Quaternary Science Reviews 30 (2011) 234–247

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Subglacial till behaviour derived from *in situ* wireless multi-sensor subglacial probes: Rheology, hydro-mechanical interactions and till formation

Jane K. Hart[a,*], Kathryn C. Rose[a], Kirk Martinez[b]

[a] School of Geography, University of Southampton, Southampton, SO17 1BJ, UK
[b] School of Electronics and Computer Science, University of Southampton, Southampton, SO17 1BJ, UK

ARTICLE INFO

Article history:
Received 8 July 2010
Received in revised form
22 October 2010
Accepted 3 November 2010

ABSTRACT

The rheology and hydro-mechanical interactions at the ice–bed interface form an important component of the glacier system, influencing glacier dynamics and the formation of till. We demonstrate that the sand-rich till at Briksdalsbreen in Norway, undergoes deformation throughout the year. On the bulk rheology scale, till deformation exhibits elastic behaviour during the winter, when water pressures are low; and linear viscous behaviour after a critical yield stress of 35 kPa, when water pressures are high during the spring and summer. On the clast and matrix scale, low water pressures, correspond with high case stress variability and till temperatures. Meltwater driven, stick-slip, glacier velocity increases were transmitted through a relatively strong till grain network, causing brittle deformation. Intermediate water pressures, during late summer were linked to intermediate case stress variability and high till temperatures associated with the heat generated from stick-slip motion. High water pressures in the till were associated with low case stress variability and low, meltwater controlled, till temperatures, and occurred in the spring and autumn. Once the till was saturated, the ductile till absorbed any stick-slip velocity increases. We discuss, with examples, the different till forming processes associated with these changing conditions, demonstrating that the resultant till will represent a complex amalgamation of all of these processes.

1. Introduction

The interaction between subglacial water and sediments is a critical component of glacier dynamics. Understanding this interaction, and any associated processes is vital for the prediction of glacier response to climate change and the reconstruction of past glacier behaviour from glacial sediments. Over the last 20 years, progress has been made in our understanding of the subglacial environment, