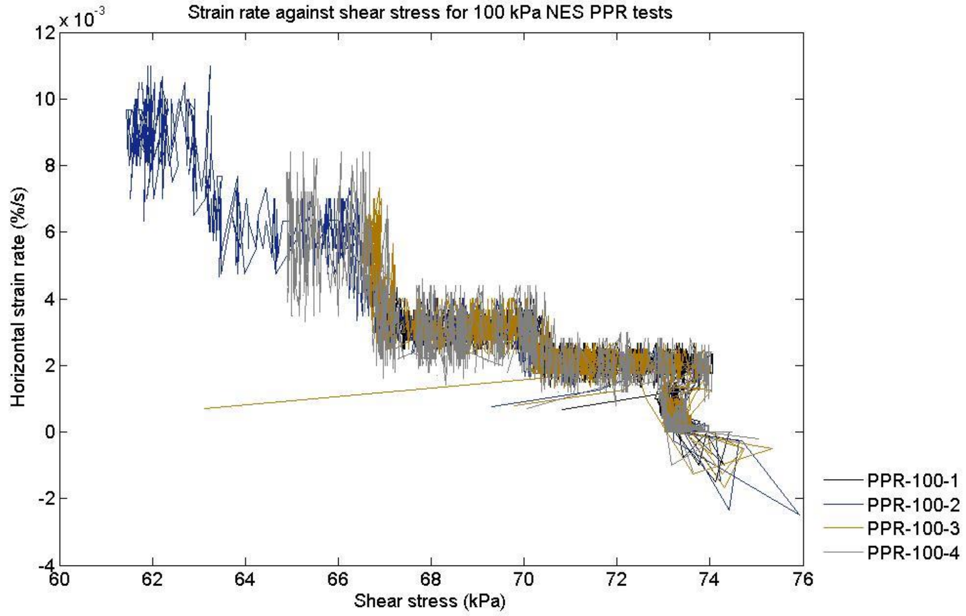


Figure 48: 100 kPa PPR testing on the BPS demonstrating shear stress reduction with increasing strain rate.

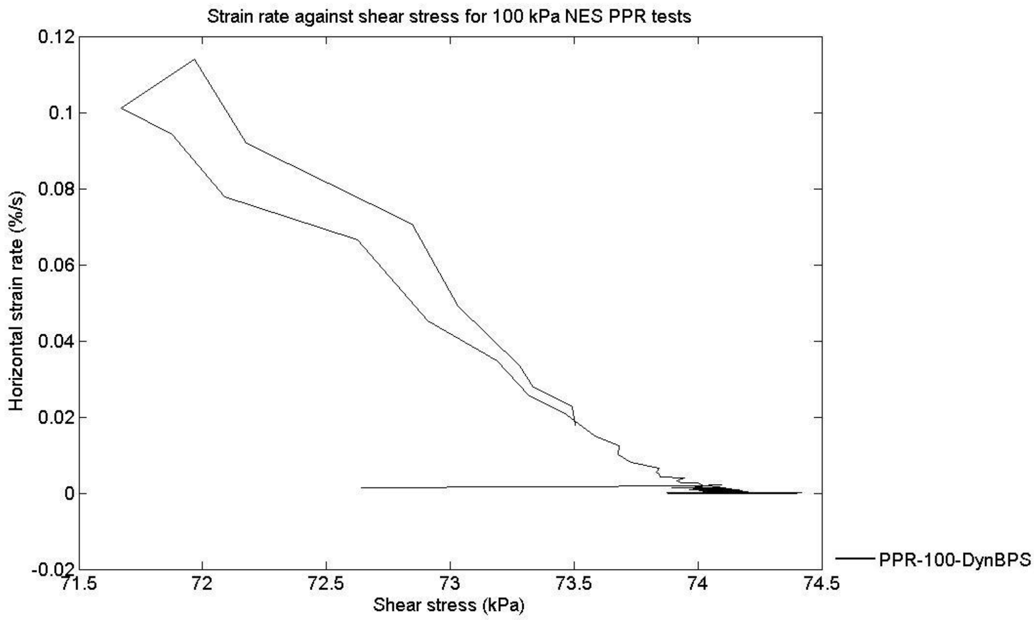


Figure 49: 100 kPa PPR testing on the DynBPS demonstrating shear stress reduction with increasing strain rate.

Aside from the interesting episodic increases in strain rates, there is an intriguingly strong relationship between the NES of a test and the peak strain rate achieved (see Figure 42 and Figure

43). Carey (2011) noted a similar phenomenon in his BPS testing of till. He suggested that this might be due to sediment stiffness increasing with confining pressure and affecting the speed at which the eventual shear surface could develop. Failure of the clay tested was marked by small amounts of displacement at higher NES followed eventually by failure. This stiffness related theory was supported by those tests experiencing less displacement before failure, presumably increasing the velocity achieved whilst also demonstrating the stiffness of the material.

That theory does not appear to apply to this situation. Whereas in Carey's tests there were a variable number of small displacements early in the tests, here instead there are a number of significant displacements. The timing of these appears to have little relation to confinement pressure, instead seemingly matching PPR rate. Further investigation involving tests using different PPR rates would be a useful initial step towards understanding this.

5.6 Conclusions

In conclusion, linear PPR of ACSAM2B till under approximately constant shear stress results in episodic increases in strain rate. These strain rate increases cease due to the inability of the experimental set up (BPS) to maintain a constant shear stress as strain rate increases. In contrast, it appears that under improved experimental conditions within the DynBPS PPR may result in a single rapid increase in strain rate that continues until 20% strain is achieved.

These results are in contrast to those presented by Moore and Iverson (2002). In this study shear related dilation strengthening did not stabilise episodic increases in strain rate. Shear related dilation was not seen to result in a decoupling of pore pressure from back pressure and so shear related variations in NES. This is due to the experimental set up. Pore pressure control of NES results in dilation throughout the testing rather than just as a response to strain.

This study provides a more accurate replication of the subglacial environment than previous studies (see section 8.3.3) and shows that when pore pressure variation controls NES, shear stress fluctuations are more significant than strain induced dilation. The significance of this finding is discussed below (see section 8.3.3.1).

Chapter 6: Foreland Flute Distribution

6.1 Introduction

The glacial geomorphology at Skalafellsjökull can be conceptualised well by the land-system approach (Evans, 2005). Along with many other outlets from Vatnajökull it fits with the temperate land terminating model. The foreland geomorphology includes subglacial bedforms with over-printed moraines and some esker deposits (Chandler *et al*., 2015) although significant fluvial reworking has modified around 50% of the foreland. The similarity of the geomorphology to the conceptual model and its near ubiquity across other glaciers in the region encourages the argument that the foreland reflects subglacial conditions at Skalafellsjökull. Evidently, the stress state and hydrology of the margin might not be replicated across the entire glacier. However, as the Glacsweb site is located in a marginal area next to the lateral moraine and has relatively thin ice (<75 m), it seems reasonable to expect some level of similarity between it and the margin.

The presence and preservation quality of the subglacial bedforms at the glacial margin provides a valuable perspective of the subglacial dynamics at Skalafellsjökull at a resolution far higher than can be derived from *in situ* sensing. Earlier in the thesis (section 2.2.2) subglacial bedform genesis, in particular flute genesis, was presented. This provides the basis of this chapter that focuses on analysis of the flutes on the foreland of Skalafellsjökull. These are then related to the subglacial dynamics monitored by *in situ* sensing and predicted by geotechnical testing in the discussion (Chapter 8).

The premise of this chapter is that regardless of their precise genesis subglacial bedforms are the result of disturbances in the subglacial environment. Their spatial arrangement therefore must reflect the spatial distribution of subglacial disturbance during the last advance. By making the assumption that the *in situ* testing site has similar bedforms the results of this foreland study can help inform as to what degree the probes may be impacted by bedform genesis. Therefore, in the context of the other chapters this chapter is focused on the spatial aspects of deformation. This contrasts with the *in situ* work that largely informs on the temporal dynamics of deformation and the geotechnical work that focuses on how the till may respond to exact conditions.

In order to frame the analysis we first elaborate on the flute genesis hypotheses presented earlier and discuss how different theories of subglacial bedform genesis might impact till mobility. This is clearly speculative and so it does not attempt to define the exact manner but rather constrain the possibilities. Analysis of the flutes on the foreland is then conducted with use of high resolution UAV (Unmanned Aerial Vehicle) survey data. The survey has been covered elsewhere (Hackney &

Clayton, 2015; Chandler *et al*., 2015) so only an outline is included here and attention is focused on the analysis. Finally, the results of the analysis and their implications for subglacial dynamics at Skalafellsjökull are discussed. They are used to hypothesise about the implications for the *in situ* sensing and geotechnical testing presented later.

Flute literature is relatively sparse compared to the extensive literature on bedforms as a whole. Some of the wider literature is applicable, but combining the literature on flutes with the large and ever expanding literature on other bedforms is problematic. The debate over whether subglacial bedforms can be considered as a continuum (Rose, 1987; Stokes *et al*., 2013, Ely *et al*., 2016) is substantive. The concept is appealing and qualitatively there appears to be similarities between bedforms from flutes to MSGLs. Quantitative data though has until recently (Ely *et al.,* 2016) been lacking and theories that display scale invariance are possibly conceptually flawed (Evans I, 2003).

Analyses of large scale mapping projects (e.g. Clark *et al*., 2009; Stokes *et al*., 2013; Spagnolo *et al*., 2014, Ely *et al*., 2016) have started to provide substantive quantification of palaeo-bedforms enabling a robust discussion over their similarity. It appears that the concept of a continuum can be invoked at least from drumlins to MSGLs (Stokes *et al*., 2013). Between the two forms there is a dramatic increase in elongation but width remains relatively similar. This is consistent with expectations about bedform elongation increasing with ice velocity (Hart, 1999; Stokes and Clark, 2002; Briner, 2007; King *et al*., 2009). Evidence that drumlins and MSGLs exist on a continuum moderated by varying elongation (Stokes *et al*., 2013) is problematic for also including far narrower flutes in the continuum and few studies invoke this overlap (e.g. Rose, 1989). Ely *et al*. (2016) confirm that whilst some bedforms can be thought to be a continuum, flutes appear to be a distinct landform.

Therefore, it is prudent to not try and transpose theoretical aspects of the work on other bedforms to flute genesis. Based on this perspective the investigation has been conservatively designed based on the rather more limited flute literature and so the early part of the thesis includes minimal content from the wider bedform literature. The discussion however contains more bedform literature led by the suitability of the results for making comparisons.

6.1.1 Flute genesis and till mobility

Flute genesis in the subglacial environment is primarily of interest to the thesis in respect to *in situ* sensing results. In a standard model of subglacial deformation, e.g. similar to that advocated by Boulton and Hindmarsh (1987), the dominant vector of deformation would be expected to be in line with ice flow. Theories of flute genesis all involve till at some point diverging from this that has obvious implications for subglacial sensing.

The obstruction model (e.g. Boulton, 1976; Morris & Morland, 1976; Clark *et al*., 2003; Roberson *et al*., 2011; Eyles *et al*., 2015) involves a cavity opening in the ice behind an obstruction lodged in the subglacial till. As detailed in section 2.2.2 till is either thought to flow into the cavity at the obstruction end and then be carried along in the flute (Gordon *et al.,* 1992) or for the cavity to propagate down ice and till to flow in at the tail of the flute (Boulton, 1976; Morris and Moreland, 1976). When till enters at the head of the flute it may (Dyson, 1952) or may not (Boulton, 1976) be required to be frozen to facilitate its transportation.

In this model there is room for considerable disturbance of 'normal' down glacier subglacial deformation at which ever point (head or tail) the till enters the flute. After that, normal deformation should continue as Boulton's (1976) dismissal of basal freeze-on as a widespread mechanism in temperate glaciers seems appropriate at Skalafellsjökull. Therefore, it would seem that the degree of disturbance due to flutes should reflect how frequently they are initiated or how fast they are propagating.

The instability model of flute genesis (Schoof & Clarke, 2008) suggests a rather different influence on subglacial deformation. It involves constant, but spatially variant, lateral movement of till from troughs to peaks of flutes. From this we would expect a continual divergence from the down ice vector of deformation to some degree influenced by the size of the flutes or flow cells. This model also envisages a progression in form from flutes to MSGLs. As no link has been found between those forms (Ely *et al.,* 2016) this somewhat undermines the model's applicability.

6.1.2 Flute morphology and distribution

With till mobility due to flute genesis seemingly defined by flute initiation, propagation and/or regularity and size there is need to elaborate on flute morphology and distribution to understand their influence on subglacial dynamics. Sparsely distributed but sizeable flutes will clearly have a different impact on bed deformation compared to densely distributed but small flutes. Under the obstruction model the regularity at which flutes are initiated will be proportional to their influence on subglacial dynamics. Comparatively, under the instability model, the size of the flutes should give an indication as to the spatial variation of disturbance to normal deformation and typical size of flow cells. In either situation the spacing of flutes on the glacial foreland should be indicative of the subglacial mechanism.

Several authors have looked at the spacing of flutes. This has usually been done by considering either crest-to-crest distances (Boulton, 1976) but also by considering flute widths (Gordon *et al*., 1992) and discovered that inter-flute spacing frequently displays a typical spacing on a given foreland (Hoppe & Schytt, 1953; Baranowski, 1970; Shaw & Freschauf, 1973) and so suggested that this reflects a rhythmic process of flute formation.

However, Boulton (1976) presents a number of arguments as to how regular flute spacing may emerge from an essentially random process underpinned by a few fundamentals of glacial flow. If flutes are initiated by randomly located obstructions then the probable outcome is a Gaussian distribution. If they are produced by clusters of obstructions then instead a bimodal distribution might be displayed. In addition to this modelling, Boulton suggests that very fine spacing of flutes is prevented by lateral displacement of old flutes by ribs of ice from new flutes. This exercises some (unquantified) minima on flute spacing dependent on ice viscosity and produces a skewed distribution.

It is worth noting that whilst Boulton (1976) refers to his and other author's data on flute spacing as fitting a Gaussian (/normal) distribution, they actually appear to be closer to a log-normal distribution. It is not obvious whether he considers the distributions to be Gaussian distributions truncated by the process that limits finely spaced flutes or if he miss-labelled them and meant log-normal. The use of a model of random formation would appear to suggest the latter is true as when formation of phenomenon is based on random events this commonly results in a log-normal relationship (Hillier *et al*., 2013). Whether Boulton's theorising is correct or not it does cast useful doubt on the feasibility of determining flute genesis from large scale summary statistics. It emphasises why the scope of this analysis is limited to comparing the spacing and morphology of foreland fluting to subglacial disturbance rather than providing information as to their genesis.

6.2 Insights into deformation from Skalafellsjökull foreland

The flutes constitute perhaps the dominant surface form and representation of subglacial activity at the study site, but at the study site they are set amongst numerous other glacial features (Chandler *et al*., 2016). Mapping by Chandler *et al*. (2016) of the study site from 2012 WorldView-2 imagery shows the mix of moraines, fluting, roches moutonées and meltwater channels in the ice marginal area of interest (Figure 50). Recessional moraines are frequently found in association with flutings that drape the ice proximal side of the moraine and extend linearly between successive moraines. The frequent outcrops of bedrock with obvious ice smoothing and striations (Figure 52) along with roche moutonées suggest that till coverage was incomplete during ice occupation of this region. A section through a moraine (SKA-07 in Figure 50) suggests moraine genesis in this area is due to melt season extrusion of subglacial material with elevated porewater pressures (Evans and Hiemstra, 2005) followed by bulldozing, folding and ductile deformation by the ice front during the winter advance (Chandler *et al*., 2016).

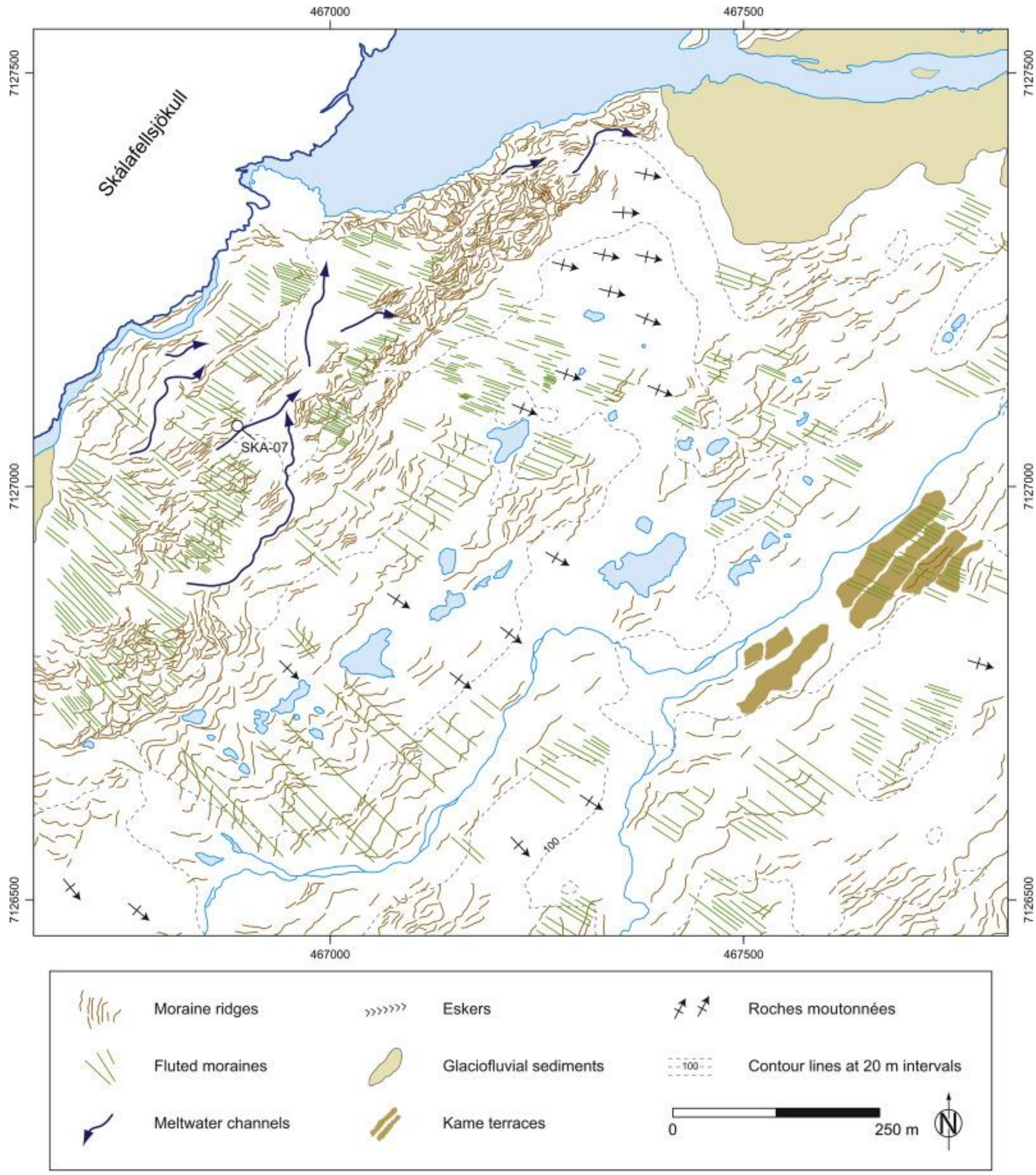


Figure 50: Mapping by Chandler *et al*. (2016) of the foreland of Skalafellsjökull including the area of interest in this study (north-west quarter). Lineations are identified but quantification focuses on moraines.

However, they are not the only evidence on the foreland that pertains to subglacial deformation. Field studies conducted by a variety of authors (Sharp, 1982, 1984; Sharp & Dugmore, 1985; Dowdeswell and Price, 1986; Evans, 2000; Roberts, personal communication, March 31st, 2016) also provides important context to this study. Three particular aspects are notable.

There is evidence for a two tiered A-B structure in the till (Evans, 2000) as at Breiðamerkurjökull (see Figure 51) (Boulton, 1979; Boulton & Hindmarsh, 1987). The upper section of the deformed till displays evidence of ductile behaviour whereas the lower unit is better characterised by brittle failures and an intermediate section displays aspects of both behaviours. Due to the apparent thickness of the A horizon it is likely that the probes will only/predominantly be impacted by ductile behaviour but the vertical strain partitioning has implications for understanding how a tilt signature might relate to the amount of subglacial deformation.

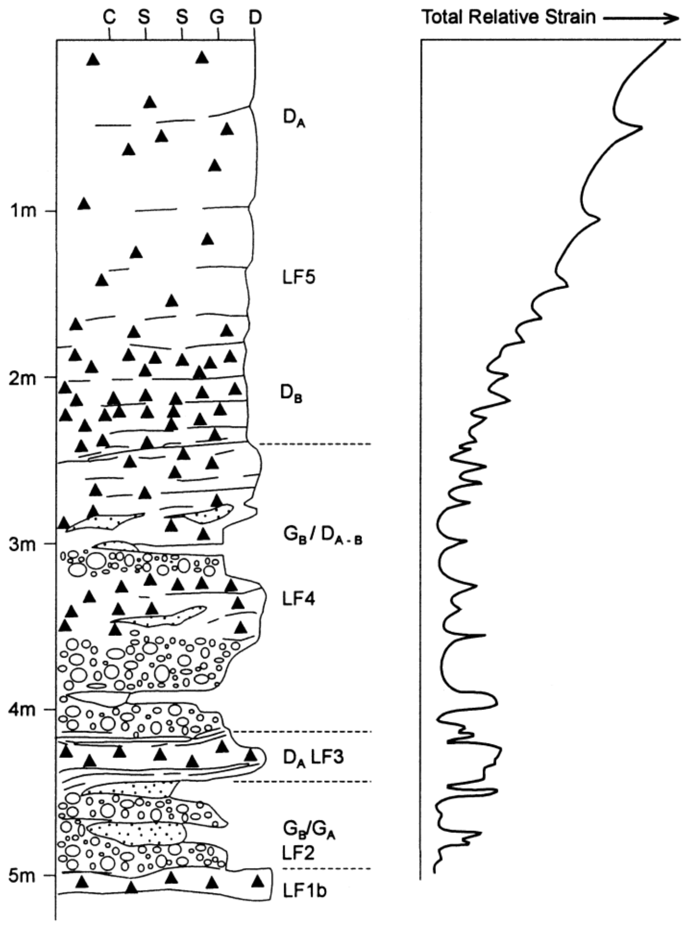


Figure 51: Stratigraphic log for the sequence at Skalafellsjökull reproduced from Evans (2000). The hypothetical strain profile shows the predicted decline in strain down through the A horizon and into the B horizon and underlying sediments.

However, the variable thickness of the till and underlying geology may influence deformation. The prevalence of rock outcrops across the foreland results in variable thicknesses of deforming till (see Figure 52c) which on occasion is bridged by large clasts. This results in lodgement behaviour occurring amongst otherwise ductile deforming till (Evans, 2000). This is similar to situations described by Hicock and Dreimanis (1992) where clasts are larger than the deforming section of till. This explains area of lodgement on the foreland with striate stoss-and-lee clasts (Evans, 2000). This patchwork variation may have a significant impact on probe behaviour presuming that the drilling during deployment would not disturb the behaviour.

In addition to influencing deformation the surfaces of the bare rock outcrops demonstrate complex small form fluvial erosion forms and p-forms (see Figure 52a-b). This may indicate a complex but consistent pattern of small scale fluvial action at the bed (Roberts, personal communication, March 31st, 2016). This suggests low till permeability and a high level of heterogeneity in subglacial fluvial systems that may be relevant when considering pore water pressures recorded by the probes.

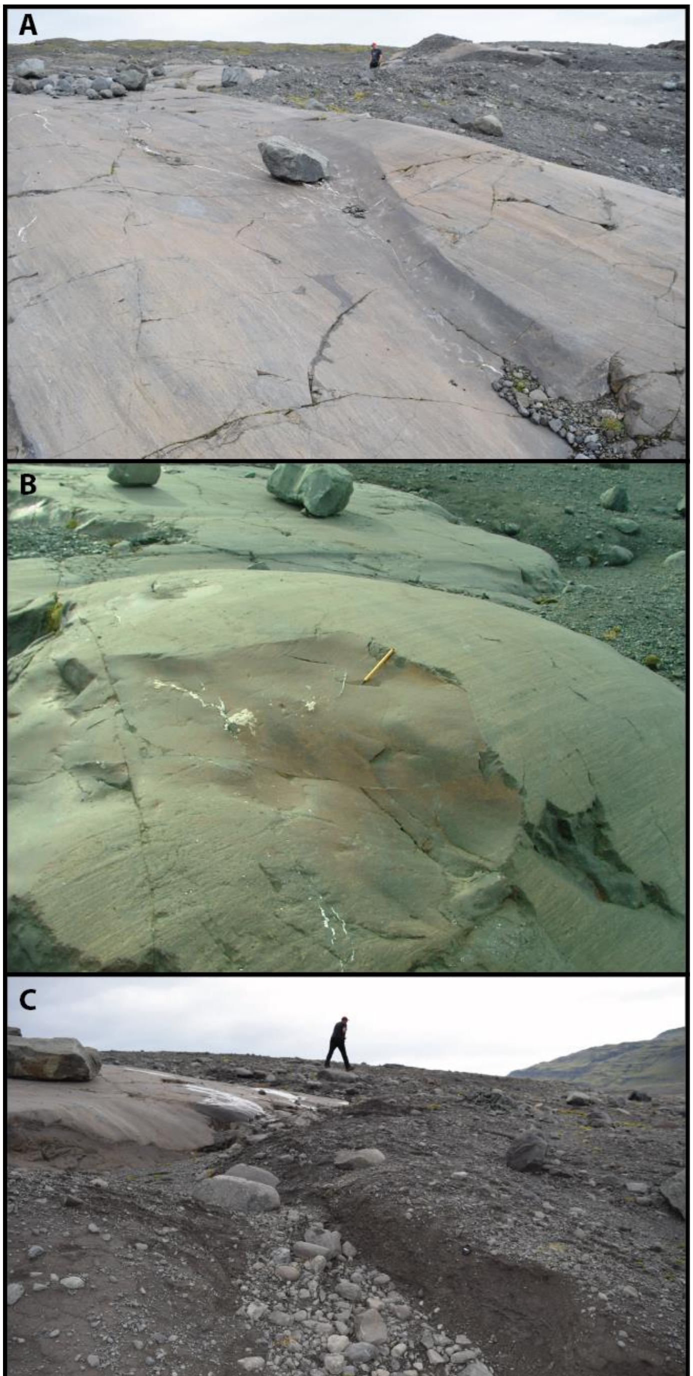


Figure 52: Aspects of the foreland particularly relevant to subglacial conditions (Roberts, personal communication, March 31st, 2016). A) P-form on bedrock outcrop. B) Water worn surface in micro-cavity. C) Till patch upstream of bedrock outcrop.

6.3 Aims

To understand the influence of flute genesis on subglacial processes at Skalafellsjökull the following question is addressed:

- Do bedforms occur on a specific scale and therefore have a determinable impact on till, and by extension, probe mobility?

This will be addressed by tackling the following two hypotheses:

1. Flute spacing at Skalafellsjökull is unimodal and log normally distributed like those in Boulton's (1976) study

This will be tackled by mapping and then analysing flutes present on the foreland of Skalafellsjökull.

Hypothesis 1 addresses the research question directly and will provide an insight into the scale at which subglacial deformation is disturbed. As spacing has often been studied in the literature and appears to be the best summary statistic for flutes, consideration of the spacing at Skalafellsjökull also provides a useful link to the literature.

6.4 Methodology

Due to the absence of an existing DEM for the foreland at Skalafellsjökull, a UAV survey was conducted during August 2013. This covered a large proportion of the immediate foreland of Skalafellsjökull and Heinabergsjökull. The UAV survey was conducted with a Quest 200 fixed wing drone during August 2013.

Table 8 below includes a summary of the survey but Hackney & Clayton (2015) contains a fuller coverage of the methodology.

As with many Icelandic investigations, the survey was subject to weather restrictions and so took place over a number of days. Consequentially lighting conditions for the imagery was variable. Due to the high latitude the sun was generally low in the sky despite the time of year (August) and cast long shadows when not obscured by cloud. During processing there was concern that the shading, unfortunately aligned with previous ice advances, might confuse identification of bedforms. The higher contrast sunny images also seemed to produce lower quality DEMs, although this was not quantified. As a result only surveys conducted in ‘flat light’ with minimal shading were used, reducing the sites available.

Table 8: UAV and Survey specification

UAV Specifications	
Model	Quest UAV 200
Camera	Panasonic DMC-LX5
Survey Specifications	
Study area	0.3 km^2
Images	117
DEM Ground Resolution	0.04 m/pixel
Error	0.572 pixels

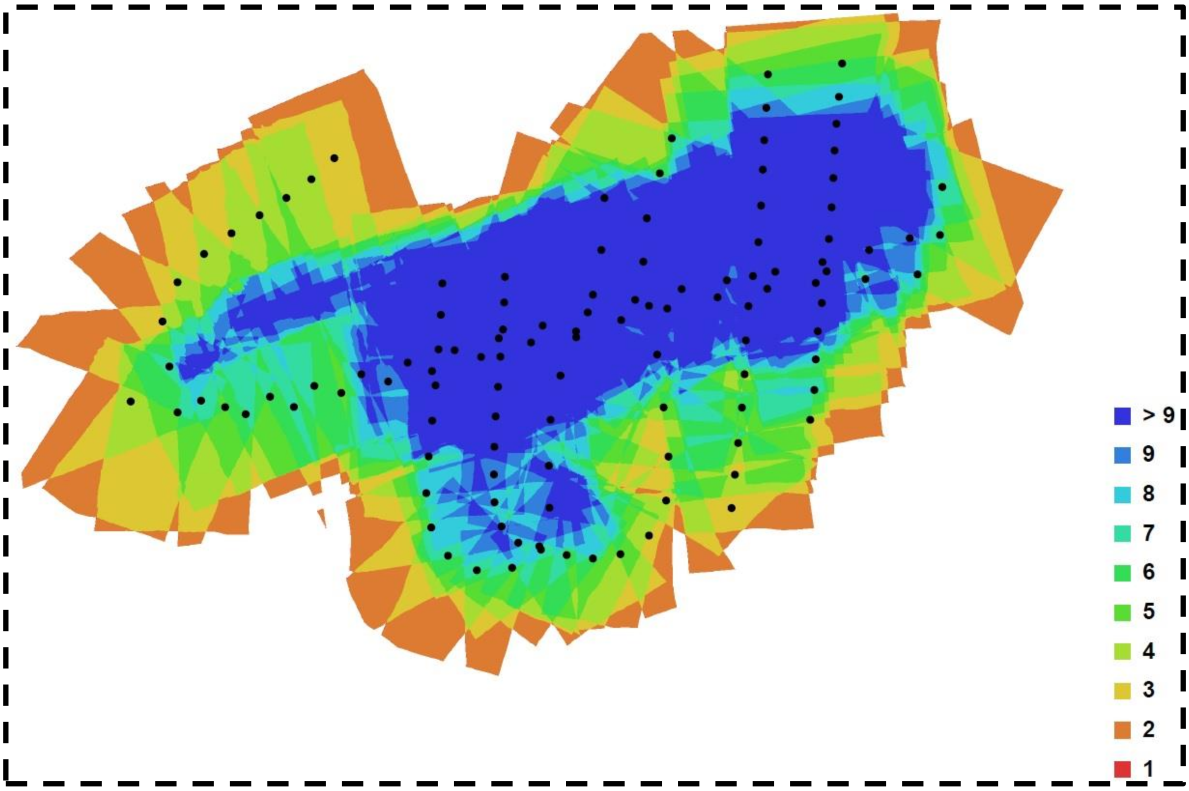


Figure 53: Camera locations (dots) and image overlaps from AgiSoft Photoscan report.

The imagery from the UAV survey was processed with SfM (Structure from Motion) techniques in AgiSoft PhotoScan to produce an orthophoto and DEM. These were then used in ArcMap to map the dimensions and locations of flutes on the foreland. The area chosen for mapping is a subsection of the foreland of Skalafellsjökull surveyed (see Hackney & Clayton (2015) for full area) but includes a large number of flutes and has significant variability in substrate making it ideal for addressing the hypotheses.

After import of the DEM to ArcMap it was hillshaded approximately orthogonally to ice flow (20°, 200°) in order to illuminate lineations produced by ice flow that had been oriented approximately 110°. A z-factor exaggeration of 2 also appeared to help with identification and was used throughout. A contrasting hill shade of 290° was used to check for unusual forms and identify more accurately the initiation point of lineations. To distinguish between sediment and rock based lineations (flutes and positive relief between bedrock grooves) the orthophoto was used. This is an imperfect methodology as a thin layer of sediment may mask underlying bedrock but without field investigation there is no other option.

Flute spacing was established by mapping the crest lines of each identifiable feature and determined as crest-to-crest distance (Hoppe & Schytt, 1953). The lines were plotted after being determined by examination of the area in each hillshade and with the orthophoto. Crest to crest distances was then identified for all features with use of the ArcMap tool 'Generate Near Table'. This tool is based on a nearest neighbour algorithm and provides the distance to nearest feature in any direction. A limitation of the feature is that the direction of measurement cannot be specified. As for comparative reasons the study is primarily interest in lateral spacing, orthogonal distances between flutes were calculated via trigonometry when the initial measurement was not performed at 90°.

This is not an exact replica of the methodology used by other authors which commonly involves transect based measurement (e.g. Hoppe & Schytt, 1953; Boulton, 1976) or more recently in bedform studies other GIS tools (e.g. Stokes *et al.,* 2013; Spagnolo *et al*., 2014). Further discussion of the possible issues this presents is included in the discussion (section 6.6), and limitations of the approach generally are discussed in section 6.6.2.

The series of figures below show the area mapped in each of its forms (DEM, orthophoto, hillshaded from three directions and with mapped lineations).

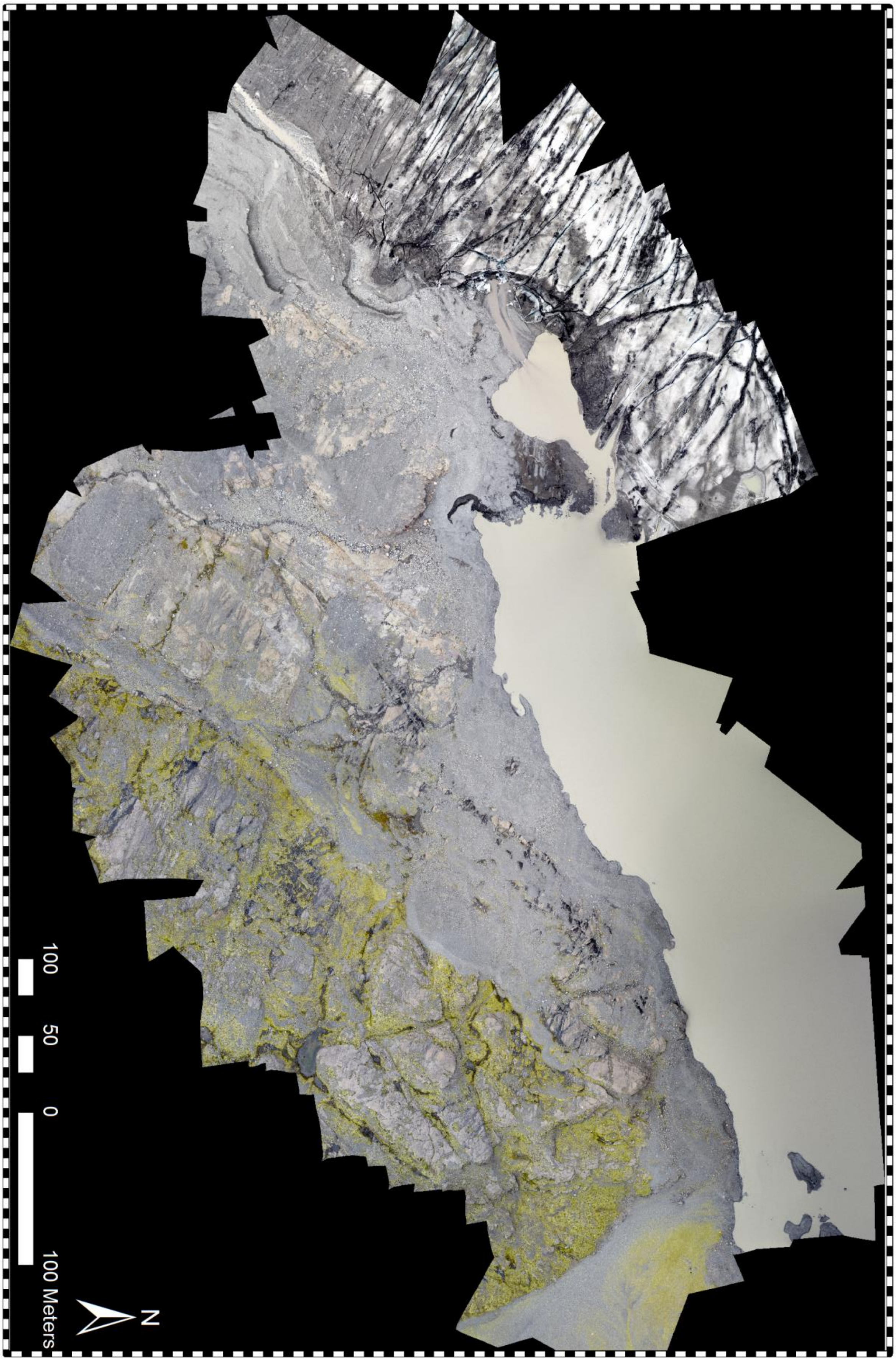


Figure 54: Orthophoto of area mapped. Southern limit for this and subsequent DEMs is due to limit of survey coverage whilst northern limit is artificial.

Figure 55: DEM of survey area

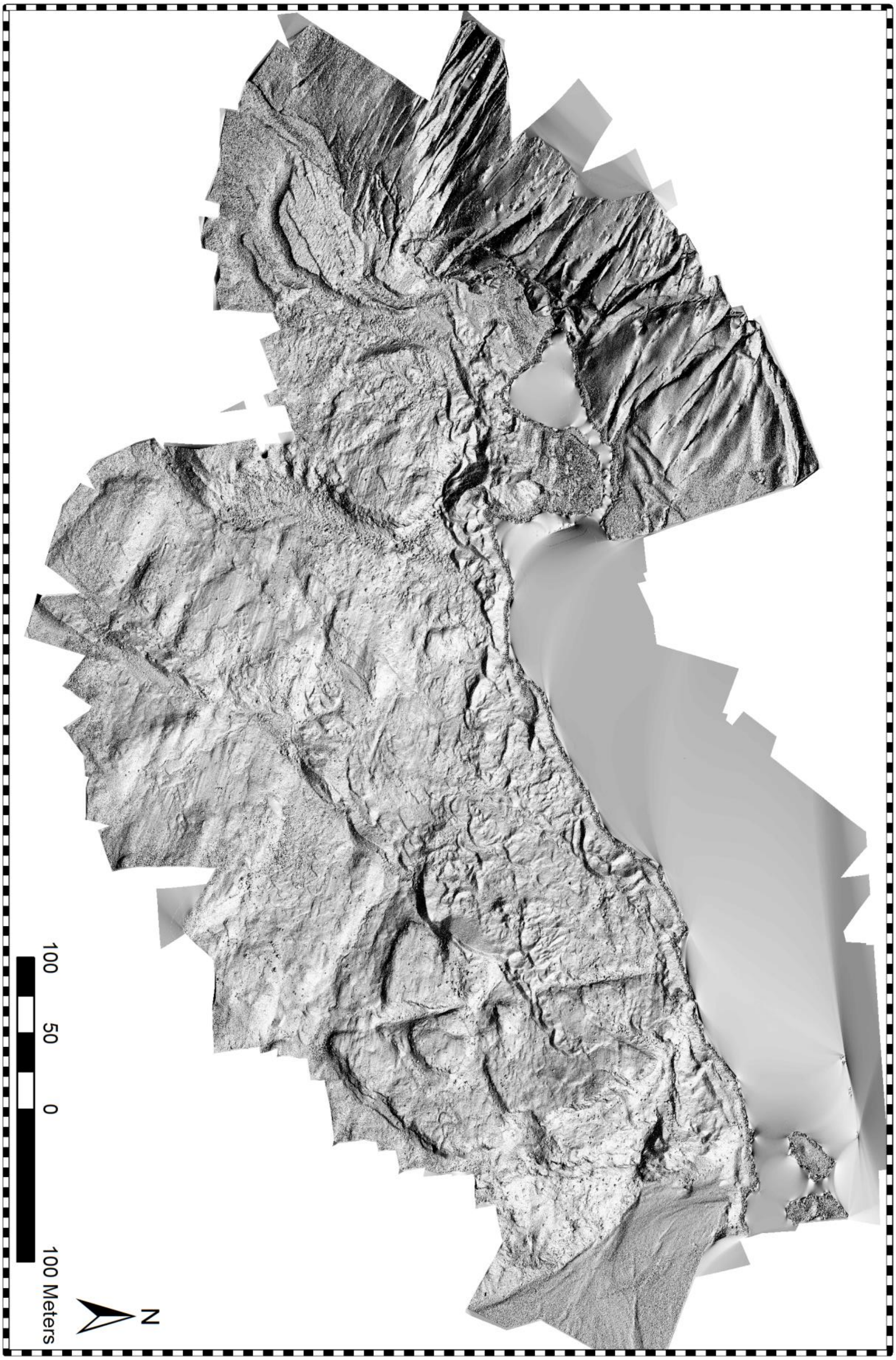


Figure 56: Hillshaded DEM of survey area. Hillshade is from 20° at a 45° azimuth with a z-factor scaling of 2. This illuminates features running parallel to ice flow.

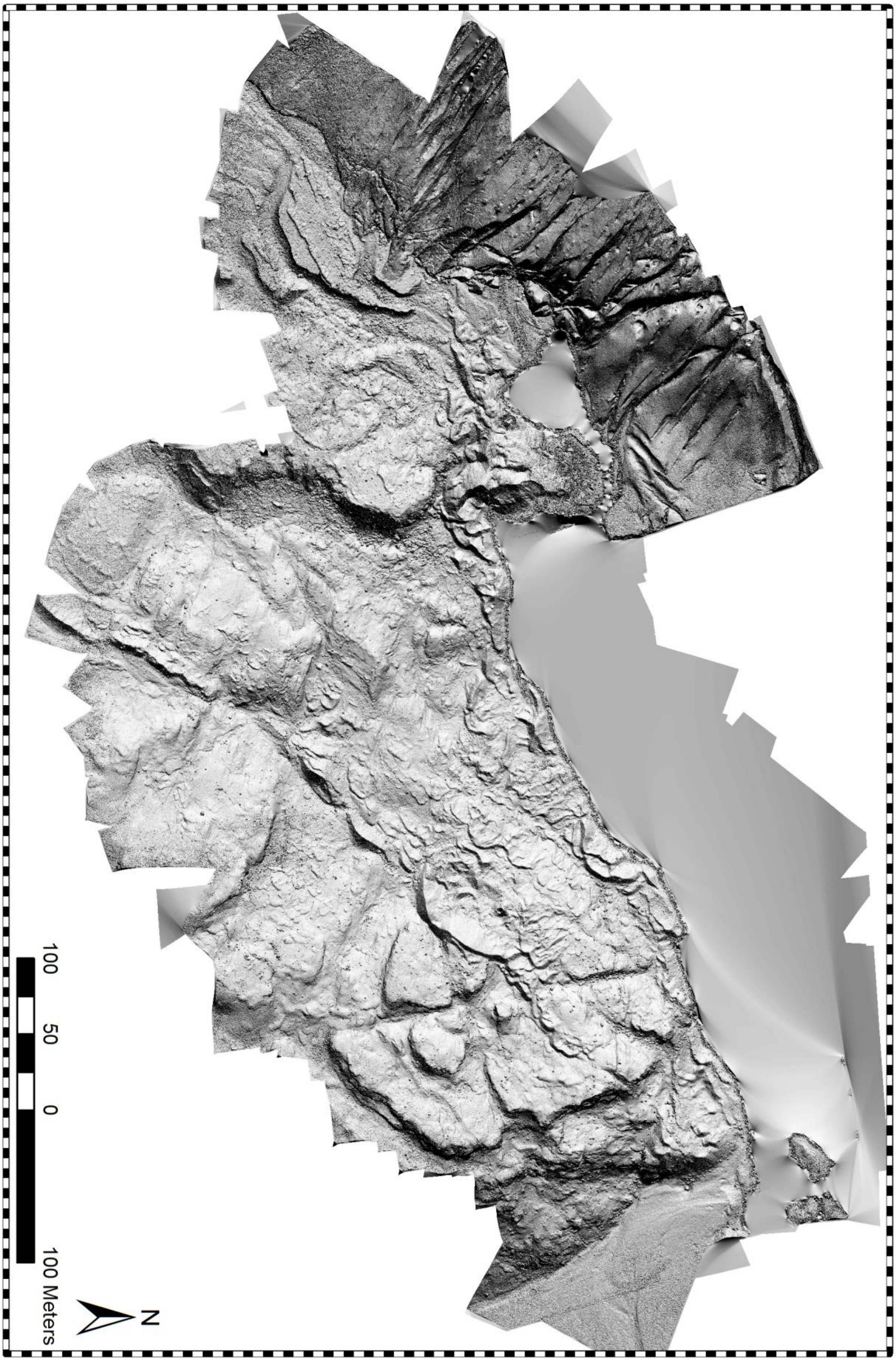


Figure 57: Hillshaded DEM of survey area. Hillshade is from 290° at a 45° azimuth with a z-factor scaling of 2. This illuminates features running orthogonally to ice flow.

The survey area is ice marginal and borders a lake to the north (see Figure 50 for wider context). The survey coverage has not been cropped so shows some areas of lower quality DEM, these have not been mapped from. The lake at the northern edge of the DEM is not resolved due to the moving surface of the water and consequent inability of the photogrammetric software to find stable features. Hillshading performed in ArcGIS is used to illuminate streamlining and moraines which exist in roughly perpendicular orientations. Streamlining runs NW-SE and so is picked out clearly in Figure 56 by a 20° hillshade. Moraines and most rock outcrops run NE-SW and so are more obvious in Figure 57 with 290° hillshade.

Figure 58 shows the mapped flutes. There is an obvious decline in feature density away from the ice margin and in some areas meltwater channels clearly influence the extent of fluting. This differs slightly from Chandler *et al.*'s (2016) mapping of the area (Figure 50). This is probably at least partially due to the resolution of the imagery used as well as differing requirements for the mapping – they were concerned with moraine properties rather than flute properties. It is plausible that minor mapping differences also arose, as some areas of rock lineations (or grooves) have been included as flutes, although this cannot be shown with certainty. Figure 59 - Figure 65 demonstrates the type of rock features present including some compound features (Figure 62) where either sediment has been deposited in the lee of a rock feature or there is just a thin layer of sediment on top of an underlying rock feature. These figures demonstrate the need for high resolution DEMs for this task and the need to use the accompanying orthophotos to determine between rock and till forms.

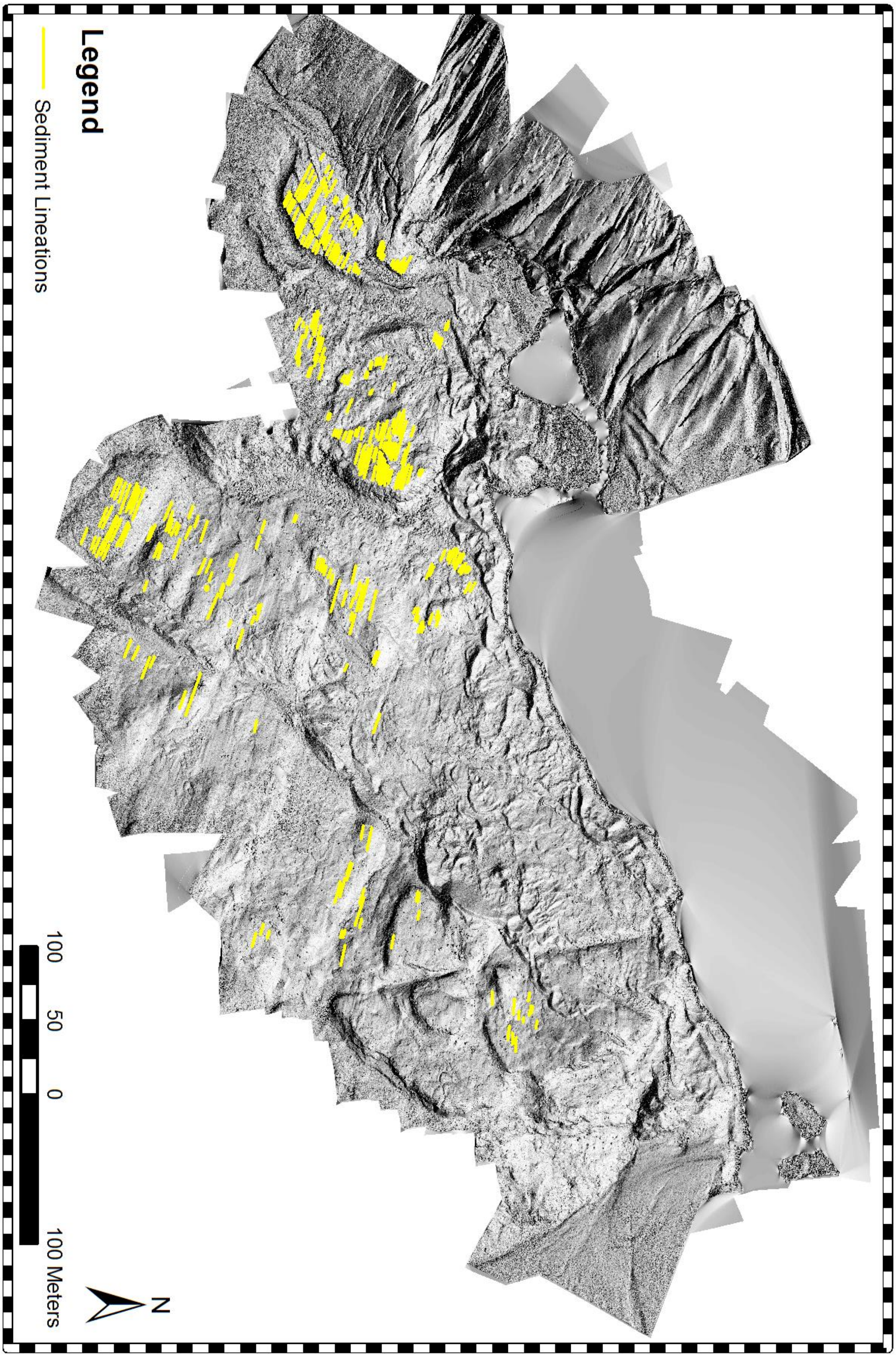


Figure 58: Hillshaded DEM of survey area with mapping results. Hillshade is from 20° at a 45° azimuth with a z-factor scaling of 2.

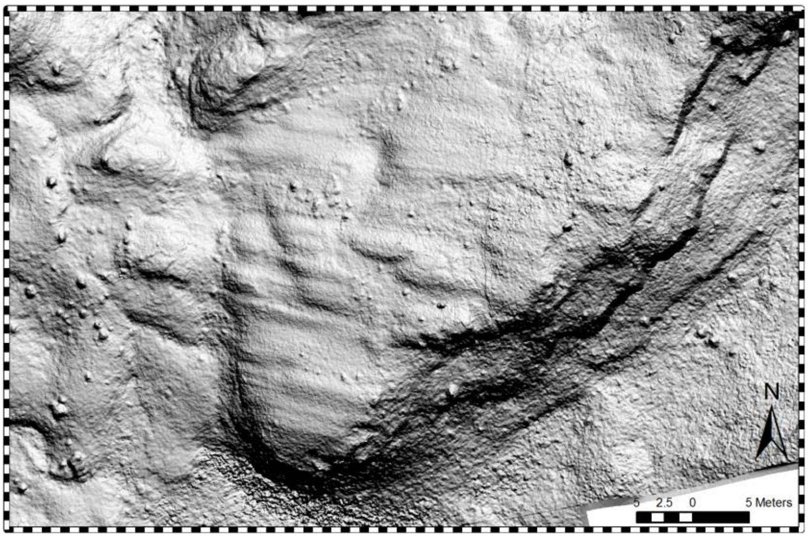


Figure 59: Orthophoto of detailed area demonstrating mapping.

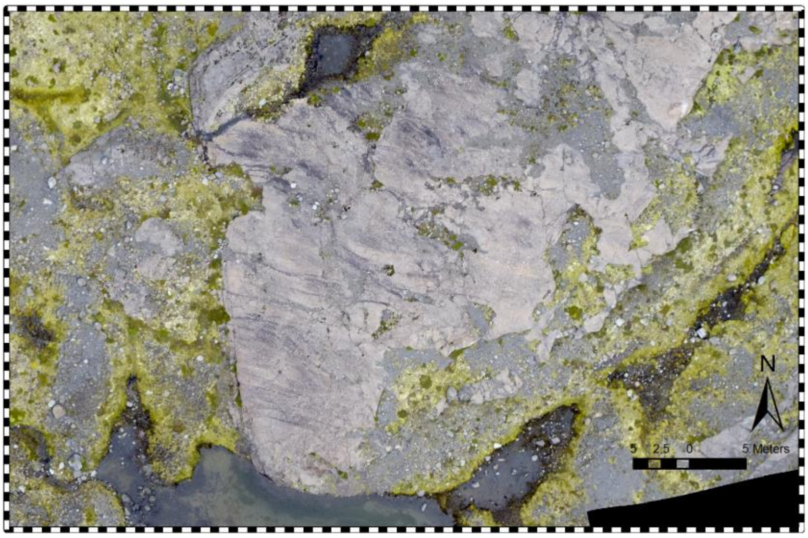


Figure 60: Hillshaded DEM of detailed area demonstrating mapping.

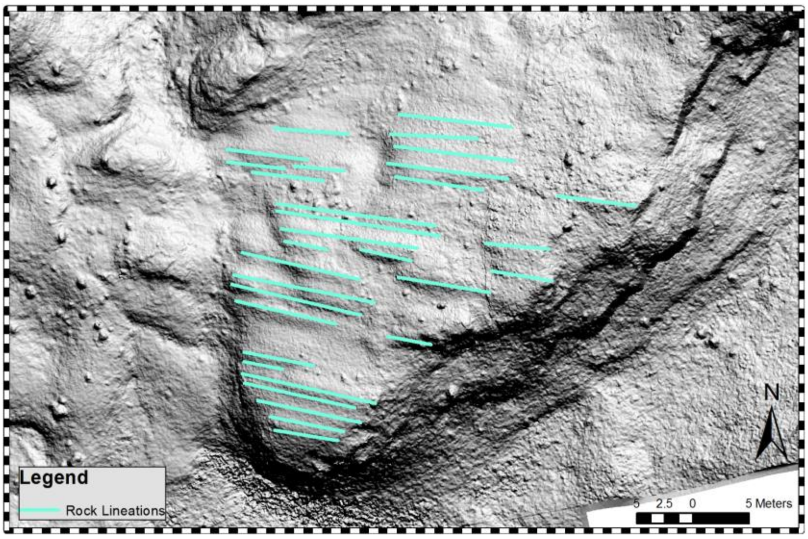


Figure 61: Hillshaded DEM of detailed area demonstrating mapping with mapped features.

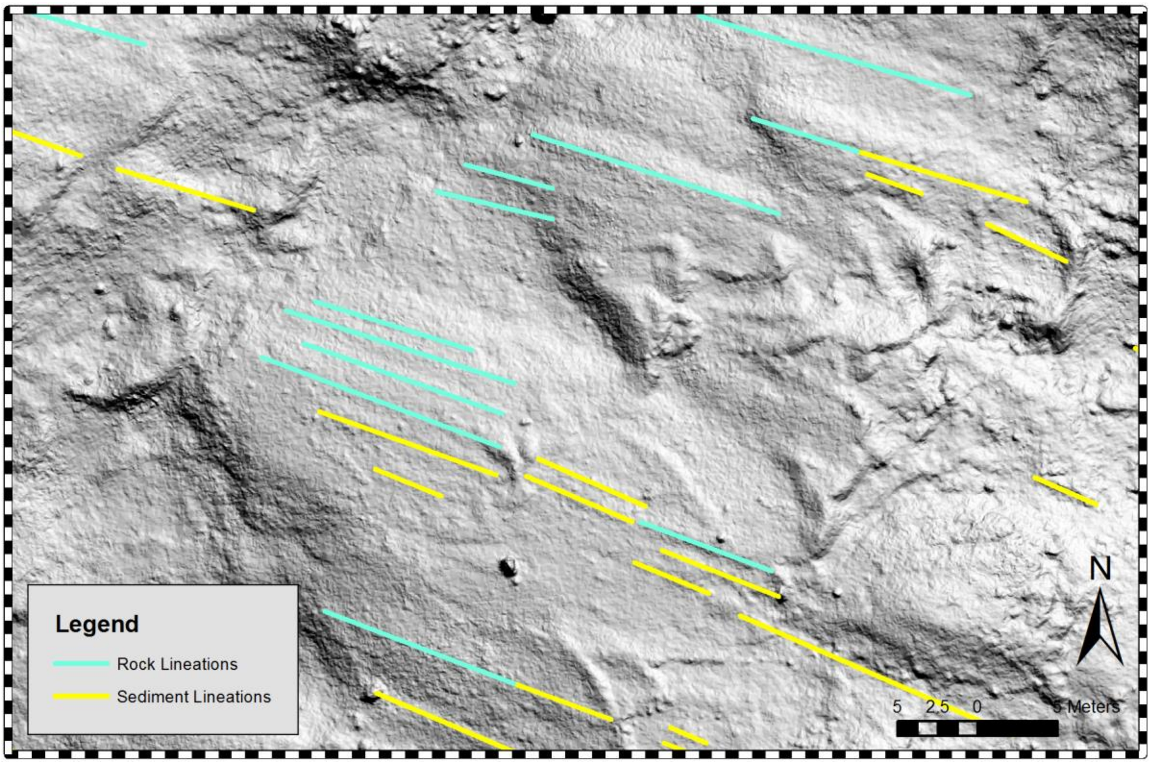


Figure 62: Hillshaded DEM demonstrated a mapping of several flutes where there seems to be a transfer between the flute material (rock vs. till) along the flute’s length.

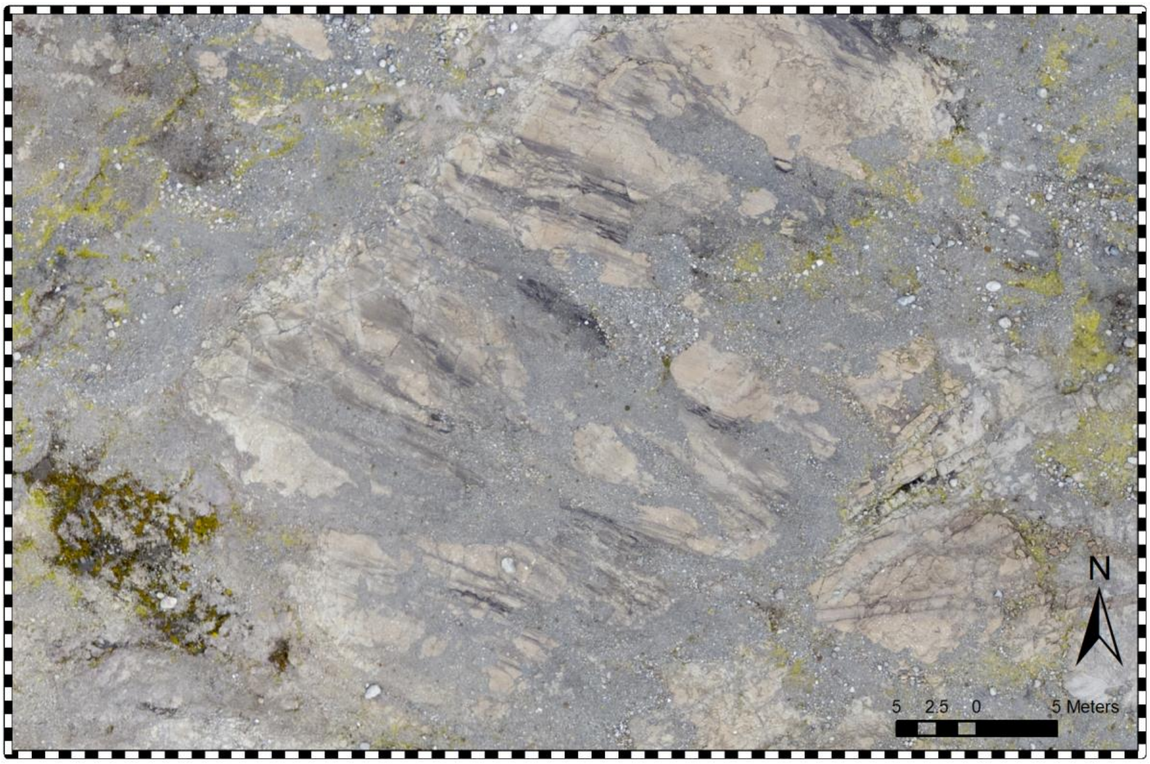


Figure 63: Orthophoto of area shown in Figure 62 in order to demonstrate the flute material transitions.

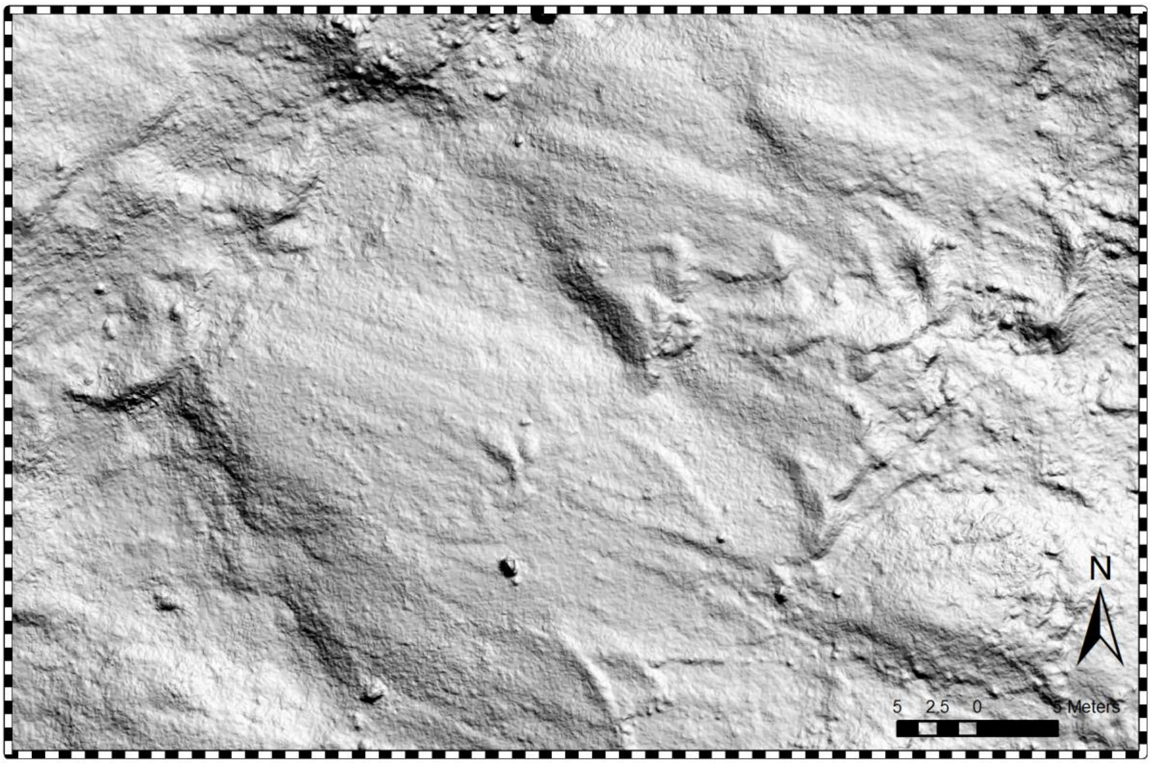


Figure 64: Hillshaded DEM of area shown in Figure 62 in order to demonstrate mapped features. Hillshade is from 20° at a 45° azimuth with a z-factor scaling of 2.

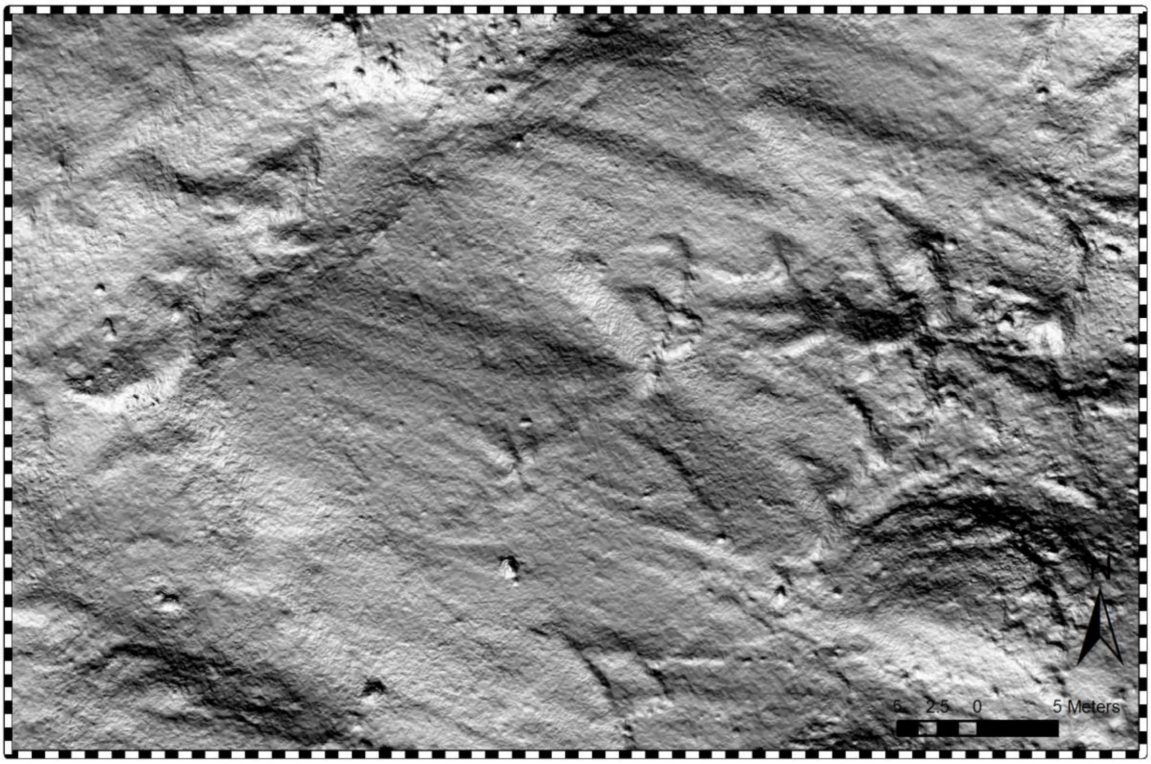


Figure 65: Hillshaded DEM of area shown in Figure 62 in order to demonstrate mapped features. Hillshade is from 200° at a 45° azimuth with a z-factor scaling of 2.

6.5 Results

Within the area mapped 322 flutes were identified on till areas.

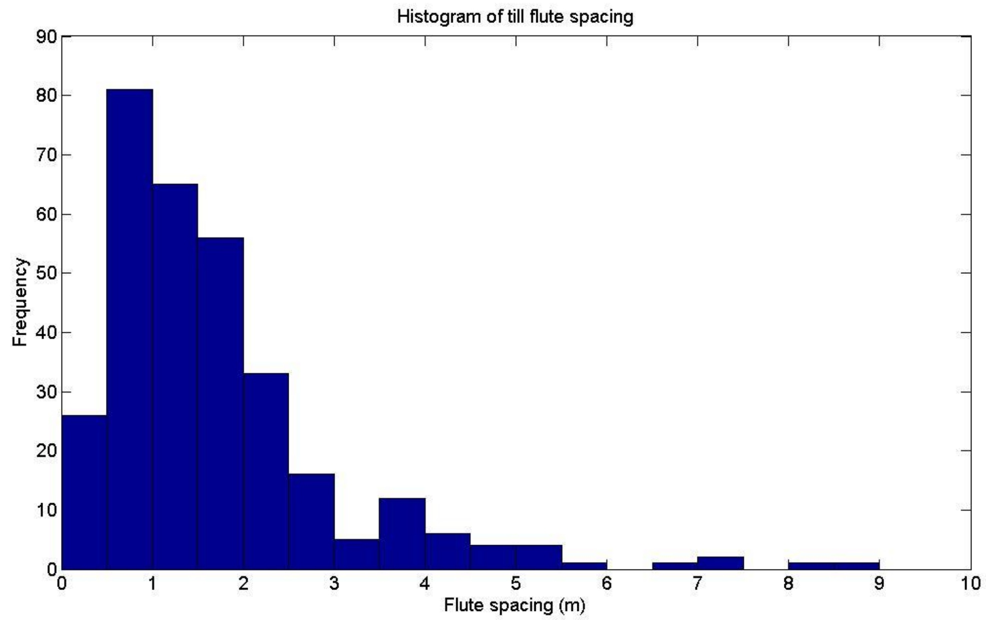


Figure 66: Histogram of till flute spacing excluding 4 outliers above 10 m. Sample size 323, mean 1.99 m.

The flutes have a unimodal distribution with a strong positive skew. Plotting the log of the measurements demonstrates that they approximate a log-normal form (see Figure 67). Statistical testing demonstrates though that they are not actually log-normal.

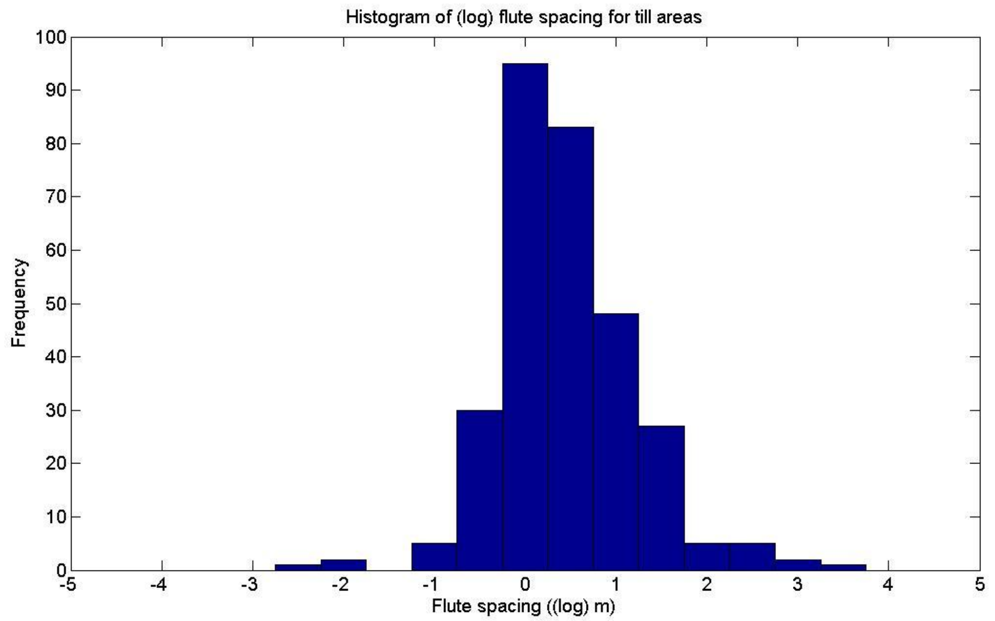


Figure 67: Histogram of (log) flute spacing for till areas.

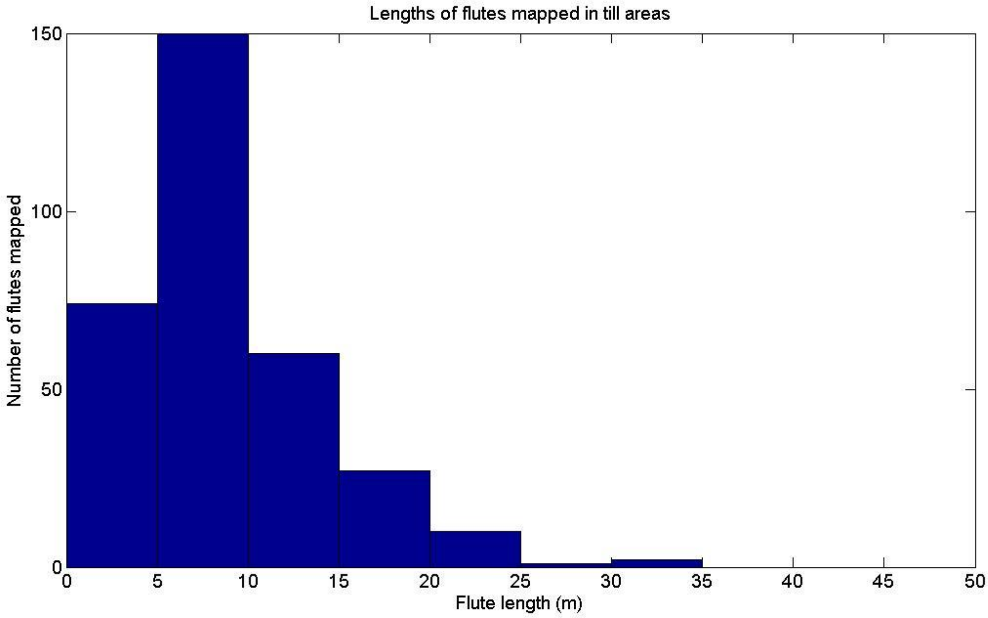


Figure 68: Histogram of mapped flute lengths in till areas.

Flute lengths (see Figure 68) displayed unimodal distributions and strong positive skews.

6.6 Discussion

The discussion is divided between consideration of factors that may have influenced the results and how the hypothesis can be viewed in light of the results.

6.6.1 Implications of mapping and analysis decisions

Before engaging with the hypothesis, the methodology is considered again in light of the results. As with all mapping based studies the data generating process of mapping should be subject to scrutiny as it clearly fundamentally impacts the results. It is always feasible that facets of the results that are seemingly interesting are actually artefacts of the mapping methodology. In this study several factors notably impacted the results: the DEM resolution, the use of the Generate Near Table tool in ArcMap, decisions about mapping of superimposed bedforms and the study site location. Before continuing onto discussion of the results *per se* first these influences on the nuances of the results are considered.

6.6.1.1 Study site location

Conventional flute theory dictates that flutes should vary based on initiation (e.g. Boulton, 1976; Morris & Morland, 1976; Clark *et al*., 2003; Roberson *et al*., 2011; Eyles *et al*., 2015) or seeding points (Schoof & Clarke, 2008) and ice speed (Stokes and Clark, 2002). The site mapped is the stoss side and top of Hjallar, a ridge extending from the western valley wall. It can reasonably be expected that ice dynamics and flute initiation or seeding opportunities would have been more complex in this area than the flatter area of the foreland to the north due to the influence of the bedrock outcrops.

Ice speed will have been reduced whilst flowing up the outcrop, especially in the later stages of its retreat, and consequentially shorter flutes would be anticipated. The complex topography of the ridge is also likely to have led to less coherent ice flow and so flutes with varying orientations. This does appear to be the case and flutes to the north of the site seem to have a less southerly direction than those to the south.

Variability in flute seeding may also impact the flutes. Both obstruction and instability models of flute formation rely to some degree on flutes being directly caused or seeded by obstructions. The mapped area includes a numerous bedrock outcrops and this is likely to have had a different impact on the flute formation than flatter areas. The outcrops may present static seeding points/obstructions and provide a ready supply of boulders that can then form dynamic seeding points (leeside quarrying suggested in Figure 52 and Figure 63). This could result in less spatially coherent patterns than visible elsewhere on the foreland. Equally though it is feasible that in the boulder rich till present across the foreland the number of feasible flute causing features are such that flute ‘saturation’ is reached. Arguably, the flute spacing minima seemingly established by flutes in the mapped area might be demonstrative of a wider process, e.g. ice viscosity (Boulton, 1976).

The danger is that these complexities result in the mapping failing to produce any information of merit about flute distribution generalities at Skalafellsjökull. In particular, within the scope of this thesis it is feasible that they do not reflect the site at which the Glacsweb *in situ* work is conducted. However, data collected at the Glacsweb site suggests a similarly complex situation (see next chapter). Ice flow there is currently slow, in the order of 3-5 m pa and an ice marginal outcrop appears to force a change in the direction of the ice. Therefore, there is little to suggest that if some underlying process appears to be illuminated by the data collection in this study site it will not be reflective of processes at the Glacsweb site.

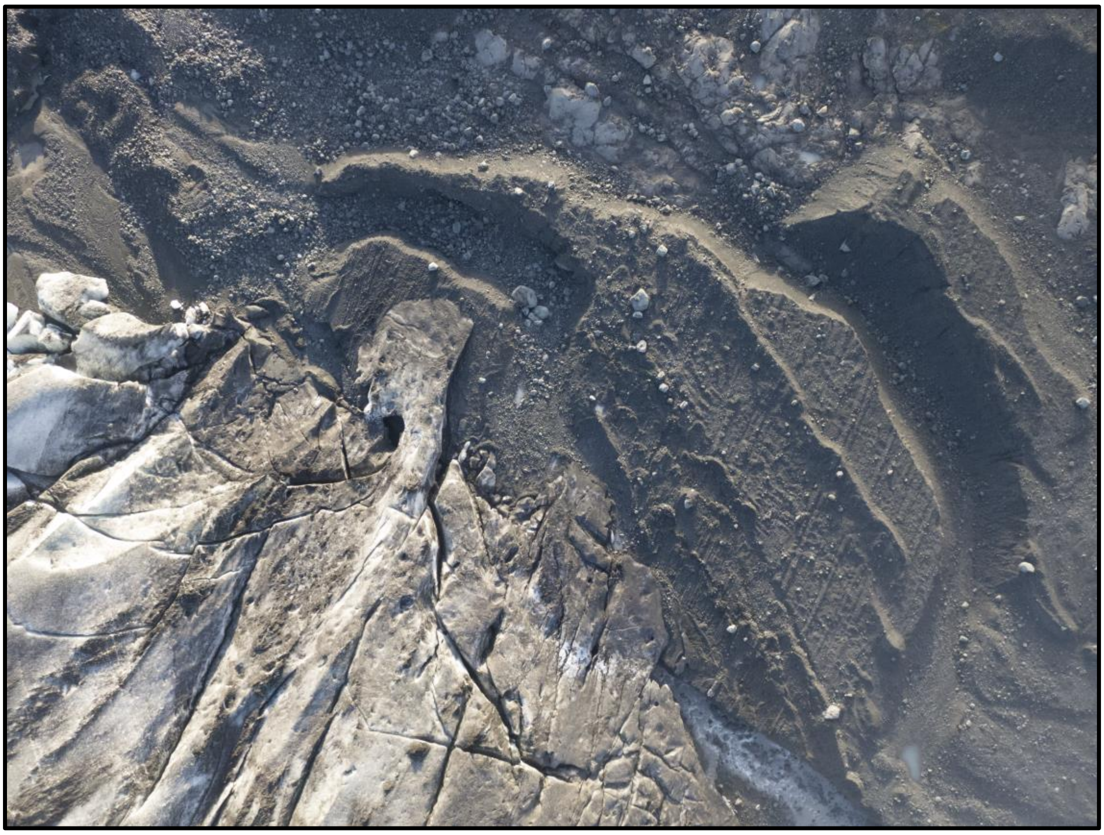


Figure 69: UAV photograph of ice marginal till displaying quantity of seed points within the environment. The mix of rock seed points and the boulder rich till is evident. Note though that few flutes have clear seed points within the image. Scale and north arrow excluded as photograph has not been photogrammetrically processed.

6.6.1.2 DEM resolution implications

Mapping was conducted using the DEM that has a spatial resolution of 0.04 m. It is feasible that the mapping was resolution limited resulting in poor characterisation of small scale features. This would distinctly disadvantage analysis of the results with respect to impact on *in situ* probe behaviour.

The DEM appeared to characterise bedrock areas clearly and there was no indication via imagery or noise in the DEM that smaller features were not resolved and so included in the results. Imagery did appear on some occasions to show smaller features distinguished by colouration, but there was no indication (e.g. shading) that the colouration was matched by a physical form. It would therefore seem that the flute mapping results are reliable.

On some occasions, the DEM of till covered areas appeared to struggle to resolve all features in that location. The imagery used to create the DEM used in this study was captured on the afternoon of the 1st September 2013, but a second survey was also undertaken at 06:00 on the 2nd September. This was not used due to cloud obscuring part of the survey but some areas imaged clearly demonstrate high levels of detail due to the particularly low sun angle. The low sun image demonstrates that there are more features present than those clearly characterised in the DEM. Evidently this is problematic, but it was considered during the mapping process. The decision was made that the basis for mapping should be consistent across the entire area studied and therefore as the morning survey was incomplete it would not be used.

6.6.1.3 Superimposed bedforms

Whilst mapping, it was important to determine the appropriate course of action when dealing with flutes across multiple scales. Frequently a clearly streamlined form is constructed of multiple distinct streamlined forms superimposed on a larger feature. This has been noted in a number of bedform studies (e.g. Rose, 1989, Stokes *et al*., 2013) but is not an aspect considered in previous studies of flute spacing.

Mapping at different scales was considered but dismissed as an option. It was initially hypothesised that flutes across the site existed on distinct scales. This could occur due to the legacy of previous advances with higher ice velocities. Alternatively, it might be that the process producing flutes differs from that producing larger bedforms like drumlins and so they can co-exist. If that had been the case then it might have enabled mapping of larger forms separate to smaller ones.

However on inspection of the area it appeared not to be the case and there appeared to be no clear scale division between different size features. The site unfortunately also lacked evidence of multiple ice directions that might have helped distinguish landforms of different scales as in Rose's (1989) study at Austre Okstindbreen where smaller flutes demonstrated 10-25° divergence from underlying MSGLs. Therefore, mapping larger and smaller was not likely to yield meaningful results.

The mapping strategy pursued in light of that discovery was to map the smallest resolvable flute in any particular location. This results in a more coherent mapping methodology. It also is pertinent to the aims of the chapter. Larger forms are interesting but if overlain by smaller forms they are less significant when considering flutes as a means to understanding deformation dynamics relating to probe movement. It is the till dynamics on the scale closest to the probes that is of interest.

6.6.1.4 Use of 'Generate Near Table' tool

Flute spacing was determined by the 'Generate Near Table' tool in ArcMap (10.2.2). It is important to recognise that this is different from the methodologies used by previous workers and provides a subtly different output. This is due to the way it replicates some inter-flute measurements and undertakes others at oblique angles.

Previously the most popular methodology has been to take spacing measurements via transects across areas of preserved foreland (Hoppe & Schytt, 1953; Baranowski, 1970; Shaw & Freschauf, 1973; Boulton, 1976). Evidently a straight transect measuring between peaks or troughs represents a reasonable choice in the field situation where perspective on the area is limited. From a remote sensing perspective, it becomes an awkward methodology to employ. The variable preservation of flutes and their occurrence in clusters with variable overlap between each flute means that transect location choice becomes important in dictating the results. It was considered that the transect methodology would have such an impact on the results in this location and reduce the number of flutes sampled that actually a different methodology, the Generate Near Table tool in ArcMap, was a better choice.

A more recent comparable method is that employed by Spagnolo in Stokes *et al* (2013) and Spagnolo *et al*. (2014) for measuring spacing of MSGLs. Stokes *et al* (2013) cites an in press publication by Spagnolo that was not available whilst writing, but some details are provided by the paper's methodology. It is similar in that it also employs a nearest neighbour style approach but there are a few key differences. The first is that the distance measurement is based on the MSGL mid-points whereas the approach in this study allows measurement between any point on the line. The results are also post-processed in a way that allows them to reflect the spacing of the MSGLs rather than the wavelength. This is achieved by initially calculating crest-to-crest distances but then subtracting half the width values of the MSGLs the measurement is taken for. Consequentially the spacing results produced are quite different in nature to the wavelength based results produced by previous studies. This could be seen to imply the authors consider individual MSGLs are formed uniquely rather than as part of a wider spatial continuum and gives greater significance to inter-feature erosion.

Figure 70 demonstrates the measurements that have been made for a small area of the mapping using the tool. These were then amended via use of trigonometry to produce distances orthogonal to the initial feature. It is important to note that results from Generate Near Table show the distance between any given feature and the nearest other feature. In some occasion where two features are isolated from others the same distance will be given for each feature.

The results reflect inter-flute spacing well, albeit better characterising the minima in flute spacing. In the context of this study where the interest is primarily in determining the possible impact of flute forming ice/till dynamics on *in situ* probe behaviour this is not problematic. The tool still provides the distance to the nearest flute and consequentially the manner of disturbance to down-ice flow.

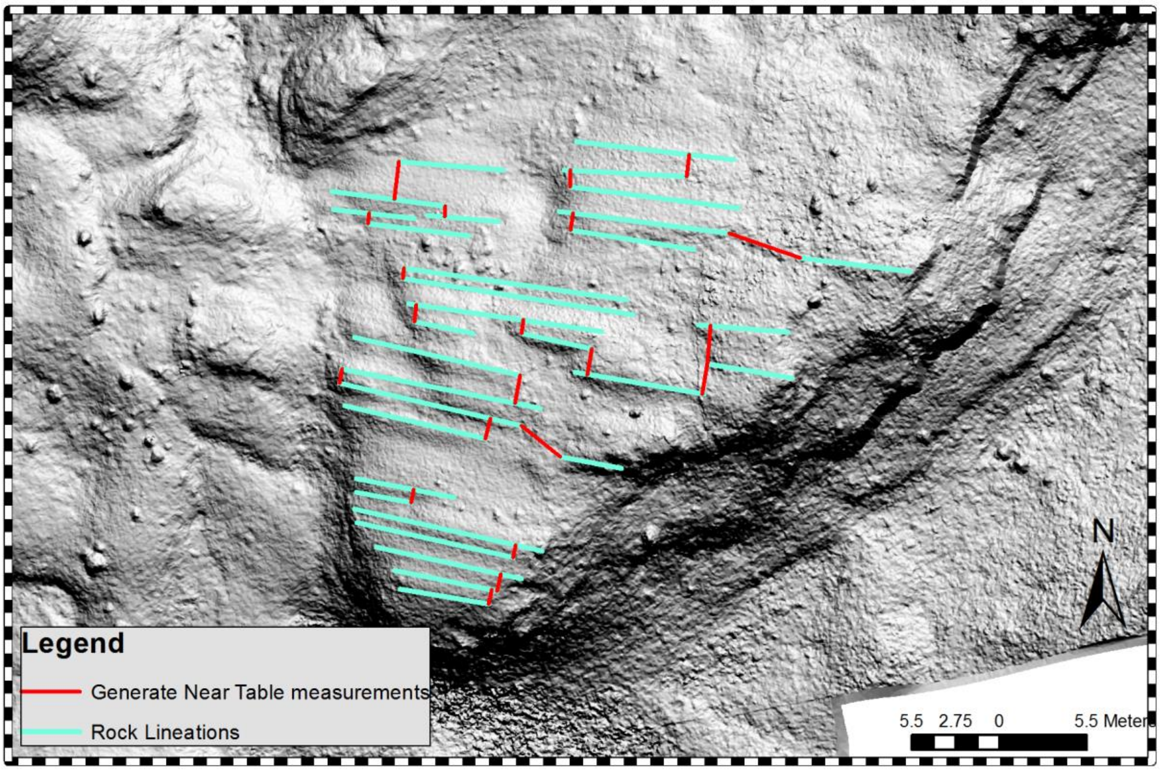


Figure 70: Hillshaded DEM illustrating how the Generate Near Table tool calculates distances between mapped features.

6.6.2 Wider limitations of this approach

The first assumption is that basal conditions at the Glacsweb site are similar to those that created the flutes at the margin. As stated in the introduction to this chapter, this is not thought to be problematic due to the marginal location of the Glacsweb site. However, when considering deep areas of the glacier the link would become increasingly tenuous. This assumption would benefit from additional evidence such as geotechnical characterisation the till at each site, but that is beyond the capability of this study.

Mapping all flutes may not be a suitable approach when attempting to illuminate subglacial processes. Chandler *et al.* (2016) mapped two different generations of flutes across the foreland that had different spacing, whereas here metrics are produced for all flutes. However, as this study is concerned with the minimum spacing distances the impact of this may be relatively small. In future studies separation of the generations would still be prudent.

A number of further issues with using the flutes as an analogue are created by the lack of field verification in this study. The primary issue is the inability to tell when flutes are drapes over underlying the bedrock. Another issue is the difficulty assessing preservation level. Fluvial incision is visible in some areas and will clearly have particularly impacted flute lengths.

Finally, the metric chosen are limited. Crest-to-crest spacing is a valid choice, but more complex metrics may have produced valuable insights. In this study the use of crest-to-crest spacing assumes that all areas in between are subject to deformation related to the genesis of the flute. This clearly may not be the case. A better approach would be to use the 3D form of each flute and map the extent of each individual feature. However, whilst the spatial resolution is high, vertical resolution is comparably poor and also variable or noisy due to the lighting. This prevents each flute visible being accurately mapped in any other way. More complicated approaches could be undertaken, but with a consequential fall in the sample size. A future study should certainly aim to obtain a higher resolution survey and attempt mapping of each flute along with the 3D form in order to better characterise the disturbance caused by their formation.

6.6.3 Flute metrics

Hypothesis 1 is accepted, as spacing of flutes mapped are both strongly unimodal and approach a log normal distribution. They are not actually log normally distributed, but neither is the data set mapped by Boulton (1976). This is considered in section 6.6.3.1.

6.6.3.1 Flute spacing distribution

The spacing of flutes mapped at Skalafellsjökull is strongly unimodal. The unimodal nature of the distribution is likely caused by the use of a nearest neighbour rather than transect based methodology. The distribution appears to be log-normal and this may be due to the random nature of the flute creation.

In studies that have employed transect based methodologies there appear to be a number of reasons that bimodal distributions of flute sizes may occur. Causal factors may include clustering, variable preservation, underlying scales of formation and mapping decisions. These factors are all present at Skalafellsjökull. An extensive discussion of how they could have impacted the results had a transect based methodology been employed can be found in Boulton (1976).

However, in studies that employ a nearest neighbour methodology it is highly improbable that anything other than a unimodal distribution will occur. Whereas a transect based methodology will always register less densely fluted areas as having higher spacing that may not be the case here. Because the methodology always selects the closest feature, regardless of whether it is replicating the value, it infrequently registers larger values.

Despite this disparity in the methods unimodal distributions are common in bedform spacing studies (e.g. Boulton, 1976; Clark *et* al., 2009; Fowler *et al.*¸2013; Hillier *et al.*, 2013; Stokes *et al*., 2013; Spagnolo *et al.,* 2014). Spagnolo *et al* (2014) suggests that many of them are log-normal distributions (e.g. Fowler *et al.*¸2013; Hillier *et al.*, 2013), an attribute mentioned in passing by Boulton (1976). The distribution produced in this study appears to conform to that model. Unsurprisingly it seems that the strength of conformity across all the studies is somewhat proportional to the sample size.

The tendency towards a log-normal distribution in bedforms is perhaps unsurprising as it appears frequently in natural phenomenon. It suggests that the conditions of growth (duration, occurrence, physical parameters) are random (Hillier *et al*., 2013). The possibility that this could be representative of glacial bedforms would appear to be strengthened by its appearance in multiple studies with different methodologies.

6.6.3.2 Implications for subglacial dynamics and probe behaviour

The key finding is that at 1-2 m the flute spacing is such that their formation can be expected to impinge significantly on probe behaviour. At approximately 0.15 m long, the probes are likely to be impacted by any lateral movement of till related to the flute formation. The extent to which this occurs and its timing will be dependent on the manner of flute genesis occurring.

Should an obstruction based genesis (e.g. Boulton, 1976; Morris & Morland, 1976; Clark *et al*., 2003; Roberson *et al*., 2011; Eyles *et al*., 2015) be dominant then the till can be expected to predominantly be deformed in a down ice direction but occasionally experience significant lateral disturbance due to the initiation or cessation of a flute. As flute lengths recorded in this study are unlikely to be representative of their subglacial extent, it is not possible to assess the probability of either of these situations occurring.

Alternatively, if the instability based genesis (Schoof & Clarke, 2008) is dominant then constant movement should be expected between the furrows and crests of the flutes. The magnitude of this flow is clearly unknown but the probes would seem to be ideally sized to detect it if present. Had the flute spacing been smaller, predominantly under 0.5 m perhaps, it would have been improbable that probe movement would have reflected any particular dynamic of probe movement than the general down-ice vector of movement. Equally had flute spacing been far larger than the probes then the lateral movement of till may have been imperceptible from the down ice vector.

Regardless of the manner of flute production, it would seem highly unlikely that simple down glacier motion of the probes will be ubiquitous, and the density of flutes suggests that it may not even be dominant. It seems more probable that subglacial deformation at Skalafellsjökull could be relatively turbulent at the scale of probe motion.

These suggestions of highly heterogeneous and dynamic subglacial conditions are supported by the previously known foreland characteristics (see section 6.2). The evidence for significant vertical and horizontal variations in deformation appears in many ways to be similar to the evidence from the flutes.

6.7 Conclusions

Using UAV collected aerial imagery a photogrammetric orthophoto and DEM were produced for the purposes of mapping. From this, 322 flutes were mapped.

Analysis of flute spacing via GIS tools demonstrated that the flute spacing distribution is approximately log-normal as stated by hypothesis 1. This mirrors findings in earlier studies (e.g. Boulton, 1976) and several recent studies of other bedforms (Clark *et al*., 2009; Hillier *et al*., 2013; Stokes *et al*., 2013; Spagnolo *et al*., 2014).

With flute spacing in the order of metres probe behaviour is likely to be influenced by flute genesis. An obstruction based flute genesis may result in significant lateral movement of the probe but only during initiation or cessation of the flute. This would mean only irregular influence based on flute lengths. If flutes are generated by some form of instability based genesis then they are likely to have a consistent impact on probe behaviour due to the constant lateral movement of till.

Chapter 7: *In situ* sensing of the subglacial environment

7.1 Introduction

The Glacsweb project has now run for close to 10 years. Over that time it has made a number of scientific breakthroughs and has evolved significantly. That evolution has seen major changes in the design of the probes and the distributed sensing network.

Whilst there have been developments in the range of sensors involved in the Glacsweb project, the most recent deployments of subglacial probes have been less successful than those at Briksdalsbreen. Neither the 2008 nor the 2012 deployment has produced concurrent subglacial data for probe movement and water pressure. The 2008 deployment probes successfully recorded water pressure but not tilt. The 2012 deployment recorded tilt but not water pressure. This prevents reproduction of the type of analysis undertaken by Hart *et al*. (2011) where till rheology is determined by consideration of the relationships between concurrent water pressure and tilt changes. Aside from the probes, dGPS encountered issues that made data impossible to process and geophones were installed but did not produce usable data.

Glacsweb's deployments have clearly demonstrated the difficulty involved in *in situ* sensing under glaciers. Producing wireless instruments capable of running on a low power system and communicating by radio from under close to 100 m of ice remains a non-trivial task. It is worth recognising that to date Glacsweb's achievements remain relatively unchallenged. The field of *in situ* sensing in glaciology has been quiet over the last decade and only one comparable project has been undertaken (Smeets *et al*., 2012) where data was predominantly transferred via wire rather than radio.

However, in light of the issues with the data availability, the purpose of this chapter is not to make any significant statements or concrete analysis. The data availability and fidelity is incomparable to the geotechnical results. Instead, it provides context for the findings of chapter 4 and 5, informs more generally about the subglacial environment at Skalafellsjökull, provides the basis for hypothesising about it and helps refine the direction of future more successful *in situ* deployments.

The most extensive data set from the 2008 and 2012 deployments is dGPS recordings of surface velocities. These provide clear evidence for temporal variability in ice velocities popularly referred to as 'stick-slip' motion. If these are the result of variations in subglacial deformation then it follows that there will be similar variations in subglacial probe water pressure and movement data.

The consistently variable surface velocities suggest that although subglacial water pressure and movement data were not collected simultaneously it is unlikely water pressure data was collected in a period when ice velocities were not variable.

With this understanding, the water pressures and tilt data are analysed in isolation for evidence of 'stick-slip motion'. For water pressures that is expected to be in the form of temporal variability on a similar scale to that of the dGPS data. For probe data, it is again expected that temporal variability might be similar but also that up glacier movements might occur as have been recorded in numerous other experiments and linked to ice-bed decoupling and stick-slip motion (section 2.3.1.3).

Alongside this analysis, the chapter provides context for the geotechnical testing presented in later chapters. Data from the subglacial probes, GPR (Ground Penetrating Radar) surveys and dGPS provide subglacial water pressures, ice thickness and surface velocities that can be compared to the conditions used in testing. All of these findings are then later interpreted in the discussion to consider whether the rheology can be considered consistent across the geotechnical and *in situ* findings.

7.2 Aims

Within the limitations of the data available, this chapter addresses aims 1-3 of the thesis:

1. To establish if the rheology of the till at Skalafellsjökull is consistent across the different modes of investigation.
2. To assess how pore pressure variations impact the behaviour of till samples in geotechnical experimentation, and to what extent the variations and behaviour is replicated at Skalafellsjökull (as observed by the *in situ* study).
3. To determine whether Skalafellsjökull moves in a 'stick-slip' manner and to what extent this can be explained by subglacial conditions.

In doing so, it characterises the glacial environment at the test site, identifying the main influences on glacial movement there, and provides valuable context for the findings of the geotechnical study. These aims are addressed using data from the 2008 and 2012 Glacsweb deployments. Further to these core aims, it provides an outline of the 2012 deployment, identifies issues and suggests possible alterations to future projects.

7.3 Methods

Due to the complexity of the Glacsweb project some aspects will not be included in the thesis. Technological details of the deployments mentioned are available in separate publications (Martinez *et al.,* 2009; Martinez *et al.,* 2012). Here a general overview of the deployments is given alongside specific details on the progression in the Glacsweb system and specifics of the probe and dGPS deployment.

As detailed in chapter 3 the Glacsweb site is situated on the southern edge of Skalafellsjökull at approximately 800 m altitude. Sensors and dGPS have been deployed over a small area relatively close to the ice margin (see Figure 11 & Figure 76). The general infrastructure of the sensor deployment is outlined by the system schematic Figure 71.

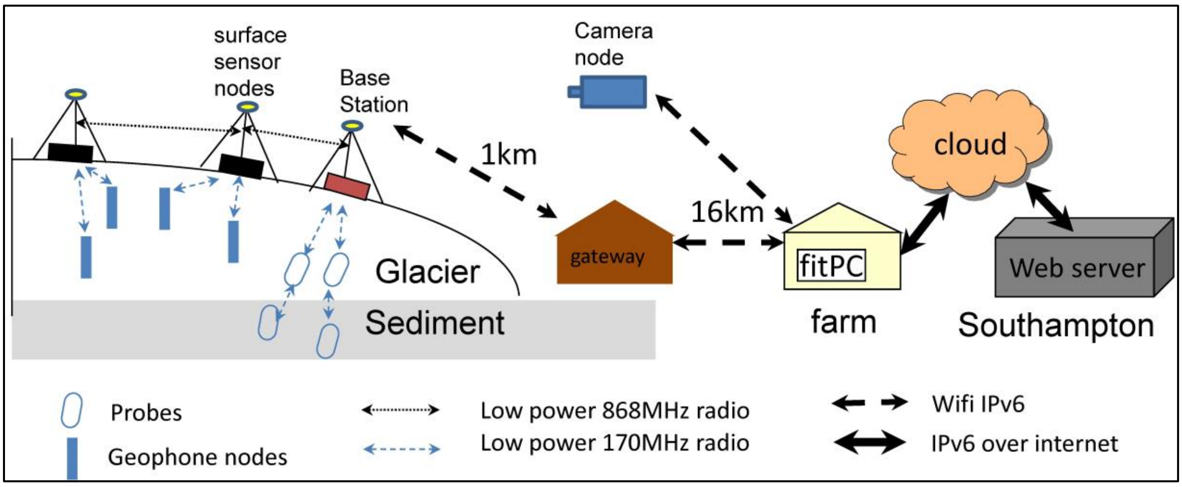


Figure 71: The Glacsweb system at Skalafellsjökull (Martinez, 2014)

7.3.1 Overview of deployments

Three deployments were attempted from 2008-2012 with varying levels of success. Each deployment had slightly different aims and the progression between deployments was characterised by increasing complexity. The technology used became more advanced and the network of instruments deployment increased in its extent.

The first deployment in 2008 is covered briefly here but more extensively in existing publications (Hart *et al*., 2011; Martinez *et al.,* 2009; Martinez *et al.,* 2012). It involved deployment of relatively simple probes, slightly updated from the Briksdalsbreen deployments, but unfortunately without functioning tilt meters. A single dGPS was located on the ice and initial GPR surveys were conducted.

A second deployment was attempted in 2011. This was unsuccessful. It became apparent the probes would not be able to be deployed and the extent of the data collation was retrieval of dGPS data and extension of the GPR survey.

The August 2012 deployment was the first I was involved in. It involved the successful deployment of probes, extension of the GPR survey and the placement of four additional dGPS on the ice surface and one on the lateral moraine as a control. Geophones were also deployed, but the data has not yet been successfully processed. This was likely due to inadequate closure of the boreholes around them, and so they are not included here aside from in figures that indicate their location.

After the 2012 deployment no further deployments were made. However, due to issues with the automated data retrieval systems four further trips were made in September 2012, June 2013, August 2013 and September 2013. These were primarily to collect data but also involved maintenance of the dGPS and the probe base station.

7.3.2 Glacsweb system

The probe design has changed in each Glacsweb deployment, but some aspects remain consistent. Probes are between 0.1 and 0.2 m in length, are made of plastic, run on low power processors and transmit data via radios. They have all also had sensors for tilt, water pressure, conductivity, temperature and case stress. However, in each deployment changes have been made to the probes that have impacted the results.

One constant through each installation is the manner of deployment. Boreholes were drilled through the glacier with hot water drill made from a modified Karcher HDS1000DE hot water jet wash. Drilling proceeds at approximately 150 m/hr and so it would take just over 30 minutes to reach the glacier’s base at Skalafellsjökull. The hole produced is approximately 0.15 m in diameter providing sufficient room for a probe. If a borehole is accidently drilled into an englacial cavity or channel it is usually obvious due to rapid drainage. For added assurance, a custom video camera is used to inspect the bottom of boreholes before probes are deployed.

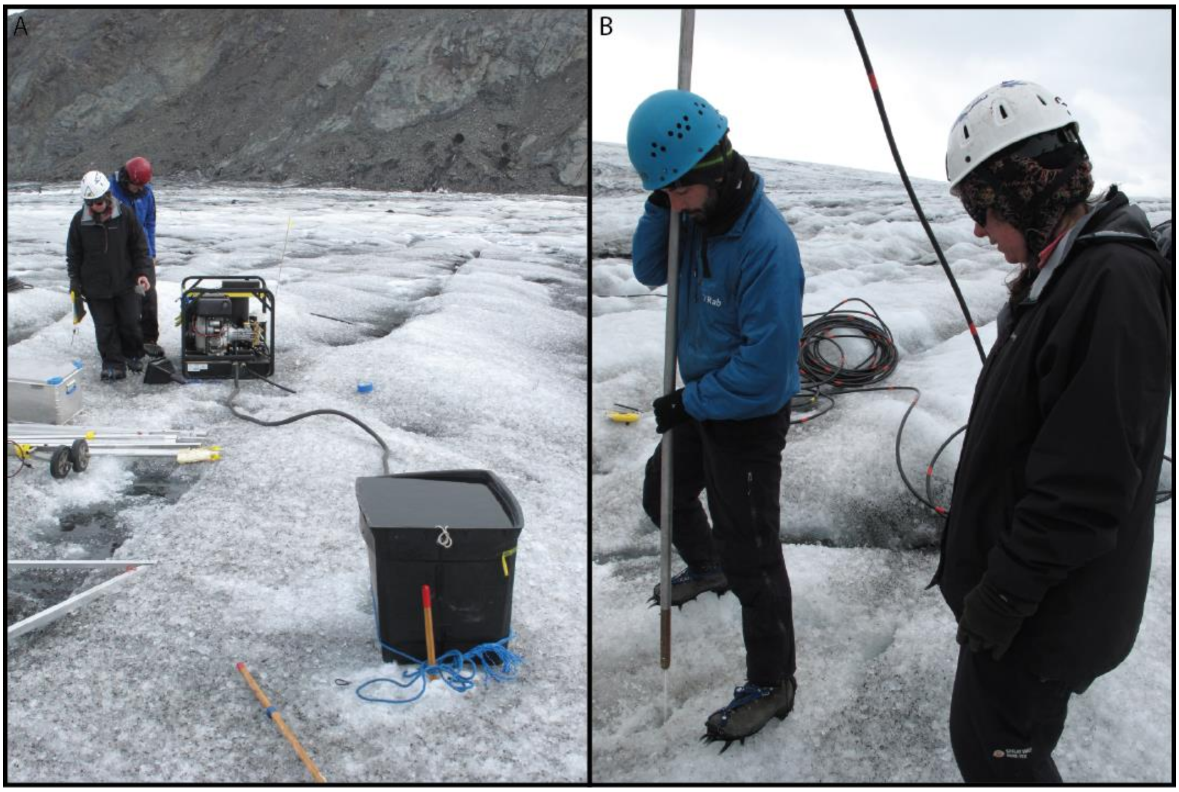


Figure 72: A) The Karcher jetwash with water supply. B) Initiation of a new borehole with the hot water drill.

With the switch to Skalafellsjökull, a number of changes have been made to the system and probes. Some have come through improvements in the technology available and others have been enforced due to the different nature of the glacier. Perhaps the most significant design change has been evolution in the data transmission and the use of probe relays. Skalafellsjökull is significantly larger than Briksdalsbreen and provides an opportunity to progress probe deployments to increasing depths with time. This is unfeasible whilst relying on a simple link between the probes and a surface base station due to radio range limitations caused by water within the glacier. To circumnavigate this issue the probes deployed at Skalafellsjökull are programmed to be able to communicate with the surface base station via other probes (Padhy *et al*., 2010). This ability to 'hop' data to the surface provides much greater flexibility and to a degree counters the issues communicating long distances through wet ice.

The structure of the network and links used has also changed. Four different frequencies are used for data transmission. The selection of each frequency is made on a balance of range, power requirement, the size of data being transmitted and availability. A higher frequency permits faster transfer of data but has a poorer range than a lower frequency transmission.

The probes use the longest wavelength with a 170 MHz link to the base station. This provides the best range through the ice and is suitable for the relatively small amounts of data transmitted. The geophone surface network is then run on a slightly higher 868 MHz link. The geophones have a better power supply and do not communicate through ice, so the higher frequency is advantageous. From the base station data is transmitted to the café 1 km away and then onto a farm 17 km away. This is done via a 2.4GHz Wi-Fi link. The power demands are less significant due to wind and solar generation options on the base station and generator power availability at the café for the majority of the year. The higher frequency link means that transmission of the larger GPS data files (4 Mb/day) alongside the probe and geophone data is achieved efficiently. As an additional safeguard, if the Wi-Fi connection is not available the base station defaults to a 3G connection. As the 17 km link between the farm and café can be intermittent so this helps provide data continuity.

7.3.3 2008 Probe Installation

During the 2008 field season 7 probes were deployed. Detailed information about the probe technology is available in Martinez *et* al., (2009). Of the 7 deployed 4 survived >12 months and 2 survived >18 months (hence, some references to probe data from as late as 2010 below). Unfortunately, none of the probes produced tilt data due to failure of the accelerometers after deployment.

7.3.4 2012 Probe Installation

Four probes were deployed in 2012, probes 31-34 (see Figure 11 & Figure 73). Probe 34 unfortunately failed shortly after deployment. Probe 33 functioned correctly but became jammed in the borehole and did not reach the subglacial zone. Probes 31 and 32 were successful in reaching the subglacial zone and functioned largely correctly. However, unfortunately neither produced water pressure data due to a fault with the connection occurring after pre-deployment testing.

Data was retrieved via manual intervention during subsequent trips in August 2013 due to issues with automatic data retrieval. Unfortunately attempting sizeable downloads irregularly meant the recovery of less data than would be possible via the automatic method. Consequentially the data coverage from 2012 onwards is limited and only covers Autumn/Winter 2012.

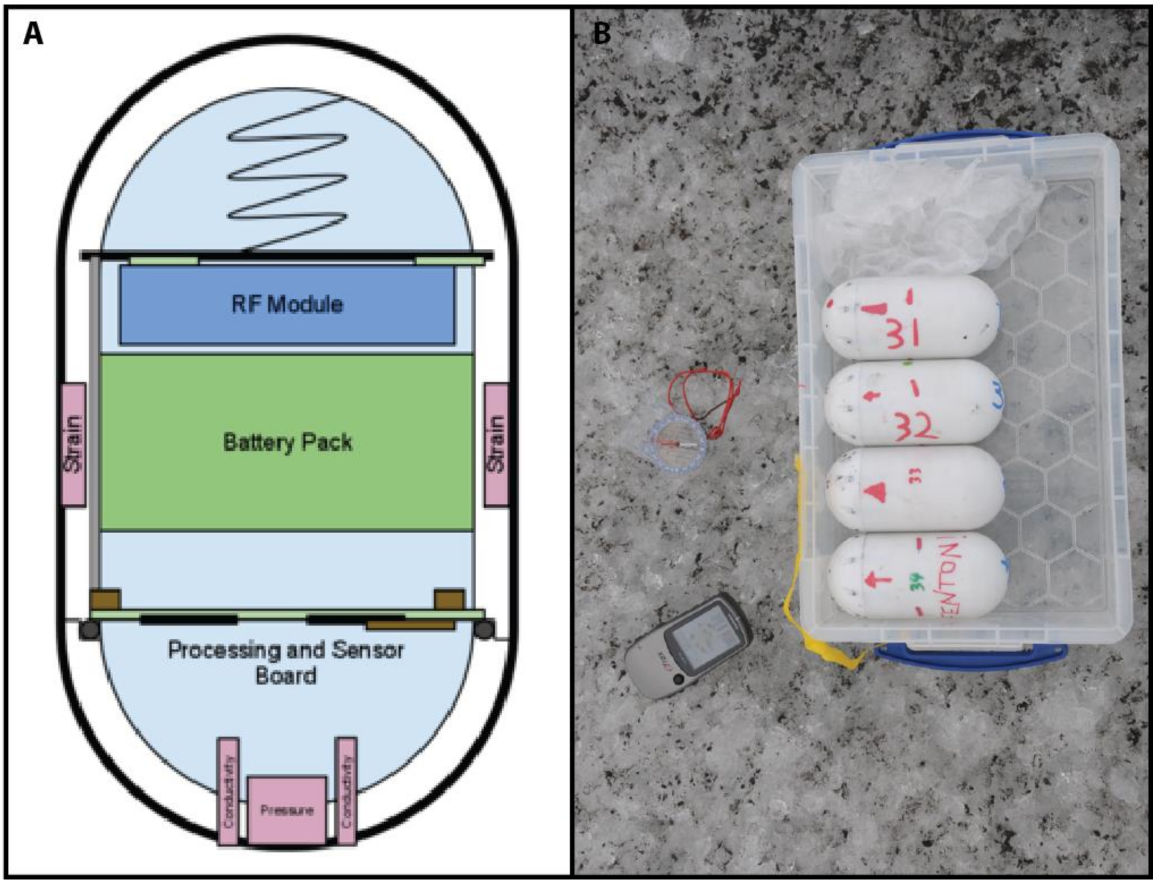


Figure 73: A) Schematic of 2008/2012 probe design. B) 2012 Probes ready for deployment.

7.3.5 dGPS

To determine the surface velocity at the Glacsweb site dGPS were used throughout both deployments. All units were used in static logging modes and the data post processed after retrieval into hourly and daily positions with TRACK (v. 1.24) (http://www.unavco.org/, http://geoweb.mit.edu/~tah/track_example/). The reference station at Höfn was throughout, a baseline of approximate 30 km.

Data has been processed for individual fixes on an hour-by-hour basis and then velocities derived from those points. No vertical data is present due to the additional complexities of estimating uplift separately to down glacier progress. Similarly, although the pattern of movement is not a simple down glacier vector, each fix has been used in the production of velocities, rather than just the down glacier movement. This may mean error due to pyramid movement is included but a secure correction of this is non-trivial and beyond the scope of this work. In both cases the additional processing is an obvious extension of this work.

7.3.5.1 2008 Installation

In 2008 two Topcon dGPS were deployed. One was located on the roof of the café and used as a control, the other was attached to the base station on the ice (labelled 'Base Station' in figures). The Topcon design enabled interface between the dGPS and the Glacsweb system. This allowed files to be retrieved and scheduling to be managed remotely. Both antennae were set to record for 2 hours each afternoon. The recording length was determined as a compromise between power demands and positional quality.

The installation at the café proved problematic. The exposed position of the building required the antenna to be installed in a moderately sheltered position to avoid damage during the winter. This resulted in multi-pathing errors that on occasion prevent successful processing. Base station scheduling also resulted in recording between the antennae frequently being non-synchronous and shorter than planned. Consequentially, from 2008-2011 dGPS data could only be resolved on a maximum of a monthly scale.

7.3.5.2 2012 Installation

In 2012 a number of additional dGPS were installed alongside the existing units deployed in 2008. They constituted four Leica 1200 units loaned from the NERC GEF facility. Unlike the Topcon units, they could not be integrated into the Glacsweb network due to hardware limitations. Instead, the units operated as static loggers and data was recovered during summer trips.

Four of the units were deployed on the glacier and the fifth on the moraine. The moraine based dGPS was used to provide additional short base line reference alongside the existing more distant unit on the café. Figure 76 shows the lay out of the dGPS. The dGPS were initially set to record constantly through the summer and batteries were recharged on a subsequent trip at the end of the season. This permitted hourly velocities to be processed through this period (see Figure 82). Thereafter they were set to log for 2 hours at 14:00 each day. Power was provided by 9 external batteries housed in cases that also contained the loggers (see Figure 75). Three solar panels attached to the pyramids provided supplementary power until early autumn when they were quickly covered by snow.

Deployment of ice based dGPS requires careful consideration. The high annual ablation rates of >3 m/a mean that recording only the glacial velocity is non-trivial. One method is to mount the dGPS antenna on a pole that is drilled into the ice. This was tested from 2011-12 but due to the ablation rate it was not found to provide a stable platform. Instead aluminium pyramids were constructed which formed a relatively stable platform for the dGPS (see Figure 74).

Tilting of the pyramids remains an unquantified issue, as clearly it will result in the movement of the antenna. Tilting might occur due to differential ablation across the ice on which the pyramid rests or via snow pack shear in the winter. The former is managed to some degree by the deliberate selection of flat areas of ice away from existing supraglacial streams. However, tilting is an inevitable outcome of differential ablation caused by the shading of the ice by the battery case. The data shows a range of sudden lateral movements and it is thought that these are likely artefacts caused by tilting.

Alongside problems with ablation, issues were also encountered with accumulation during the winter. The exact amount of snow accumulation is unknown but it exceeded the height of all pyramids. Shear of the sizeable snow pack resulted in damage to all pyramids (see Figure 74) and water flow through it due to ablation and precipitation damaged some equipment. In the winter of 2012/13 and 2013/14 recordings were not managed past January although it is not clear whether that was due snow covering the antenna, power running out or water damage.

After initial deployment in August 2012, the units were revisited in August 2013 and data was recovered from all units. One GPS power supply (GEF 4) was found to be damaged irreparably due to water ingress (see Figure 75) and GEF3's pyramid has been destroyed. GEF3's power supply was transferred to GEF4 and all power supplies were recharged with a generator.

Figure 74: A) GEF9 dGPS pyramid with power supply and solar panels. Solar panels were attached in an upright position for the winter period. B) Recovery of GEF3 after 12 months. Pyramid destroyed by falling into a crevasse and thick snow. C) GEF10 after 12 months. Some damage due to snow shear and meltwater re-freeze.

Figure 75: A) Water intrusion into GEF4's power supply after 12 months. B) Damage to the power controller.

7.4 Results

7.4.1 dGPS

5 dGPS were deployed on the glacier from August 2012 – September 2013 (see Figure 76-Figure 80 note that all data is plotted, so gaps in coverage are present). Availability varied (see Table 9) with some lasting further into the winter either due to surviving better or generating more power from their solar panels. The Base Station only provided annual velocities collected on subsequent trips due to intermittent data recording problems. Ice velocities determined by the dGPS vary with ice depth. Surface velocity determined from daily dGPS positions shows relatively little variability (Figure 81). Surface velocity determined from hourly dGPS positions is highly variable displaying a diurnal pattern (see Figure 82 and Figure 83).

Table 9: dGPS availability. Green means full availability, orange partial availability and red no availability.

	Aug-12	Sep-12	Oct-12	Nov-12	Dec-12	Jan-13	Feb-13	Mar-13	Apr-13	May-13	Jun-13	Jul-13	Aug-13	Sep-13
GEF3														
GEF4														
GEF9														
GEF10														

Table 10: Annual velocities of dGPS deployed on Skalafellsjökull. Aside from GEF3 the velocities are an average of recordings over the season. GEF3 only has data for the winter of 2012 so is an extrapolation from that.

	2008/9	2009/10	2010/11	2011/12	2012/13
Base Station	3.96 m	2.96 m	2.87 m		3.34 m
GEF10					11.89 m
GEF4					9.96 m
GEF9					13.17 m
GEF3					42.00 m

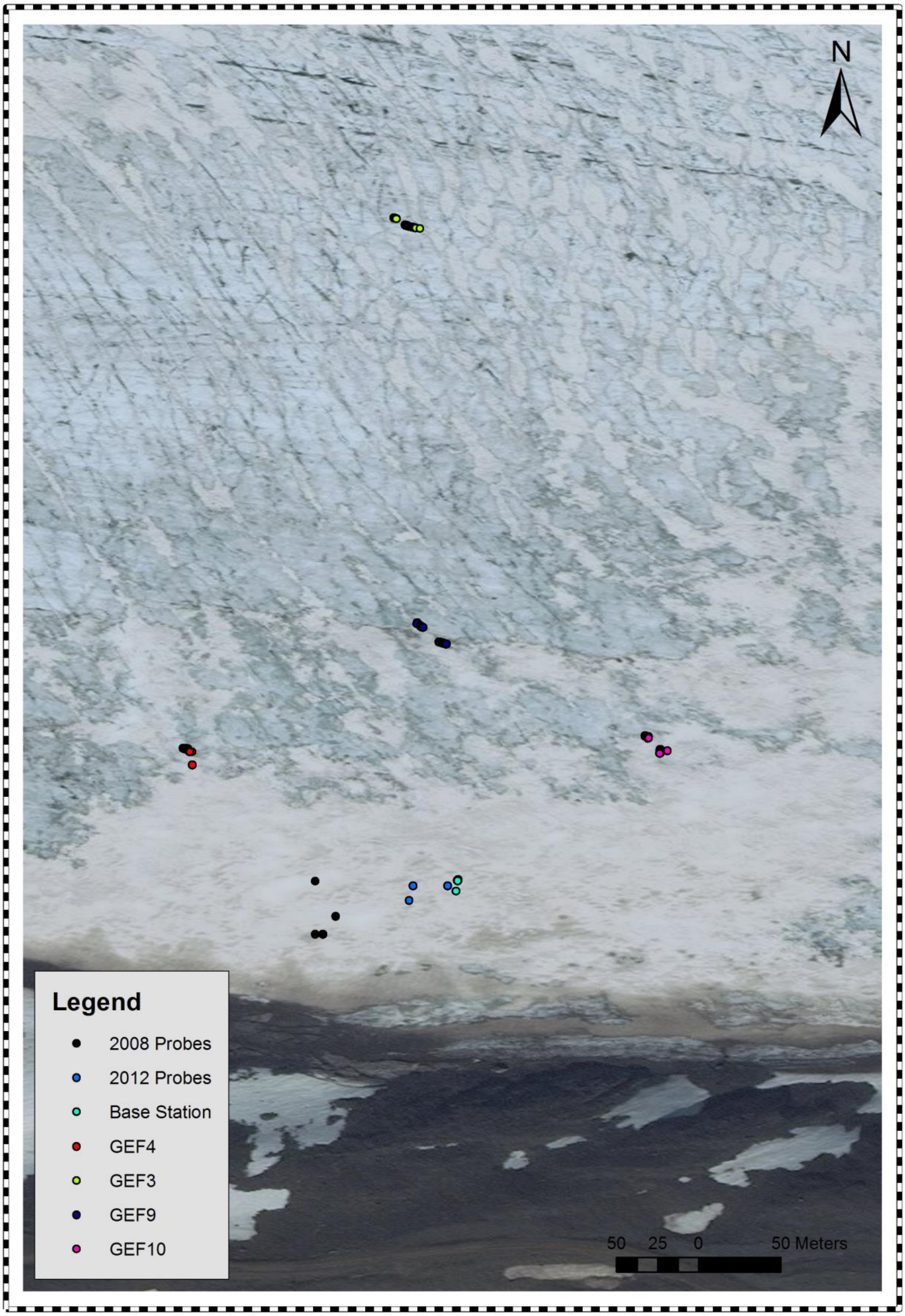


Figure 76: Layout of dGPS and probes deployed on Skalafellsjökull, including general movement patterns of dGPS. See Figure 12 for contextual view of site. Subsequent figures show enlargements of individual dGPS unit results. Gaps in winter coverage are particularly obvious on GEF4, GEF9 and GEF10.

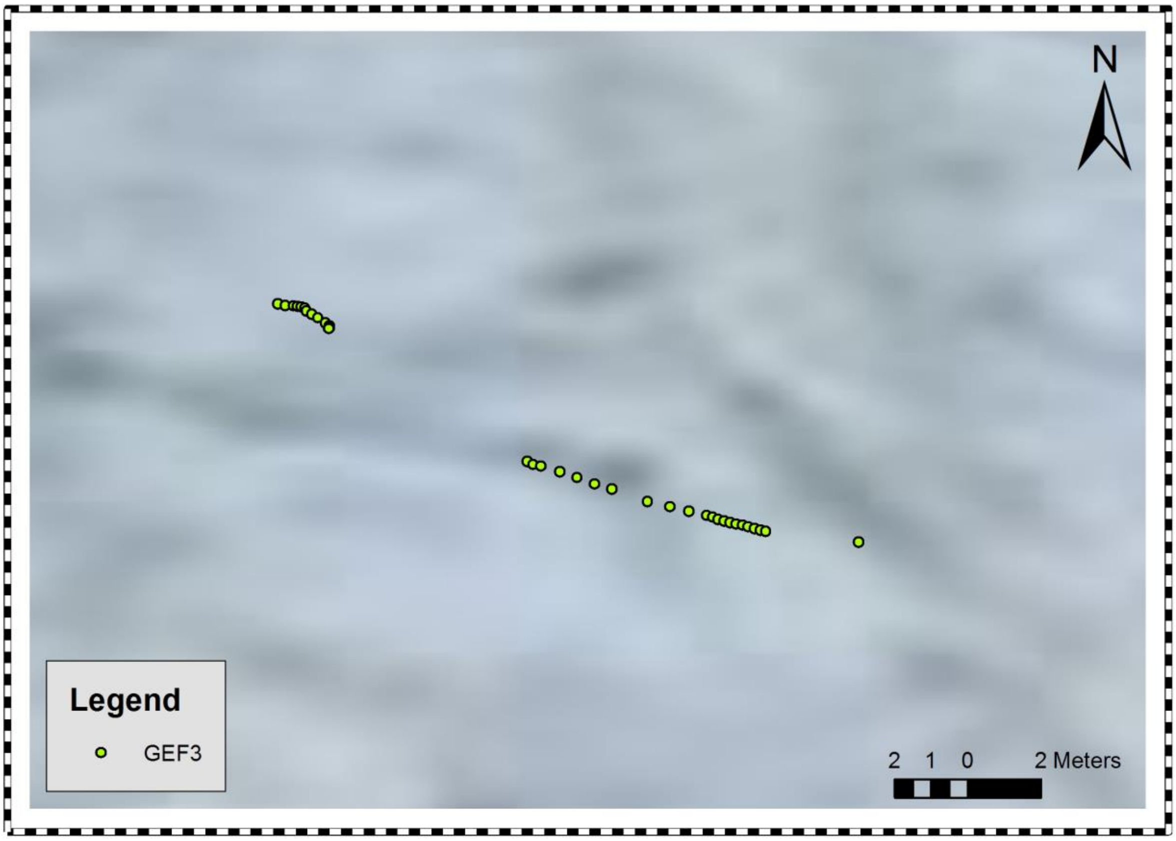


Figure 77: GEF3 daily fixes for availability in 2012 as per Table 10 (enlarged from Figure 76).

Figure 78: GEF4 Daily fixes for availability in 2012/13 as per Table 10 (enlarged from Figure 76).

Figure 79: GEF9 daily fixes for availability in 2012/13 as per Table 10 (enlarged from Figure 76).

Figure 80: GEF10 daily fixes for availability in 2012/13 as per Table 10 (enlarged from Figure 76).

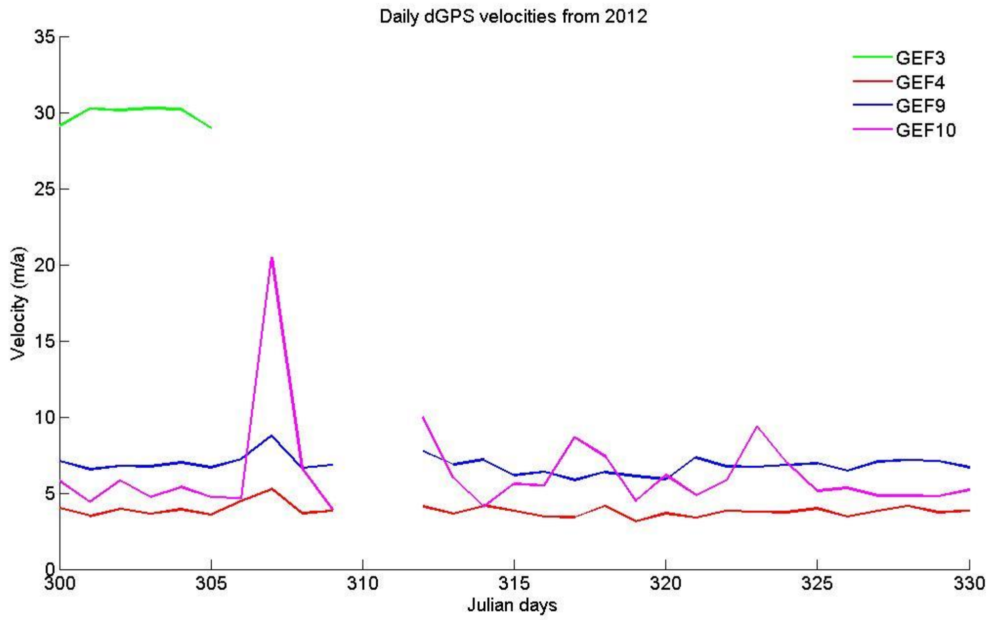


Figure 81: Daily velocities from dGPS.

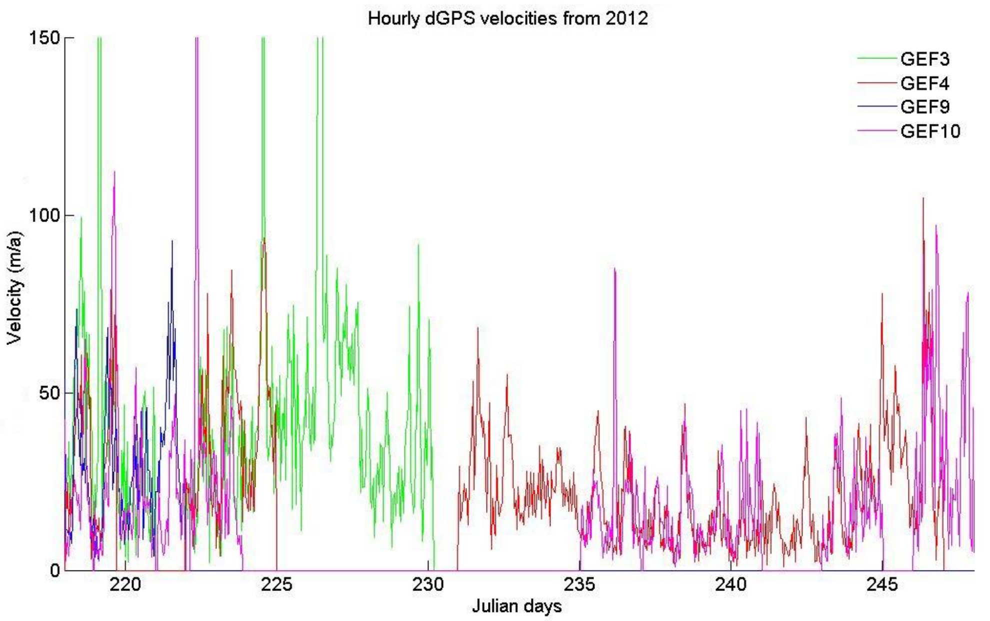


Figure 82: Hourly dGPS velocities for days 218-250.

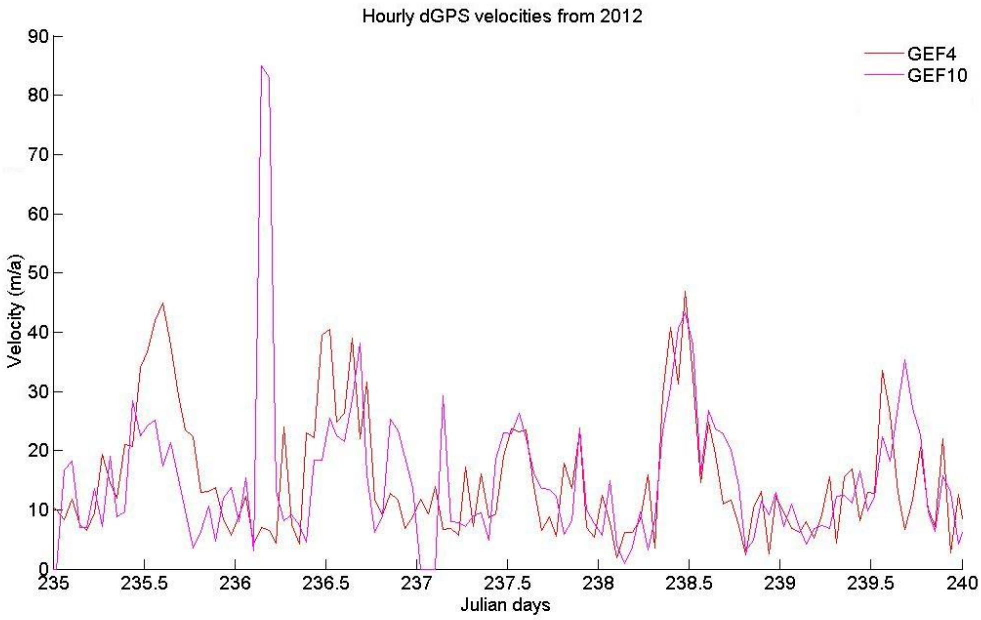


Figure 83: Hourly velocities from day 235-240 demonstrating peak velocities repeatedly occurring during the afternoon.

7.4.2 Probe data

Figure 84: Location of probes deployed in 2008 and 2012

7.4.2.1 Water Pressure Data (2008)

Water pressure data is available sporadically from four probes during 2008 and 2010 (Figure 85). The lack of continuity reflects data having to be retrieved from the base station manually due to the automated process not functioning. Pressure variability differs between the probes. In addition to this data, during a 2013 field season bore holes drilled in 2012 were found to all be approximately 80% full suggesting the bed there was behaving similarly to probe 21. Comparatively, water was never seen at that level within moulins or crevasses within the same area. This observation has been corroborated by GPR suggesting minimal amounts of water are stored within the ice (Hart *et al*., 2015).

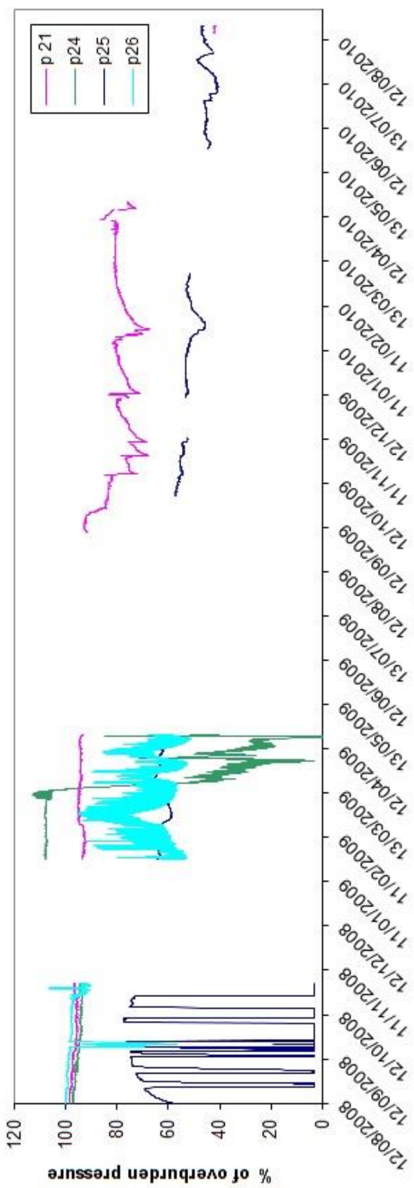
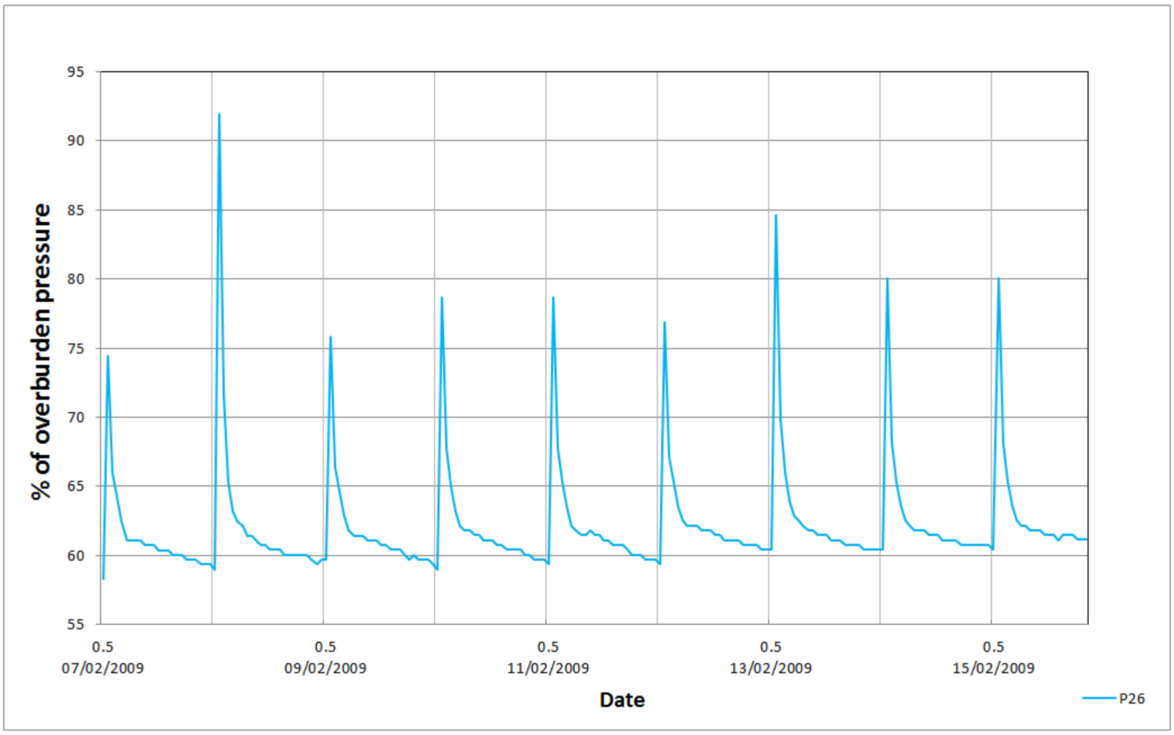


Figure 85: Pore pressure data from probes deployed in 2008.

All probes experience pressure fluctuations, but the magnitude varies. P26 records a diurnal signal from 27/01/2009 – 21/04/2009 with a sharp jump in pressure, in the order of 100-200 kPa, at 13:00 every day. The pressure then dissipates, primarily within the hour, and then gradually over the following 22 hours. This could be demonstrating classic connectivity to a meltwater fed system. However, the regularity of the input raises suspicions that the signal may instead be related to the probe's radio which turns on at 13:00 every day.



Other probes experience more sedate changes. Probe 25 experiences gradual changes, for instance from 26/02/2009 – 20/03/2009 there is a steady increase in pressure of approximately 90 kPa. Probe 21 experiences similarly steady rises, for instance approximately 70 kPa from 09/11/2009 – 12/12/2009. However, these steady rises are terminated by a sharp fall in pressure of a similar magnitude.

7.4.2.2 Tilt data (2012)

Tilt data is available for approximately day 220-330 (see Figure 86 and Figure 87). Because of the manner in which data is transmitted there are occasionally non-coherent gaps between x and y tilt. Both probes tilt by similar amounts over the recording period and probe 31 displays some up glacier oscillations between from day 310-330.

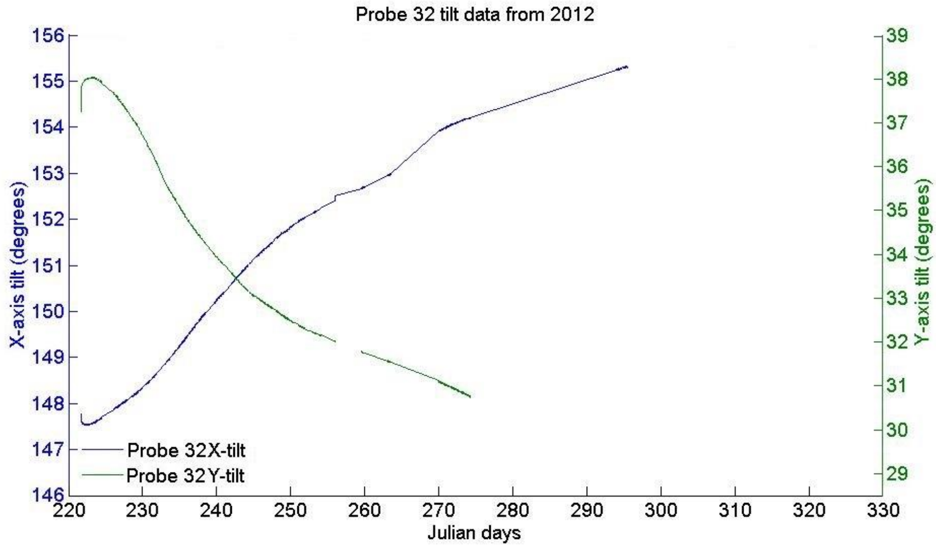


Figure 86: Tilt data for probe 32 during 2012.

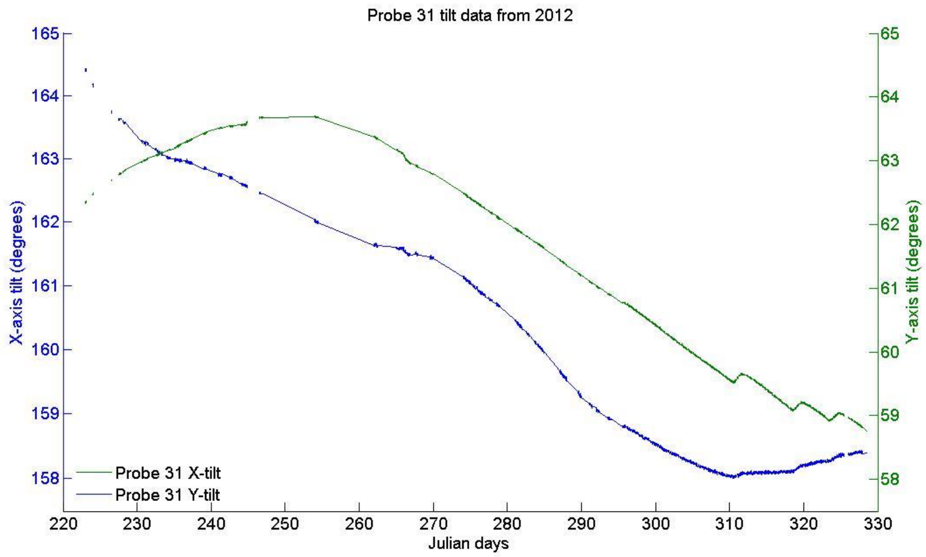


Figure 87: Tilt data for probe 31 during 2012.

7.4.3 GPR Survey

GPR has been used to survey the site during trips in 2008, 2012, 2013 and 2014. Results are available in Hart *et al*. (2015). For the purposes of this study only ice depths are required from the survey (see Table 11).

Table 11: Ice thickness at probe and dGPS sites when first deployed.

Site	Ice Depth	Year Measured
GEF3	185	2012
GEF9	126	2012
GEF4	105	2012
GEF10	96	2012
Base Station	54	2012
Probe 21	58	2008
Probe 24	57	2008
Probe 25	59	2008
Probe 26	73	2008

7.5 Discussion

The results present a complicated view of glacial motion and the subglacial environment at Skalafellsjökull. dGPS and water pressure data is discussed in turn with reference to specific behaviour and general patterns. The behaviour of the site more is then discussed more widely.

7.5.1 Glacial motion

7.5.1.1 dGPS data

Hourly dGPS data has a high temporal variability (Figure 82 & Figure 83). This suggests that Skalafellsjökull moves in a ‘stick-slip’ manner comparable to other studies (e.g. Fischer & Clarke, 1997; Bindschadler *et al*., 2003; Roberts & Hart, 2005), although the actual cause is not apparent from the data alone. At a daily resolution ice velocity is relatively stable and proportional to ice thickness as might be expected.

The diurnal nature of the velocity variations is suggestive of a link between surface velocity and meltwater delivery to the bed. This matches observations elsewhere (Zwally *et al*., 2002) and suggests that to some degree coupling between subglacial hydrology and movement occurs.

The manner in which the dGPS were deployed did cause some concern that their movement might be dominated by surface melt in the summer and then snow shear in the winter (see section 7.3.5.2). Movement patterns (Figure 76-Figure 80) are largely consistent, with the occasional erratic data point. Without further analysis, this would seem to suggest that they are characterising the ice movement well but occasionally subject to interference. Further processing and removal of the non-glacial signal would be ideal.

7.5.1.2 Probe water pressure data

Probe data from the 2008 deployment is the primary source of data about subglacial water pressures at Skalafellsjökull, but there are a number of others that should also be considered. GPR data suggests that there is very little water stored within the glacier (Hart *et al.*, 2015), water levels in moulins and crevasses has always appeared to be low and contrastingly the water levels in several boreholes has remained consistent and high after drilling. Combined, these data sources build an impression of a subglacial environment that varies spatially between regions of high and consistent water pressures and other areas of relatively low but temporally dynamic. From the data available this does not appear to be a system where ice velocity is dictated consistently by simple surface water inputs modulating till strength.

7.5.1.2.1 Spatial heterogeneity

The water pressure data from the 2008 deployment is the primary data source from the Skalafellsjökull deployments (see Figure 85). The probes demonstrate high initial values. This is consistent with the pressure head of the water filled borehole. These initial values eventually fall. This adjustment to a lower and usually variable pressure appears to signify coupling with the subglacial environment. There are a number of points of interest there.

Firstly, the time taken to match the subglacial environment is highly variable and perhaps much longer than might be anticipated. Probe 25 appears to immediately couple with the subglacial water pressure but the other probes take much longer. Probe 26 takes just under 3 months, probe 24 takes 7 months and probe 21 takes 13 months. Presuming that the water within the borehole produces greater pressure than would usually be experienced by the till, coupling to the natural subglacial pressures must require that influence to be removed. That may either be because the borehole closes due to ice creep or because the pressure head diffuses into the surrounding till. This poses an intriguing question: how does the probe 21's borehole maintain pressures close to ice overburden for 13 months when post-coupling data suggests that the natural pressures are closer to 80%? It is a situation that seems compatible only with very low hydraulic conductivity till suggesting that coupling and subsequent changes in pore pressures might be dependent on mechanical reorganisations of the environment around the probe.

Secondly, after coupling with the subglacial environment the manner in which pore pressures changes differs. Probe 24 and probe 26 display highly variable pore pressures whereas probes 21 and 25 have much more consistent pressures. This is most likely due to variable proximity to meltwater channels and so differing impacts of diurnal melting. The relative stability of probes 21 and 24 may again suggest that hydraulic conductivity of the till is very low.

Thirdly, the behaviour of probe 21 is unusual. It builds slowly in pressure over a time scale varying from weeks to months followed by sharp falls over a matter of hours to a base level at around 70% of overburden. The periodicity is not dissimilar from the periodicity of the underlying trends of probes 24 and 26 but the falls are much sharper. It is also difficult to reconcile why if the gradual changes of probes 21 and 25 signify distance from meltwater inputs they do not both behave similarly.

Fourthly, the difference in average pressures between the probes again suggests spatial variability within the system. As aspect is similar across the ice surface ablation and water inputs would not be expected to vary much spatially. Therefore, it might be expected that subglacial water pressure might be relatively similar across the site. However, each probe appears to maintain (or oscillate around) quite distinct water pressures. As the pressure transducers have a linear response this is unlikely to be instrumentation error and so must reflect actual spatial heterogeneity. Particularly interesting in this regard is the pressure difference maintained between probes 24 and 25 considering their proximity. The lack of coherence must suggest, again, a low hydraulic conductivity.

In summary, the data is suggestive of a system with high heterogeneity and till with low hydraulic conductivity. Some areas are well coupled to very dynamic water inputs but other areas are isolated and relatively stable. This heterogeneity is maintained over small baselines and boreholes took extensive periods to adjust to the background pore pressures, both suggesting low hydraulic conductivity.

These assertions are further supported by other more qualitative observations. At no point over the approximately 2 months of fieldwork on the Skalafellsjökull has there been an observation of high water levels within moulins or crevasses. This matches findings from the GPR surveys. The radar return from the ice suggests that water storage is minimal (Hart *et al.*, 2015). Contrastingly, two of the boreholes drilled in 2012 were found again in August 2013 and found to both be 80% full of water.

7.5.1.2.2 Stick-slip signal

The dGPS data demonstrates stick-slip behaviour, but if Probe 26 is discounted as erroneous, no probes have collected comparable data. Changes in water pressure are steady, and usually occur on a timescale of weeks. This is clearly different to the strong diurnal signal present in the dGPS data.

As well as lacking a diurnal signal, the probe data does not appear to conform to Zwally effect (Zwally *et al*., 2002) models whereby there is a state change in the entire subglacial environment due to water input. Similarly there's little evidence of wide spread de-coupling of the ice and bed (e.g. Iverson *et al*., 1999) as on only one occasion are pressures registered that are higher than overburden pressure . However, sliding cannot be entirely dismissed, as it may not require pore pressures to exceed overburden and complete ice buoyancy. Iverson *et al.* (2007) noted in experiments at Engabreen that sliding appeared to be feasible at pore pressures >70% of overburden.

Probe 21 registers the most intriguing pressure data with periodic rises followed by sharp falls. The speed of the pressure drop, approximately 40 kPa over 6 hours, exceeds any other change. It seems feasible that the speed of the fall might be reflective of a mechanical rearrangement. Therefore, this may result in something akin to 'stick-slip' behaviour. However, the lack of a similar signal elsewhere suggests that it is unlikely it is related to the strong diurnal nature of surface velocity.

It is feasible that the exact value differs at Skalafellsjökull but if a similar situation is occurring then it could explain the rapid pressure drops in probe 21 once pressure reaches a relatively consistent upper value. However, some areas are clearly isolated from transient inputs that may or may not be generating sliding these and may be deforming more consistently. Perhaps counterintuitively it appears that the more connected areas have lower pressures than disconnected areas of the bed. The rapid falls in pressure are also visually very similar to those seen in Moore & Iverson's (2002) experimentation where the fall in pore pressure is due to dilation. However, the scale is very different. In the experimentation a pressure drop was <2 kPa over the course of a minute. The magnitude of the pressure change here is difficult to ascribe to dilation.

7.5.1.3 Probe tilt data

Tilt data from the 2012 probe deployment does not appear to reflect stick-slip movement. There is no variability comparable to that detected by the dGPS even at a daily level. Change in tilt is relatively smooth and consistent. There is some evidence of oscillations between days 310 and 330 on probe 31 that is discussed in section 7.5.1.4.

Before continuing, it is worth considering what probe movement reflects. Previously it has been used as a direct proxy for strain (Hart *et al*., 2011) and been expected to behave as passive markers that accurately reflect deformation. However, it may in fact be a far more complex signal from which extracting strain magnitude is non-trivial.

Suspended in a deforming medium a probe will change in tilt angle because there is a velocity variation along the length of the probe. Therefore, the rate of tilt change would be an expression of the gradient of strain rate through the medium. The signal is complicated by the manner in which constant deformation yields a changing tilt rate with time. Consider a probe sat vertically in the medium. If the gradient of deformation decreases linearly with depth, the rate of tilt change will be greatest initially as the difference in strain rate between the top and bottom of the probe is greatest whilst it is sat vertically. As over time the probe becomes increasing inclined, it sits within a thinner section of the medium. Consequentially the difference in strain rate between the top and bottom of the probe is reduced and so the rate of tilt change also reduced. Therefore, even if there is a linear gradient of deformation the tilt signal will be non-linear.

This initial complication suggests that taking tilt rate to reflect strain is only appropriate as an approximation over short time steps. The manner in which probe movement reflects strain gradient also complicates estimating the contribution of deformation to surface movement. As the probe only provides the gradient of deformation in its immediate vicinity, it is in itself not enough to estimate total deformation contribution. Also required are estimates of the thickness of the deforming layer and how strain is vertically distributed through the till e.g. whether it conforms to Boulton *et al*.'s (1987) model or a more complex reality.

So clearly interpreting probe tilt data is non-trivial. The complexity is increased by variable coupling between the probe and till and a number of site specific issues such as ploughing and obstructions within the till.

Coupling between the probe and till is an area that has fortunately received some attention (Keller and Blatter, 2012; Jaber *et al*., 2013). Both focus on a key question; can an object in a deforming medium be a perfect Lagrangian vector? This is clearly important, as there is an assumption throughout the *in situ* literature that probes perfectly represent deformation. This is unlikely to be the case and till may flow around the probe and/or have its velocity field disturbed by the probe's presence. Jaber *et al.* (2013) demonstrate that behaviour of a Newtonian fluid is best represented by a probe with a 4:1 length:width ratio. The probes used for the 2012 deployment have an approximately 2:1 ratio and so may not represent deformation perfectly. The analysis assumed zero slip between the medium and the probe. This is a possibility due to the smooth probe casing, and might exacerbate coupling issues.

The above situations assume perfect deformation through the section of till within which the probe is emplaced. This is an idealised situation and sediment property heterogeneity is known to result in variable strain distribution within deforming sediment (Goodwin and Tikoff, 2002). This presents the possibility that a probe may sit across the boundary of deforming and undeforming sediment. This would presumably result in some form of ploughing of the probe through either the deforming or undeforming sediment, or perhaps both. This would have an unknown impact on the tilt results.

Alongside unevenly distributed strain obstructions will clearly impact the probes behaviour. This is perhaps best evidenced by the foreland fluting discussed in chapter 6. Lodgement, potentially against an obstruction, has been employed to explain oscillations in tilt by Hart *et al.* (2011).

In summary, tilt data is exceedingly complex to analyse. Whilst the wired nature of their sensors will have been detrimental to their results, there is value in deploying a vertical array of sensors like Truffer *et al.* (2000). This provides a better opportunity to judge deformation distribution

The data from probes 31 and 32 suggest consistent deformation. Considering the dGPS data this is perhaps unsurprising. Whilst the hourly data shows high levels of variability, the daily data is relatively consistent. Matching trends from the probes suggest that this movement is to some degree related to consistent deformation. This is evidently a different situation to that depicted by the probe water pressure data that suggest spatially variant NES, and so presumably spatially variant strain rates within the till. With just two probes though it is not possible to determine whether the similarity in tilt data is simply chance or suggestive that variable local pore pressures belie similar deformation – e.g. global controls taking precedence over local ones.

7.5.1.4 Tilt oscillations

As covered in section 2.3.1.3 up glacier movements of subglacial sensors, usually in an oscillating manner, appear to be a common feature of *in situ* sensors. Their occurrence remains unexplained but there are compelling theories linking water pressure increases to up-glacier movements of till. This might be due to movement of the ice upwards and extrusion of the till (Blake, 1992), elastic recovery of horizontal strain (Iverson *et al.*, 1999), elastic recovery of consolidation (Tulaczyk *et al*., 2000) or because of lateral deformation due to filling of spatially variant cavities with water (Jacob *et al*., 2010). Recent observations have also highlighted that it is plausible that they simply represent flow reversals and up-glacier movements of the ice (Fudge *et al*., 2009; Murray *et al*., 2015). Whilst the exact reason is unknown, the majority of theories suggest that it coincides in some manner with significant water inputs to the subglacial environment.

At Skalafellsjökull, tilt data was only recorded on the two probes deployed in 2012 and only extends through to late 2013. Probe 32 recorded no oscillations but probe 31 records three up glaciers movements of similar magnitude during 2012 on days 310, 318 and 323. Two of the events coincide with particularly warm days, although subsequent warm days fail to produce similar movements. Unfortunately, data for probe 32 is not available beyond day 300 so it is not possible to determine how widespread the events may have been.

To what extent can we assign these oscillations to any of the existing theories? Pore pressure data collected in the 2008 deployment indicates it is unlikely that these have occurred due to decoupling of the ice and bed. Therefore, theories by Blake (1992), Iverson *et al*. (1999) and Tulaczyk *et al*. (2000) that require this would seem not to fit this situation. This is further supported by the spatial heterogeneity in pore pressures as Iverson and Tulaczyk envision a wide spread decoupling. It would seem that even if decoupling had occurred at Skalafellsjökull it will have been a localised effect. Presuming any lateral connectivity in the ice exists, this might prevent the physical decoupling that could fulfil the theories even if basal pore pressures exceeded overburden. In an attempt to provide a more quantitative view on the suitability of Tulaczyk *et al.*'s (2000) theory the dilation of till from Skalafellsjökull under appropriately varying pore pressures will be considered in chapter 8.

However, could perhaps decoupling and sliding be a small scale local effect? Iverson *et al*. (2007) demonstrate at Engabreen that sliding may occur when pore pressures are in excess of 70% of overburden pressure. Therefore, perhaps pore pressure peaks observed, around 85% of overburden, may indicate sliding occurring. Encouragingly the periodicity of peak pressures in probes 21, 24 and 26 is very similar to the periodicity of the oscillations observed in probe 31, both in the order of 10-20 days. Sliding and a mechanical rearrangement of the environment might also help explain the rapid pressure reductions in probe 21. Whether sliding is feasible in very localised areas is questionable though.

Applying Jacob *et al*.'s (2010) theory may be simpler. The concept of short term lateral deformation forced by transient water inputs into a spatially variant drainage system is far more flexible than the glacial alternatives. It could also fit the data well. The oscillations occur late in the year and not on consecutive warm days. This might suggest a dependence on the water inputs overwhelming the drainage system and forcing lateral deformation with each episode forcing some adjustment in the system and preventing successive episodes. The theories suggested for spring advances (Röthlisberger and Lang, 1987) could be seen to be similar but requiring a more spatially homogeneous closure of the drainage system and consequentially a greater vertical component to the glaciers response as the system's capacity is exceeded. However, whilst this is an appealing theory, it is unclear how well the hydrological system must be developed in order for it to function. As noted in Chapter 3, there are not many moulins and hardly and crevasses at the Glacsweb site.

In summary, the water pressure data available and infrequent occurrence of oscillations at Skalafellsjökull does not appear to support decoupling based theories (Iverson *et al.* 1999; Tulaczyk *et al*., 2000). Neither does there appear to be any evidence of flow reversals (Fudge *et al*., 2009; Murray *et al*., 2015). Jacob *et al*.'s (2010) theory of lateral deformation due to water input into spatially variant cavities seems more plausible but there is no direct evidence to support it.

7.5.2 Unified theory of motion at Skalafellsjökull

In summary, the data available shows that there is a strong diurnal relationship to surface velocity, subglacial water pressures are spatially variant but do not match the surface's diurnal pattern, and daily averaged probe tilt is consistent with surface movement and experiences infrequent reversals that possibly coincide with pressure peaks. This suggests that movement may be determined by a global mechanism and longitudinal and/or lateral coupling to faster moving areas rather than local basal conditions.

The dGPS data demonstrates relatively consistent daily velocities but the hourly positions show a strong diurnal relationship. The consistency in the daily signal and agreement between magnitude and ice thickness suggests that velocity is predominantly determined by driving stress. The diurnal variations though indicate that daily melt water inputs are important in controlling velocity over shorter periods.

There is little evidence from the water pressure data of a widespread diurnal variability. Pressure data either demonstrated high and consistent pressures or variable but lower pressures. This would appear to suggest that only some areas are well coupled to the subglacial drainage system and these are better drained rather than being higher pressured. From this it is hard to conclude that local conditions and NES variation control the diurnal velocity variation unless the ice is highly dependent on a mosaic of poorly drained areas (e.g. Boulton & Dobbie, 1998; Piotrowski *et al*., 2004; Sane *et al*., 2008).

The tilt data available appears to agree with the daily dGPS velocities. It shows relatively consistent deformation for the majority of the period data is available for. The three oscillations recorded between days 310 and 340 are likely to be related to meltwater inputs into the system but bear little similarity to the more regular oscillations seen in other studies (e.g. Iverson *et al*., 1999; Hart *et al.*, 2011). Considering the diurnal velocity variations are likely to be related to melt water inputs, this would appear to be additional confirmation alongside the water pressure data that the dynamics around the probe site are not a major control on velocity

Therefore, from the evidence available two situations appear feasible. Whilst conventionally it would be expected that the subglacial drainage system would be the highest pressure area and the pressure would diffuse outwards from there to lower pressure more distal areas, the opposite appears to be true here. If the diurnal velocity variations are due to local pore pressure variation, it would appear that velocity increases as the ability of well drained areas to resist flow decreases. However, the spatially heterogeneous pressures recorded could suggest that basal hydrology at the probe site has little influence on surface velocity. Instead, global influences on local shear stress could be the predominant control on motion.

The latter situation would appear to be consistent with the location of the site (see Chapter 3 for full description). The Glacsweb site is marginal, with flow largely directed into the lateral moraine. Down the glacier from the site, the moraine bulges slightly into the glacier, and further away there is a significant bulge in the glacier (Sultartungnajokull) away from the main flow to the coastal plain. All of these factors suggest that the area may be dependent on global factors, longitudinal and lateral coupling to faster moving areas resulting in propagation of excess shear stress. In light of the lack of a distinct signal for water pressures that matches the diurnal fluctuations in velocity it is reasonable to ascribe these fluctuations to shear stress fluctuations rather than NES fluctuations.

7.5.3 Comparison to geotechnical testing results

The geotechnical work presented in this thesis found that the till rheology was plastic (see discussion in Chapter 8) and that dilation did not appear to be a significant control on increases in strain rate. Instead, it appeared that whilst in a stress condition close yielding, strain rate was highly susceptible to changes in shear stress.

Data from the *in situ* work can be easily compared to the conditions used in the laboratory. The geotechnical testing used strain rates of 5 or 50 m/a. This is broadly comparable with the daily averages seen here which vary between 5 and 30 m/a depending. Hourly velocities are much higher, regularly exceed 50 m/a and sometimes exceeding 100 m/a. This may mean testing higher strain rates in future experiments would be advisable. However, with probe tilt data only registering daily averages it is difficult to know to what extent these higher velocities are dependent on bed deformation rather than sliding.

Water pressure data is also comparable. PPR rates used in the geotechnical testing were 2 kPa/hr and 0.25 kPa/hr. Here similar pressure increases of around 100 kPa over 20 days, or 0.2 kPa/hr, were recorded. Pressure did fall much faster, but that has not been replicated in the laboratory so its impact on strain rate is unclear.

The results from the *in situ* work appear to corroborate the lack of dilation control in the geotechnical experimentation. Here there is no evidence of dilation control with fluctuations comparable to those found in Moore & Iverson's (2002) experimentation not present in the water pressure data. Fluctuations are present, but on a much longer time scale. Instead, surface velocity fluctuations appear to be controlled by changes in driving stress. The consistent changes in tilt of the probes suggest that although water pressures are only around 70-85% of overburden, deformation is occurring. This would imply that fluctuations in shear stress are large and so this further diminishes the possibility that dilation control is occurring.

7.5.4 Considerations in future deployments

This deployment has produced useful data, but improvements could be made in future deployments. The most obvious change is deploying probes with both functioning water pressure and tilt meters. More pertinently, efforts should be made to capture the short term dynamics at the site.

This, and previous Glacsweb deployments, have been largely focused on longevity and seasonal change. In future deployments changing the focus towards short term changes and attempting to monitor local conditions accurately would be a productive approach. This could be achieved by switching to recording data each minute rather than each hour (water pressure) or day (tilt). Recording and transmitting this data would substantially reduce battery life, but this is a reasonable trade off considering the paucity of data available at this resolution. Access to this data would be extremely useful for a host of future experiments using a BPS, and possibly using the DynBPS.

Data resolution could also be improved by deploying the probes in a grid formation, perhaps 16 with approximately 10 m between each probe. With that type of deployment local water pressures could be monitored in detail and so the forcing on deformation would be more clearly illuminated.

Finally, whether surface motion is due to sliding or deformation is clearly a significant issue when trying to replicate subglacial conditions in the laboratory. A successful deployment of geophones should assist with differentiating between the two modes. Sliding is likely to produce a distinct signal to deformation, especially if decoupling due to high pressures is involved.

7.6 Conclusions

This chapter aimed to address three of the thesis aims, and in doing so identify the main influences on glacial movement at the site and provide context for the findings of the geotechnical study. These aims have been successfully addressed, with the exclusion of aim one (rheology) which is discussed in Chapter 8.

Data from dGPS showed the surface velocity to be variant on an hourly, and relatively stable and related to ice thickness on longer time scales. This was suggestive stick-slip motion as described by other studies.

Subglacial water pressures were spatially heterogeneous and show no widespread link to surface velocities. Areas thought to be better connected to surface inputs of meltwater have lower and more variable water pressures than areas thought to be poorly connected. Therefore, there was no clear and consistent link between water pressure data and stick-slip motion.

Tilt data from the probes was available as a daily average and showed consistent movement patterns. This perhaps reflects the relatively stable diurnal movement signal produced by the surface dGPS. Tilt oscillations were seen but more rarely than in previous studies. There was no evidence of widespread decoupling occurring as required by Iverson *et al.* (1999) and Tulaczyk's (2000) theories.

Daily velocities were comparable to strain rates used in the geotechnical experimentation. Hourly velocities exceeded them, but it is unclear whether they reflect sliding or deformation. Water pressure fluctuations were comparable with increases in the order of 0.2 kPa/hr. There was no evidence recorded of dilation control, although the temporal resolution of the data may have impacted this finding.

With no consistent link between surface velocity fluctuations and tilt or water pressure data, it would appear that driving stress fluctuations are likely to be responsible. This is probably consistent with the site's location in a marginal area of the glacier. Longitudinal or lateral coupling to faster moving areas of the glacier is probably responsible for propagation of excess shear stress and velocity fluctuations at the site.

Chapter 8: Discussion

8.1 Introduction

This chapter first considers the crux of the thesis and considers the implications for the findings of the geotechnical experimentation. It then moves on to discussion of the site at Skalafellsjökull, and tries to develop an understanding of the processes at work with the findings of all the data chapters.

8.2 Relating geotechnical findings to the glacial analogue

Episodic increases in strain rate have been recorded in the geotechnical experimentation here and elsewhere (Moore & Iverson, 2002). It is reasonable to consider how each experiment relates to the glacial analogue. Could the inherently variable velocity of the glacier be dependent on factors identified in the experimentation?

As covered in section (2.2.3.2) there are three major explanations put forward for why the glacier surface experiences stick-slip motion. These include periodic build up and release of shear stress (Bahr & Rundle, 1996; Fischer & Clarke, 1997), externally influenced movement, e.g. tidally influenced movement (Bindschadler *et al*., 2003; Gudmundsson, 2007; Winberry *et al*., 2011) and rheologically defined episodic motion, perhaps dilation controlled (e.g. Iverson *et al*., 1999a; Hooyer & Iverson, 2000; Moore & Iverson, 2002; Roberts & Hart, 2005; Iverson *et al.,* 2007; Rathbun *et al*., 2008; Iverson, 2010; Hart *et al*., 2011). The latter explanation has attracted the greatest literature, but the substantive contribution came from Moore and Iverson (2002).

Moore and Iverson (2002) argued that as they recorded dilatant strengthening regulating episodic increases in strain rate occurring in over-consolidated till it was likely that this also impacted deformation of till in the subglacial environment. The evidence from experimentation here is that at the very least dilation is not a consistent regulator of subglacial deformation as under the PPR method of NES reduction there was no evidence it had an impact on strain rates.

This focusses the debate primarily on whether the experimental setup in these experiments or those conducted by Moore & Iverson (2002) is more representative of the subglacial environment. Four situations are considered in turn below where subglacial bed deformation occurs due to changes in the stress state are the till. The first situation is comparable to Moore & Iverson's experimentation, the second and third are more similar to experimentation presented here, and the final situation is complex and less clearly aligned with either.

8.2.1.1 Bed deformation due to normal stress driven changes in NES

Moore and Iverson's (2002) experimentation involves periodic removal of normal stress and so a reduction in NES. This initiates strain that is then controlled by dilatancy. In most real world situations normal stress is not dynamic on a similar time scale to other variables involved in the stress state of till (water pressure and shear stress). The normal stress is applied by the ice overburden that is only changing on a seasonal basis. However, this model is very comparable to some tidewater glaciers. Tidal uplift of the glacial margin and the consequential drop in normal stress can propagate up a glacier (Bindschadler *et al*., 2003; Gudmundsson, 2007; Winberry *et al*., 2011). In this situation the till would be deforming in an over consolidated state and so the dilatancy may be sufficient to impact strain rates.

8.2.1.2 Bed deformation due to pore pressure driven changes in NES

Strain initiation due to NES reduction by an increase in pore pressures within the till is the situation that has been modelled within this thesis. This is perhaps the most common reason for diurnal fluctuations in glacial velocity. As described in chapter 5, the pore pressure increase results in dilation to such a degree that when strain is initiated the resultant dilation is not sufficient to outpace the supply of pore water to the site, so NES does not increase.

This has implications for the behaviour of subglacial bed deformation. Previously shear induced dilation hardening has been suggested as a manner of causing stick slip motion (Iverson *et al*., 1999a; Hooyer & Iverson, 2000; Moore & Iverson, 2002; Roberts & Hart, 2005; Iverson *et al.,* 2007; Rathbun *et al*., 2008; Iverson, 2010; Hart *et al*., 2011) and distributing strain within a section of till (see Figure 88) (Iverson *et al*., 1998; Tulaczyk, 2000; Boulton *et* al., 2001; Iverson & Iverson, 2001; Fowler, 2003). The complex behaviour of distributed strain, due to dilation and other causes, has been suggested as a reason for viscous rheologies matching large scale glacial behaviour (Fowler, 2003).

Boulton *et al*. (2001) illustrate how dilation strengthening may result in strain distribution during deformation (see Figure 88). Their model envisages shear stress and water pressure rising, deformation occurring and the shearing resulting in dilation. This dilation is significant to strengthen the till sufficiently to prevent further deformation. As a result, the shear stress exerted by the ice is transferred through the now competent till to weaker till below.

In this study the lack of dilation strengthening arising from shear induced dilation suggests that in similar subglacial conditions it cannot be employed as a reason for strain distribution occurring. A revised version of Boulton *et al*.'s (2001) model has been produced to illustrate how deformation may proceed without dilation strengthening (see Figure 89). In this model the rising pore pressure results in dilation occurring in the undeforming till. As a result, when deformation does occur the dilation associated with shearing is not sufficient to lower pore pressures and strengthen the till to the point at which deformation would cease. This means that strain is not distributed downwards as the deforming till never becomes sufficiently competent.

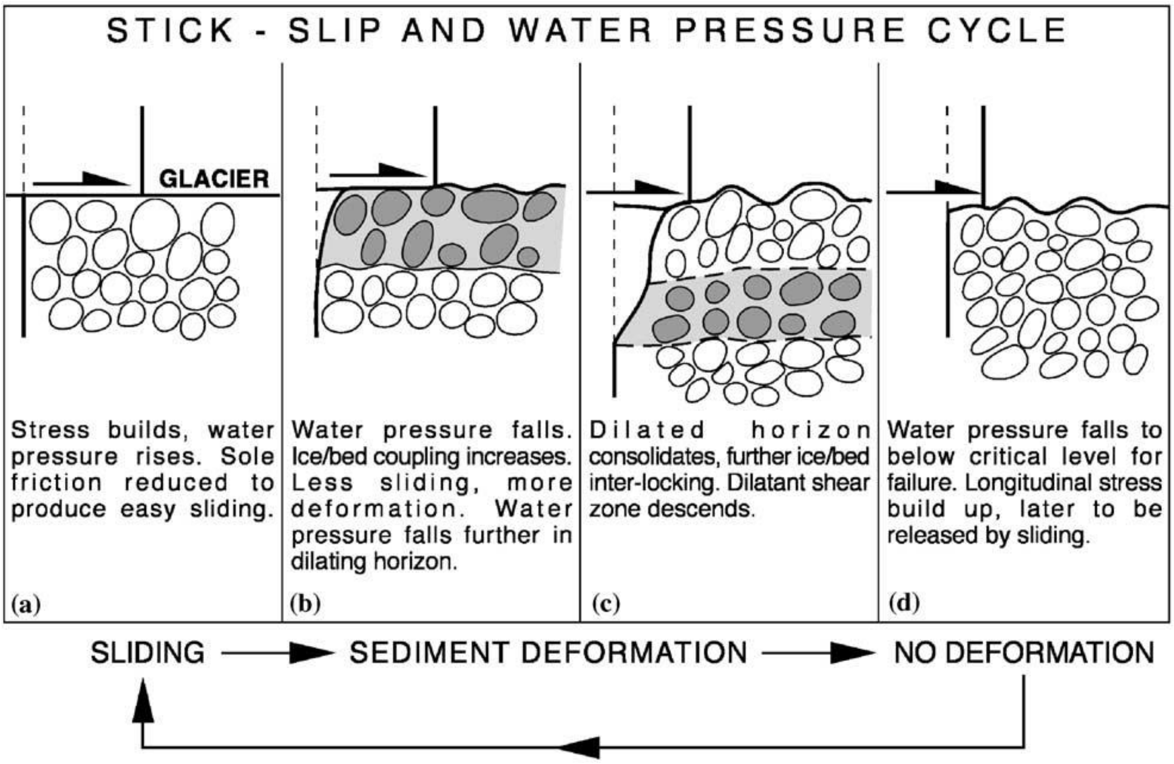


Figure 88: The mechanism by which dilation hardening may result in strain distribution within the deforming zone. In the absence of dilation hardening other mechanisms must be responsible (reproduced from Boulton *et al*, 2001).

As complications in deformation due strain distribution have been suggested as a means for the plastic-viscous scale divide (Fowler, 2003), this revised model may have implications for the scale at which this occurs. Strain distribution can occur due to other factors such as lithological variations causing competency contrasts (Goodwin & Tikoff, 2002) or large clasts lodging between the ice and underlying undeforming till (Evans, 2002), but if these are not widely significant then presumably meso-scale factors such as sticky spots or marginal drag must cause the scale divide.

The experimental evidence also suggests that dilation strengthening is not significant as a means for producing stick-slip movement. For the same reasons it demonstrates why strain distribution will not occur, Figure 89 also shows why dilation strengthening is unlikely to result in stick-slip movement. It may have some impact on till strain rates but there is no evidence to suggest that it could produce the kind of velocity variations recorded in the field.

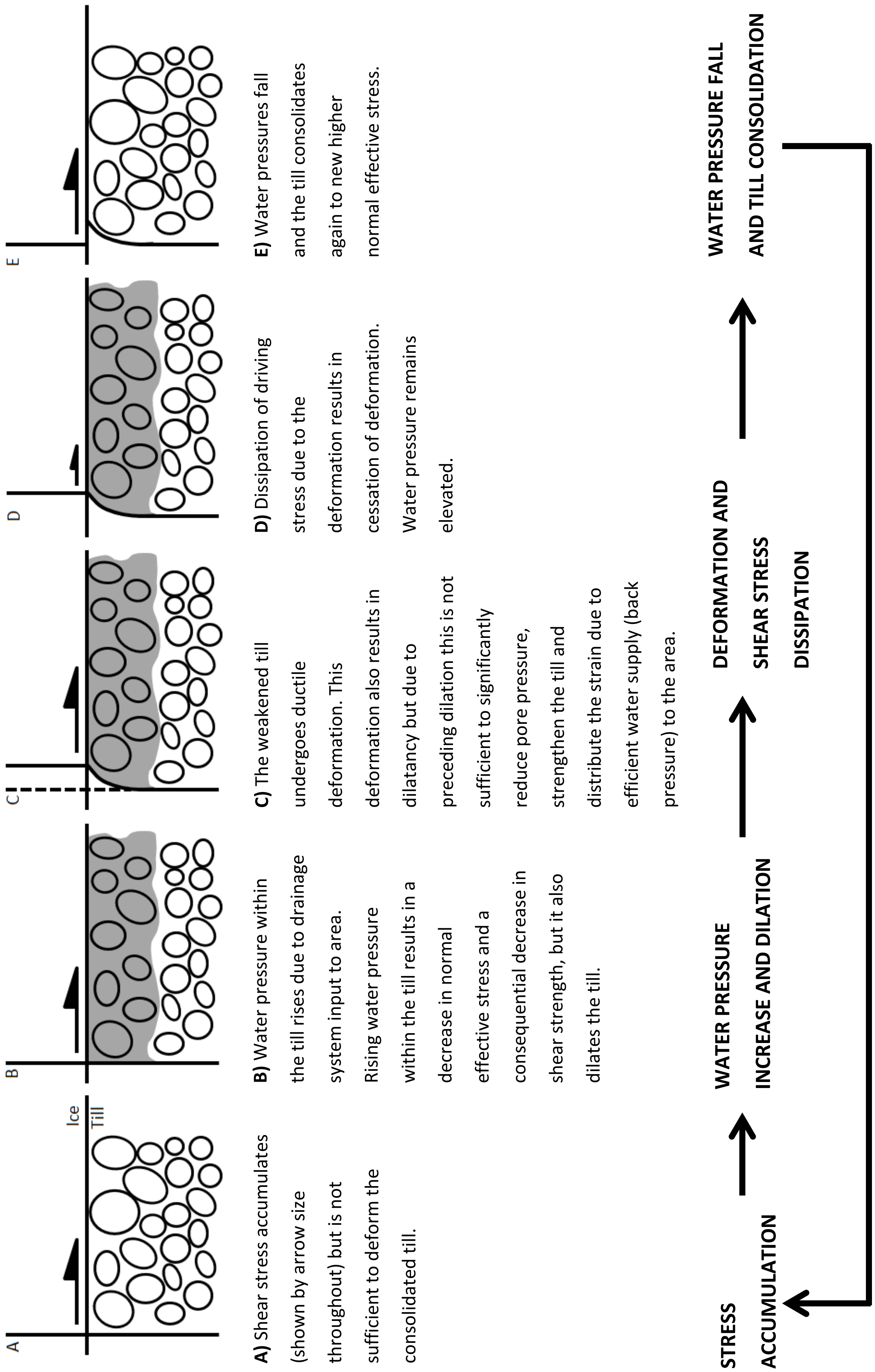


Figure 89: A revised version Boulton *et al.*'s (2001) stick-slip figure that takes into account the lack of dilation hardening.

8.2.1.3 Bed deformation due to shear stress elevation

The final possibility for changing the stress state of the subglacial bed and initiating deformation is increasing shear stress. This could be caused by areas of the glacier decoupling from the bed or reaching a residual state, and excess shear stress being distributed to non-deforming areas.

In this situation dilation control would again be unlikely. Presuming the non-deforming areas of till are in equilibrium with the water pressure, dilation strengthening should not occur.

8.2.1.4 Multi-factor situations

The influence of dilatancy is less clear when variable conductivity to the subglacial drainage system results in the subglacial bed having a mosaic of higher and lower pore pressures (e.g. Boulton & Dobbie, 1998; Piotrowski *et al*., 2004; Sane *et al*., 2008). In this situation the behaviour of the higher pressure areas should be well replicated by the PPR experiments thesis. Rising pore pressures, reducing NES, will result in sufficient dilatancy such that when strain is initiated further dilatancy is not a control on it. Areas of till with lower pore pressures may behave differently. If excess shear stress from the deforming areas is bridged to the non-deforming areas then dilatancy would not be significant. However, if the reduction in NES at the high pressure areas results in a general reduction of NES across the wider area, again due to bridging through the ice, the lower pressure areas would then be in an over consolidated state comparable to that modelled by Moore and Iverson (2002). This would mean that they would be subject to dilatancy, perhaps significant enough to limit deformation across the entire area.

8.2.1.5 Summary

In the majority of cases, dilatancy is unlikely to be a control on subglacial bed deformation. A tidewater margin may result in a greater level of influence, but for terrestrial terminating glaciers there are no obvious reasons for reductions of NES due to normal stress reduction. There may be occurrences where the bed is a mosaic of high and low pressure areas and dilatancy increases in importance. However, even in that situation the dilatancy seems unlikely to be more than a minor factor.

8.3 Glaciation at Skalafellsjökull

From the five data chapters presented a theme emerges of heterogeneity contrasting against homogeneity. Why does this contrast exist and to what extent is it reflective of the environment rather than a product of the data collection? Are some elements more heterogeneous and seemingly unrelated to the system because they are insignificant, or have they just been incorrectly sampled or misunderstood?

The data collected on flutes in chapter 6 captures the dichotomy well. At a small scale, densely fluted areas demonstrate significant heterogeneity. However, mapped over a larger scale their spacing is unimodal and spatially consistent. The possibility this distribution reflects random growth rates (Spagnolo *et al*., 2014) highlights the importance of scale in the data collection. If all the processes examined here are assumed to tend towards similar relationships, small scale random behaviour resulting in larger scale homogeneity, then the contrasting homogeneity and heterogeneity within the thesis may be simply a product of the scale at which data collection has been conducted.

This issue of scale is problematic as the data sources in this research vary in both their spatial and temporal coverage. In some cases there is overlap and in others none at all. From the data available and the previous literature drawn on it has not been possible to state definitively which data sources are comparable and which are not. This complicates analysing the thesis as a whole and drawing thematic links.

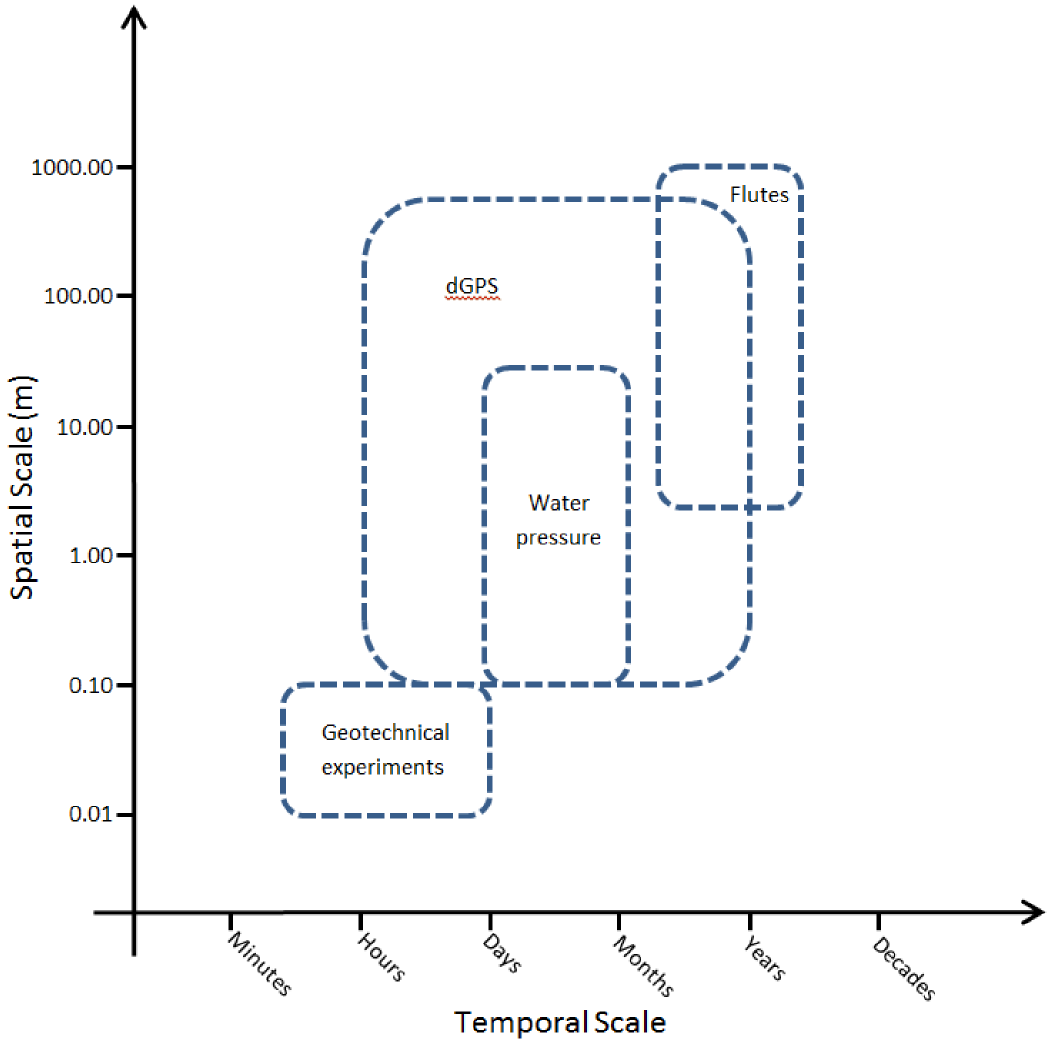


Figure 90: Conceptual perspective on the scales aspects studied in the thesis exist at.

Figure 90 is a conceptual diagram of the scale of the different data sources. The geotechnical experimentation is the finest spatial and temporal scale dataset. Experiments were on a small 0.01 m wide section of till and expanded on the controls on till deformation with dynamism in the hours-days scale. The *in situ* data is broader scaled in both dimensions. Water pressure data informs on the immediate conditions around each probe, probably spanning an area measured in centimetres (Iverson *et al.*, 2007). The 4 probes that provided water pressure data combined inform on an area measured in the 10s of metres. The temporal resolution enables events in the order of days-months to be resolved but struggles to inform on seasonality or really capture inter-annual variability due to data availability limitations. dGPS data has a similar extent but provides a broader coverage in every direction. Hourly recordings provide a finer temporal resolution and observations are available for several years at the Glacsweb probe base station. Similarly, the spatial spread of dGPS deployed enables understanding of velocity variations across an area approaching kilometre scaling. Data on flutes exceeds all other data sources in its temporal and spatial scaling. The spatial information varies from that of the individual flute spacing, approaching sub-metre resolution, up to the kilometre scale area that the spacing relationship appears to hold over. The temporal scaling is harder to judge but the coherence between individual annual advances would appear to place a limit on its lower extent. At the other extent it is reasonable to consider that there are probably underlying influences from decades of ice flow over the area, or probably the entire local LIA advance.

8.3.1 Flutes at Skalafellsjökull

Glacial bedforms are formed subglacially and so provide an insight into conditions and dynamics during glaciation. To date large quantification studies have focused on drumlins and MSGLs with flutes receiving relatively little attention. This is partially due to widespread acceptance of obstruction based theories for flute genesis (see section 2.2.2). Work over the last decade on instability based genesis suggests that there remains some uncertainty in how flutes are created, maintained and propagated.

Previous studies that have quantified flute distribution have focused on crest-to-crest spacing. An updated GIS based version of this methodology has been employed here that has similarities to Stokes *et al*.'s (2013) approach to measuring MSGL spacing.

Results suggest that the spacing distribution is similar to other studies. It is unimodal, positively skewed and approaches log-normal. This type of distribution has been replicated by a number of studies (Hoppe & Schytt, 1953; Baranowski, 1970; Shaw & Freschauf, 1973) despite variations in location and methodology. The quasi-log-normal nature of the distribution may reflect random initiation and growth (Hillier *et al*., 2014).

More pertinent to the thesis as a whole is the scale at which flute genesis, in whatever manner it takes, results in disturbance of the subglacial environment. From the flute data alone no prediction is made about what form this disturbance might take. However, previously it has been suggested that this is the scale above which till rheology changes from plastic to viscous (Hindmarsh, 1997).

The *in situ* data has poor spatial resolution. It cannot suggest whether the subglacial environment at the subglacial site reflect disturbance on a scale similar to that seen in the foreland flutes. What is apparent though is that pore pressures are highly spatially heterogeneous. It is not possible to discern how this is related to the presence of genesis of flutes. It is improbable though that the two could be completely unrelated due to the control water pressures are expected to exert over deformation. Considering the anticipated scale related issues discussed above, this may imply that the heterogeneity in water pressures suggested by the data available could simply be a product of the spatial resolution of the data. Therefore, the lack of apparent significance may be an artefact of the data collection. Alternatively, it may be that the heterogeneous pore pressure data reflects a subglacial deformation occurring in a similarly heterogeneous mosaic-esque manner. The frustrating aspect here is that the scaling of the pore pressure data falls between the scales where the flutes are chaotic and where they are ordered. Therefore, it may be that its heterogeneity reflects flute genesis but it is impossible to derive a certain conclusion.

8.3.2 *In situ* sensing

8.3.2.1 Water pressure heterogeneity

Water pressures at Skalafellsjökull were found to be highly heterogeneous. Pressure heads produced by borehole drilling took a variable but lengthy time to dissipate indicating variable but low hydraulic conductivity. The bed varies between being connected and unconnected to the subglacial water system. The manner of pore pressure variation is different even within (presumed) connected and unconnected zones. The style of water pressure change and average values vary hugely with even unconnected areas appear capable of rapid (negative) changes in pore pressure.

This matches a number of previous findings. Murray and Clarke (1995) conducted an extensive borehole study of water pressures at Trapridge Glacier and found that even over short distances subglacial hydrology appeared to be highly heterogeneous. Some regions appeared to be connected and highly variable, others unconnected and much more stable. Regions appeared to be able to switch between being connected or unconnected and able to maintain a high pressure gradient between the two. Unconnected areas did not display the variability seen in connected areas but were still capable of rapid changes, sometimes anti-correlated with connected areas.

Fudge *et al*. (2008) produced similar findings on Bench Glacier. They again used boreholes, this time 16 arranged in a grid. Again, they found that although pairs of boreholes might display similar behaviour three distinct diurnal behaviours were displayed and connectivity was limited to tens of meters. Significant pressure gradients were again displayed and there was no evidence of flow between high and lower pressure areas.

Working on a much smaller scale, Iverson *et al*.'s (2007) experimentation at Engabreen demonstrated that although areas of till could be connected via diffusion through the till, connectivity more readily occurred via transmission across the ice-till interface. Artificial elevation of local water pressures via pumping was detected by sensors ~0.9 m away within 5 minutes. Had the pressure diffused through the till it would have taken in the order of 5 hours (based on laboratory observations of till diffusivity). This experimentation potentially suggests a mechanism for small scale heterogeneity in situations where pressure is rising rapidly to high levels, but potentially is less significant in more steady and lower pressure variations therefore providing a situation and time dependant factor in pore pressure variations.

The data available on pore pressures at Skalafellsjökull shows significant heterogeneity. However, it seems that this heterogeneity at Skalafellsjökull is relatively typical across other studies. Iverson (2010) argues that water pressures dictate glacial movement, but whilst that may be true on a larger scale, here and elsewhere there is evidence that at a local scale (i.e. the area of the Glacsweb site) their heterogeneity prevents a simple link being established between pore pressures and glacial velocity.

8.3.2.2 Probe tilt oscillations

Probe tilt oscillations and up-glacier movements are common in a number of studies (Blake, 1992; Iverson *et al*., 1995; Hooke *et al*., 1997; Iverson *et al.,* 1999; Truffer *et al*., 2000; Tulaczyk *et al*., 2000; Hart *et al.,* 2009) and have been found in this study. Three distinct up glacier movements were recorded in probe 31 on days 310, 318 and 323. Up glacier movement of probes is obviously counterintuitive and has attracted reasonable attention.

The most common theory is that it represents some form of elastic relaxation of the till and subsequent dilation due to decoupling of the ice and till (Iverson *et al.,* 1999). The heterogeneity of the water pressures recorded makes this idea seem relatively implausible. The ice is never fully buoyant and areas of high pressure seemingly exist alongside areas of relatively low pressure.

The geotechnical experimentation conducted in this thesis means it is possible to assess dilation due to reduction in pore pressures and dilation of the till. This can then be used for a rudimentary analysis of whether this is likely to produce dilation significant enough to produce the movement signals recorded.

Observations of dilation during testing appear to show that Tulaczyk *et al*.'s (2000) prediction of elastic recovery of vertical strain may be feasible. Triaxial testing of till from WIS demonstrated that in an overconsolidated state pore spacing in the till had a linear response to cycling of normal stress. As till is expected to generally reside in an overconsolidated state they concluded that up-glacier tilt could potentially be produced by rapid normal stress decreases associated with decoupling and sliding. The geotechnical experimentation conducted in this study has not entirely replicated that experiment with more dilation occurring during NES reduction. During the testing a normal effective stress decrease of 15-20% due to pore pressure inflation resulted in an approximately 1% dilation of the sample. The oscillations recorded were a reverse of <0.5° from a

60° tilt. Presuming perfect coupling between the probe and the till a 0.5° increase from a 60° inclination would require the till to dilate by 0.5%.

This is an exceedingly rudimentary calculation compared to the extensive modelling conducted by Tulaczyk *et al*. (2000). Despite that, it would appear to demonstrate that the theory could hold at Skalafellsjökull. Indeed as a pore pressure increase comparable to 15-20% of overburden is required, it may even be feasible without full decoupling and sliding occurring.

Whether or not the oscillations signify decoupling, perhaps there is other evidence that suggests decoupling is occurring. There is evidence that sliding and decoupling may actually occur at relatively low pore pressures, possibly as low as 70% (Iverson *et al.,* 2007). If sliding is assumed to be possible during the period Skalafellsjökull was monitored then there is some circumstantial evidence for its occurrence. Primarily this is that the peaks in pore pressure in probes 21 and 26, the oscillations in probe 31 and peaks in surface velocity all have similar periodicity. Full ice buoyancy is not achieved but if sliding can occur at Engabreen at 70% overburden pressure then it could be a conservative suggestion that it is occurring at peak pressures (approximately 85% overburden pressure) at Skalafellsjökull. Evidently this is speculation rather than proof.

The theory Jacob *et al.* (2010) present for oscillations remains interesting because it would fit with every situation. It simply requires lateral variation of the cavities within the system and then inconsistent pressurisation of the cavities would result in lateral shear stress developing. There is no reason why oscillations could not be produced by the conditions that also force sliding, both would require significant pressure inputs. So regardless of the plausibility of the theory for dilation forced oscillations, this theory could be applied. Clearly though it needs more research in a glacial situation. This should take the form of a higher spatial resolution *in situ* study that could track tilt oscillations and relate them usefully to spatially variant surface water inputs.

8.3.2.3 dGPS data

The dGPS deployed on the surface of Skalafellsjökull near the Glacsweb site show that the glacier's motion is relatively consistent. Daily velocities are stable and proportional to ice thickness. Diurnal velocities vary significantly, rising to a peak velocity commonly around 5-10x the minima recorded, but do so consistently.

Significant variations in velocity have sometimes been attributed to decoupling and sliding (e.g. Iverson *et al*., 1997). However, this diurnal velocity signal is unlikely to be the product of widespread sliding at the site. Neither does it seem that it is the result of localised pore pressure driven variations in normal effective stress and consequential weakening of the till. As discussed, there is little evidence through 2008-10 of widespread variations in pore pressure that could indicate a diurnal scale coupling between glacial velocity and pore pressures. This suggests another factor controls diurnal fluctuations and this is discussed below.

8.3.3 Geotechnical experimentation

8.3.3.1 Till rheology at Skalafellsjökull

The rheology of till has been a very active focus of discussion over the last few decades. Evidence abounds that on the laboratory scale it behaves plastically (Kamb, 1991). However, some argue that there is scale dependence to the rheology and for larger scale ice movements a viscous rheology can be employed (Hindmarsh, 1997). Evidence for and against these arguments has been provided from a number of glacier based studies. Work on the WIS (Whillans Ice Stream) has demonstrated a plastic rheology holds there (Tulaczyk, 2006). Other studies have provided evidence for a viscous rheology, including the Glacsweb work at Briksdalsbreen (Hart *et al*., 2011). There has been some suggestion that different lithologies may be responsible for the differing behaviour (Altuhafi *et al*., 2009).

At WIS, it has been postulated that the velocity variations, ten-fold diurnally, are not the product of changes in basal pore pressures (Tulaczyk, 2006). This is not based on subglacial sensing but the persuasive argument that the lack of vertical movement in the ice as detected by dGPS and the implausibility of sufficient meltwater transfers to the bed on the time scales required rules it out as an agent. That enables the ice stream to be used to determine rheology as with no variation in normal effective stress the velocity variations are likely to be due to variations in shear stress. As pore pressures appear to have no widespread similarity to the variations in velocity at Skalafellsjökull, a similar approach can be taken here.

If sliding cannot be invoked as the cause of diurnal velocity variations (see section 8.3.2.2), then it follows that deformation is responsible indicating variations of normal effective stress or shear stress must be occurring. As discussed (see section 8.3.2.1), there is no evidence that water pressures vary widely diurnally. Therefore, the velocity variations are likely to be the result of variations in shear stress due to longitudinal and lateral coupling to higher velocity areas of the glacier.

If we assume that the till behaves similarly *in* situ as in the geotechnical laboratory experimentation conducted in this study, then applying the plastic rheology discovered there seems appropriate. This study has not replicated the experiments conducted by Tulaczyk (2006) into strain variation, but their results were essentially the confirmation of a plastic rheology. When shear stresses exceed the peak shear strength of the till non-linear increases in strain rate can be expected with linear increases in shear stress. The results from the PPR experimentation here demonstrate a similar situation but were not deliberately controlled for those variables. Therefore, it is a reasonable assumption that strain rates of subglacial till may also increase non-linearly with shear stress if it reaches conditions close to the failure envelope defined within the experimentation conducted here. This non-linear increase in till strain rate would likely be translated into surface motion detected by the dGPS.

By applying the findings of the geotechnical investigation and theoretical estimations of the shear stress at the site we can examine the feasibility that till subglacially might reach conditions close to the failure envelope. Based on all data available from probes and borehole observations and making a conservative estimate, average pore pressures across the site are likely to be at least 60% of overburden. At that normal effective stress theoretically a <100% increase in shear stress would result in widespread yielding of at the Glacsweb site. Plausibly it could require a far lower increase as many areas appear to be close to 80% overburden pressure and so vulnerable to very small increases in shear stress.

If the fluctuations in ice velocity are due to periodic increases in shear stress this suggests a global rather than local control on velocities at the Glacsweb site. The highly spatially variable water pressures observed may result in periodic transfer of shear stress from areas connected to the draining system as they decouple, permitting deformation of till in unconnected areas residing at a higher normal effective stress. If 50% of the glacier bed were to decouple this would provide the required 100% increase in shear stress at sites still coupled to the bed. This provides a mechanism for the clear pattern of diurnal surface melting and seemingly well-developed subglacial drainage system (Hart *et al*., 2015) to influence areas of un/poorly-connected till. However, the lack of observations of systematic high pressures and decoupling within the area monitored by the Glacsweb project suggests that it is likely to be dependent on areas up-ice of the site.

If instead a viscous rheology was applied then the shear stress variations would have to be directly proportional to the velocity variations. Therefore based on the same model of spatially variant decoupling, the decoupling would have to occur over a large area. If a plastic rheology requires up to 100% increase in shear stress then up to 50% of the glacier might have to decouple from the bed, and as discussed that is probably an upper limit. Conversely, if a viscous rheology holds and a 500% increase in shear stress is required then around 80% of the glacier would have to decouple from the bed. Qualitatively, as in Tulaczyk's (2006) study, this appears to show that the velocity variations are more feasible if a plastic rheology is applied.

This finding is further evidence against arguments for scale dependent rheology (e.g. Hindmarsh, 1997). It is also in contrast to the Glacsweb study at Briksdalsbreen where probe data on tilt and water pressure was used to derive a viscous rheology (Hart *et al*., 2011). Hindmarsh predicted the diversion from a plastic to a viscous rheology occurred between the scale of flutes and drumlins, e.g. meters and tens of metres. Hart *et al.*'s (2011) findings suggest that actually it might happen at below the flute scale. Sadly, in this investigation there was no opportunity to perform a similar analysis due to the lack of concurrent tilt and water pressure data. However, considering the uncertainties involved in interpreting probe tilt data (see section 7.5.1.3) it is perhaps possible that the viscous rheology assessment is a product of the approximations involved in the calculation. Despite that, it would appear here that a plastic rheology holds from the centimetre scale (shear box) through to the kilometre scale (dGPS field survey size).

8.3.3.2 How does testing apply to movement at Skalafellsjökull

The ice surface at the Glacsweb site experiences diurnal fluctuations in velocity. These are not matched by pore pressures recorded by the probes. Consequentially, of the four situations discussed in 8.2.1, the first two do not apply. Till dilatancy is unlikely to be a controlling factor on bed deformation. Fluctuations in velocity are likely instead to be caused by shear stress fluctuations (Bahr & Rundle, 1996; Fischer & Clarke, 1997) and longitudinal or lateral coupling to higher velocity areas of the glacier.

It seems probable that the site monitored by the Glacsweb project is a marginal area that provides drag, as imagined by proponents of the sticky-spot theory (Alley, 1993). It is likely that distal areas of very weak till towards the centre of the valley transfer excess shear stress to marginal areas like this. Considering the site is only a few hundred metres into the glacier, the glacier is nearly 4 km wide and the site is located in a marginal 'bulge' that must restrict down glacier flow, it seems possible that it is an area of marginal drag.

The inclusion of significant basal slip (used here to signify deformation and sliding) increases the dependency on marginal drag, as basal drag is minimal towards the centre of the valley. Raymond (1971) assumes a horizontal water table across the glacier, so the water level constitutes a great proportion of ice depth towards the centre. As a result, the water pressures also increase towards the centre and normal effective stress decreases result in an increased amount of basal slip. If a plastic till rheology is assumed, as by Truffer *et al*. (2001) and in this study, significant shear stress must be transferred from central to marginal areas. The valley scale studies do not make linkages to the hour-to-hour ice dynamics examined in this study, but it seems a logical extension that if they cannot be explained by pressure fluctuations under the site then their origin must be related to this excess shear stress. Unfortunately, with the surface velocity data provided by the dGPS in this study it is not possible to verify how well Skalafellsjökull matches these other observations.

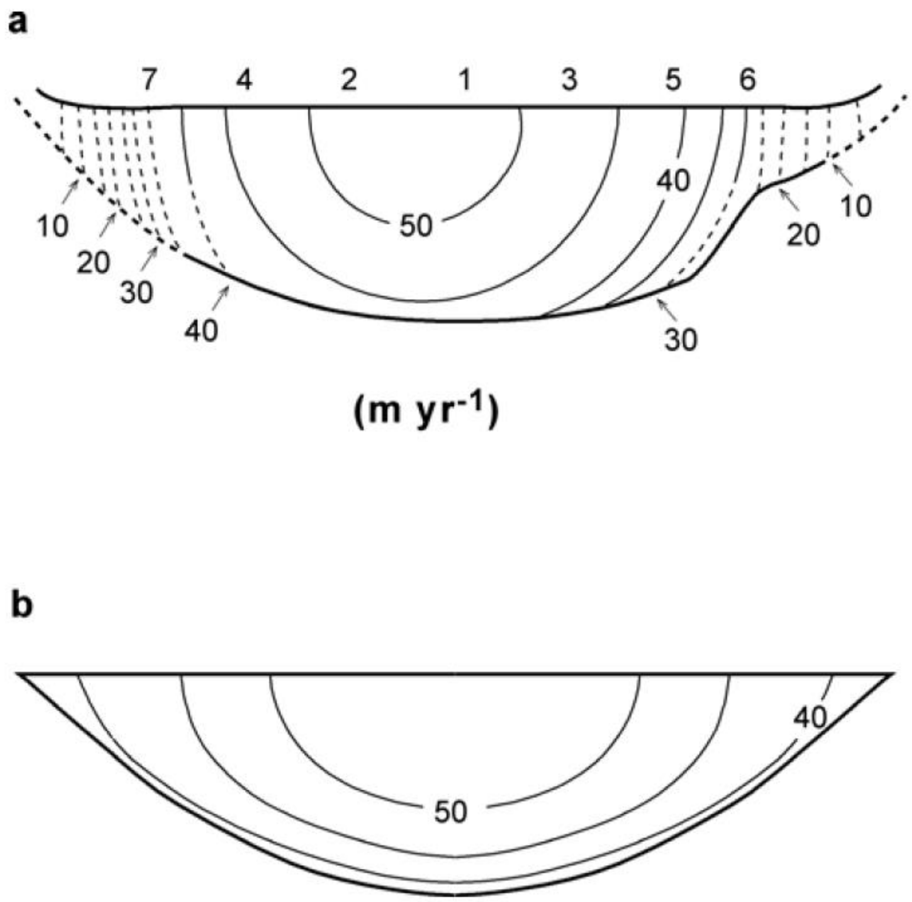


Figure 91: Distribution of velocity for (A) Athabasca Glacier as measured by Raymond (1971), and (B) Nye's (1965) theoretical distribution based on a parabolic valley form. Reproduced from Cuffey and Paterson (2010).

Cuffey and Paterson (2010, pg. 338-346) provide a detailed overview of the theoretical role of marginal areas within the glacial system which is pertinent to this discussion. The theoretical expectation for valley glaciers is that marginal areas constitute a significant proportion of the resistance to flow (Nye, 1965). The exact shape of the valley is then significant as it impacts the location of that resistance, e.g. a rectangular valley would have significantly more marginal drag than a semi-circular valley as a greater proportion of the valley perimeter is located at the absolute edge of the valley. Observations from Raymond (1971), Truffer *et al*. (2001) and Harbor *et al.* (1997) show that this theoretical construct does not quite hold when significant basal slip is included (see Figure 91).

Chapter 9: Conclusions

9.1 Introduction

This chapter forms an overview of the conclusions reached throughout the thesis. It combines the more conclusions found within chapters 4-7 alongside those that have emerged from the discussion in chapter 8.

9.2 Geotechnical experimentation

Bulk samples of till were taken from an ice marginal location near the Glacsweb site on Skalafellsjökull. They then underwent geotechnical laboratory testing, predominantly in a back pressure shear box. This demonstrated that it conforms to the plastic Mohr-Coulomb model and has an angle of friction of 37.6°. These results are consistent with previous literature on glacial till and in particular with work conducted by Altuhafi *et al*. (2009) that provided a very similar angle of friction. The angle of friction is relatively high for till placing it in the top third of those reported. This is consistent with the sandy lithology. Some tendency to weaken with increasing strain rate was discovered but this may not be beyond the error of the study.

Pore pressure reinflation testing of the till was conducted to try and replicate subglacial conditions. Shear stress was held constant whilst pore pressure increased linearly. The decreasing normal effective stress resulted in episodic increases in strain rate. Usually several occurred before 20% strain was achieved. The cessation of increased strain rate events appears to be related to the inability of the shear box to maintain constant shear stress with increasing strain rates. A newer dynamic back pressure shear box demonstrated that if shear stress does not fall as significantly then 20% strain can be achieved in a single catastrophic increase in strain rate.

After initial contraction of sediment during the monotonic initialisation of the test, dilation occurs throughout pore pressure reinflation stage of testing and is related to normal effective stress reduction and strain rate. Dilation does not result in a reduction in pore pressure that might strengthen the sediment. This is dissimilar to previous similar experimentation by Moore and Iverson (2002) where dilation hardening enable sustained slow shear. This difference is likely due to the back pressure forced reduction in normal effective stress.

This is thought to be a better replication of subglacial conditions than Moore and Iverson's (2002) use of normal stress reductions. Four situations have been considered where a change in the stress state of subglacial till leads to it deforming (see section 8.2). Moore and Iverson's model applies well to tidewater glaciers, but where the stress state is altered due to pore pressure or shear stress fluctuations, the model here is more suitable. In summary, this model should be more widely applicable.

9.3 Flutes

A UAV survey was used to collect imagery of the foreland of Skalafellsjökull. From this imagery a photogrammetric DEM and orthophoto was produced. This was used to map flutes across the foreland.

323 flutes were mapped. The spacing of the flutes was analysed with a GIS tool that calculated the distance to nearest flute. The flute distribution had an average spacing of approximately 2 m. As with previous studies (Boulton, 1976; Clark et al., 2009; Hillier *et al*., 2013; Stokes *et al*., 2013; Spagnolo *et al*., 2014) the distribution was unimodal, positively skewed and approximate a log-normal distribution.

With flute spacing in the order of metres, subglacial probes are likely to be impacted by flute genesis. If the obstruction based flute genesis is correct then infrequent but high magnitude disturbances of the probes is likely to occur. Conversely, if the instability based flute genesis holds then the probes are likely to be impacted by constant lateral movement of till. No evidence of either behaviour was discovered in this investigation but it seems likely a higher resolution probe study would.

9.4 *In situ* sensing

Data from the 2008 and 2012 Glacsweb projects has been analysed with a view to understanding the subglacial environment at Skalafellsjökull and providing context to the geotechnical results. The three main strands of analysis focus on data on surface velocity, subglacial hydrology and probe behaviour. Together these also inform on subglacial till rheology.

Surface velocity was found to be diurnally variant but stable on a daily-annual time scale. Over these longer time scales it increased approximately with ice depth. The diurnal variations are similar to motion previously described as ‘stick-slip’ with almost magnitudinal increases in velocity occurring on occasion. The diurnal nature is suggestive of forcing by meltwater inputs into the subglacial hydrological system so whilst the variations are similar to ‘stick-slip’ they may not ascribe to the exact semantics of the term (see section 2.2.3.2).

Subglacial data on pore pressures from Glacsweb probes are spatially heterogeneous. High pressure gradients are maintained across short distances. Some probes appear to be located in areas connected to the subglacial drainage system and pore pressures recorded there tend to be very variable. Other probes appear to be located in areas poorly connected to the subglacial drainage system. These probes record slow changes in pore pressures but are generally at higher pressures than connected areas. One probe recorded stable rises in pore pressure with abrupt falls, similar to the patterns of pore pressure change seen in Moore and Iverson's (2002) experimentation, but with a larger magnitude (70 kPa rather than <5kPa) and duration (10-20 days rather than minutes).

Probe tilt data shows consistent daily movements, matching the stability of daily averaged surface dGPS data. Oscillations in tilt were found, but are rare. They appear to be the right magnitude to satisfy Iverson *et al*. (1998) and Tulaczyk's (2000) theories of decoupling and till dilation, but there is little other evidence that decoupling is happening. Alternative theories (Jacob *et al*., 2010) of unusual tilt data occurring due to spatially and temporally variant filling of drainage systems may be more appropriate. This theory fits the evidence available is and is worthy of consideration in other glacial *in situ* sensing investigations.

The combination of surface movement, pore pressure and tilt data suggests a very complex system. There is no clear causal link between surface movement and the subglacial data. Neither the tilt data nor pore pressure data suggest that wide spread decoupling and sliding can be employed to explain surface velocity variations. This may suggest that motion is likely to be controlled by global factors and longitudinal or lateral coupling to faster moving areas of ice. The nature of the site, on the margins of the glacier, increases the likelihood that this is the case.

9.5 Till rheology

In laboratory testing the till sample from Skalafellsjökull was found to conform to the Mohr-Coulomb model of plastic behaviour. This is in line with a growing cannon of literature that has developed since Kamb's (1991) testing, although different to results from previous Glacsweb work (Hart *et al.*, 2009).

An attempt to scale the behaviour found in the laboratory to glacial behaviour was made. This was based on the supposition that rapid increases in diurnal velocity may occur due to subglacial till exceeding its failure envelope resulting in a non-linear increase in strain rate. Testing to show this directly, as conducted by Tulaczyk (2006), was not attempted, but this behaviour approximating this situation was seen during the PPR experimentation. For this to occur at Skalafellsjökull there must either be a reduction in normal effective stress or increase in shear stress. Basic theoretical calculations suggest that an increase in shear stress of 100% would be required, or decoupling of 50% of the glacier from its bed. The former situation is plausible, and significantly more plausible than the shear stress increase required for similar increases in strain rate if a viscous rheology is applied. Widespread decoupling does not seem feasible under the Glacsweb site based on the probe data collected. Therefore, a plastic rheology and global control on shear stress seems probable.

The experimental design used for the PPR testing, with back pressure control, is thought to be a better replication of the subglacial environment than previous experimentation using periodic normal stress reductions. Therefore, the absence of dilation strengthening in the experiments here may be reflective of subglacial conditions. This is significant, as previously dilation strengthening has been suggested as mechanism for strain distribution during subglacial deformation (Iverson *et al*., 1998; Tulaczyk, 2000; Boulton *et* al., 2001; Iverson & Iverson, 2001; Fowler, 2003). This has significance for the plastic-viscous rheology debate as complex strain partitioning has been employed as an underlying mechanism for the production of large scale viscous behaviour despite small scale plastic behaviour (Fowler, 2003). Strain partitioning is still feasible but probably not due to dilation strengthening.

Dilation strengthening has also been invoked as a controlling factor in stick-slip motion (Iverson *et al*., 1999a; Hooyer & Iverson, 2000; Moore & Iverson, 2002; Roberts & Hart, 2005; Iverson *et al.,* 2007; Rathbun *et al*., 2008; Iverson, 2010; Hart *et al*., 2011). Again, here there is no experimental evidence that this is the case. Whilst stick-slip motion was found at the site studied, it cannot be explained by dilation strengthening. Instead it appears more likely that shear stress fluctuations are responsible (e.g. Bahr & Rundle, 1996), possibly due to the transfer of excess shear stress from central areas of the glacier to marginal areas.

9.6 Conclusions

This study had five initial objectives. The first four have been met fully, and the last one has been partially.

1. **To establish the rheology of the till at Skalafellsjökull**
2. **To establish if the rheology of the till at Skalafellsjökull is consistent across the different modes of investigation.**

The rheology of till at Skalafellsjökull has been shown to conform to the Mohr-Coulomb model and behave plastically in laboratory testing. Consideration of the dGPS data and probe pore pressure data combined with theoretical calculations of driving stress suggest that the till below the Glacsweb site also behaves plastically.

3. **To assess how pore pressure variations impact the behaviour of till samples in geotechnical experimentation, and to what extent the variations and behaviour is replicated at Skalafellsjökull (as observed by the in situ study).**

Testing showed that increasing pore pressure whilst holding other variables constant results in episodic increases in strain rate. Eventual cessation of the elevated strain rates occurred due to shear stress reduction. Unlike previous studies (Moore & Iverson, 2002) there was no evidence of dilation strengthening controlling strain rates. This is thought to be related to the experimental set up (back pressure control) and continual dilation during PPR. This is likely to reflect the subglacial environment better. Dilation strengthening may be less significant in the subglacial environment than previously thought and this has implications for strain partitioning and scale variations in till rheology.

4. **To determine whether Skalafellsjökull moves in a 'stick-slip' manner and to what extent this can be explained by subglacial conditions (as sensed by *in situ* probes).**

Skalafellsjökull has been shown to move in a manner indicative of 'stick-slip' motion. The temporal resolution of the subglacial probe data means that a definitive link cannot be given between surface movement and subglacial process. However, there is little evidence that local pore pressure variations can explain surface velocity variations and the marginal nature of the site suggests that longitudinal and lateral coupling to faster moving areas may be the causal factor.

5. **To assess whether bedforms occur on a specific scale and therefore whether their formation is likely to have an impact on till mobility and associated probe behaviour.**

Flutes on the foreland mapped with a photogrammetric DEM and orthophoto were found to possess similar characteristics to previous studies. Flute lateral spacing was assessed with a GIS tool and found to be on average about 2 m, unimodal, positively skewed and approaching log-normal. Therefore presuming similar flutes are forming at the Glacsweb site their genesis should impact probe behaviour. Depending on how the flutes are created this may result in low frequency but high magnitude disturbances or consistent lateral movement. Neither effect was noticeable in the probe data.

9.7 Future work

A number of opportunities relating to each aspect of this study remain unexamined.

The foreland survey results suggest that complex sediment dynamics may influence the behaviour of subglacial probes. Whilst it would not be possible to resolve features to a similar level, repeat high resolution GPR surveys of a probe site similar to those conducted by Smith *et al*. (2007) would help explore the influence of large scale sediment dynamics on probe behaviour.

In addition to considering sediment dynamics, a better understanding of the spatial variation in ice velocity and its relation to probe dynamics would also be beneficial. The feasibility of using UAV collected imagery for high spatial resolution velocity calculation has already been demonstrated by Immerzeel *et al.* (2014). This could be repeated over the site of a probe deployment. This was attempted in this study but imagery could not be collected due to weather conditions at the Glacsweb site.

One significant advantage of this data would be insight it would provide into the lateral and longitudinal coupling at the site, the global controls. The dGPS data shows that ice at furthest located dGPS (GEF3 – see Figure 76) appears to have a different vector to those closer to the margin. The UAV approach would show whether there is a gradual change in ice direction towards the margin, or if there is a more abrupt change, and whether there are pulses of higher velocity ice that propagate in a similar manner. This would aid analysis of probe data substantially and help with understanding the influence of global effects on surface velocities at the Glacsweb site.

An improved and comprehensive *in situ* survey would evidently be priorities in future work. As discussed in section 7.5.4 a change in the temporal resolution of the probes would be sensible. Previous deployments, this one included, have been focused on probe longevity and examining seasonal change. This has been sensible and undoubtedly has tackled a gap in our understanding.

The focus on longer time scales also circumnavigates issues with basal coupling as it provides plenty of time for the probes to couple with their environment and the boreholes to close. However, in future studies a focus on higher temporal resolution would help make use of the geotechnical findings by making comparison of the two data sources more viable. Changes in pore pressures and strain, in the experimentation presented here and in Moore & Iverson's (2002) work, occur in the order of minutes. Therefore, a suitable temporal resolution would be in the order of 10-60 s.

Recording and transmitting this data would have an obvious impact on battery life. This could be augmented by steps such as only initiating data recording after a defined period. That could be as long as 3 or 6 months. Alternatively, considering the strong diurnal fluctuations in ice velocity, recording for periods of 3 days a high temporal resolution before 'sleeping' again for a period might provide a compromise between tracking seasonal changes and recording higher frequency events. The largest savings in battery life would be found in changing the radio communication protocol. Currently each probe attempts to communicate to the base station for 1 hour each day. Altering this to once per week or once per fortnight would provide a substantial power saving. Furthermore, the automated data retrieval systems have not worked over the course of this study and data retrieval has been dependant on technical members of the team being on the surface to record data. Despite these issues, probes have still been trying to communicate via the automated systems on a daily basis. Switching to the probes only communicating during the summer when people can be on the surface to receive it should again decrease power expenditure.

These changes would all be software changes. With any new deployment there will always be a temptation to alter the probe hardware. This inevitably can lead to system instability and issues such as the water pressure sensor failing in the 2012 deployment. A future deployment should focus on deploying the current system, with perhaps a new battery with a higher energy density. This would allow time for focusing on producing a greater number of probes that can be thoroughly tested and de-bugged ahead of time.

This would still not lead to an unlimited supply of probes, 9 would be a reasonable target, and so the manner in which they are deployed needs to be carefully considered. Deployment could be configured such that it focuses primarily on the longitudinal and lateral coupling of bed deformation or on hydrological forcing.

To study coupling to the wider glacial system, probes would best be deployed in a line from the current area of deployment towards the direction the ice is flowing from. With probes recording at a higher temporal resolution, this would hopefully track the propagation of increased deformation or slip from central to marginal areas. The distance between probes would have to be sufficient for their temporal resolution to enable them to record the progression of the event. Winberry *et al*. (2011) tracked slip propagating at 170-375 m/s at the Whillans Ice Stream. If similar velocities were found at Skalafellsjökull it may mean that this approach would be unfeasible. Probes would either have to record data at an extremely high temporal resolution and avoid any drift in their internal clocks, or they would have to be deployed a long way apart. The latter approach would be unlikely to work as ice depths would quickly become too large for the radios to function reliably.

The alternative focus on hydrological forcing might be more achievable. It would involve deploying the probes in a grid at the existing site, with spacing between the probes kept to a minimum, probably about 10 m. Any closer and issues with precision when drilling boreholes might become problematic, although it would be worthwhile studying borehole precision anyway. With a grid of 9 probes it would be possible to track the influence of hydrological connectivity and to calculate hydraulic conductivity. Considering Iverson *et al*.'s (2007) findings that water connectivity was largely due to occasional flow at the ice-bed interface rather than via diffuse flow through the till, the probes would still need to record at a high temporal resolution.

Alongside improvements in the probe based data collection, changes to the dGPS usage and processing would also be valuable. In particular, the identification of vertical movements would help establish whether decoupling of the ice and bed occurs. Relocation of the dGPS to directly above the grid of probes would provide better coverage. It would also be worthwhile deploying RTK dGPS units during the summer months when power supply could be guaranteed. These would provide a temporal resolution capable of matching the probes.

The geotechnical experimentation in this study has been successful, but two further experimental variations have not been undertaken. PPR experimentation that represents both the rising and falling limb of diurnal pore pressure changes would be novel and interesting. It may be that there is hysteresis in strain rates with NES changes that has not been identified by previous work. Although shear stress was varied dynamically to some extent in these experiments, a more extensive examination of the role of varying shear stress inputs on strain rates would also be valuable. This would be best undertaken on the DynBPS where a variety of shear stress inputs could be tested including waveforms. Finally, as the till tested in this study does differ from that tested by Moore and Iverson (2002) it would be pertinent to attempt to replicate these findings on samples from Storglaciären with the same experimental design. Furthermore, as both tills would be sandy, broadening the approach via additional experimentation on clay based till would be sensible. This would have a lower angle of friction, and perhaps more significantly, a lower hydraulic conductivity.

Appendices

List of references

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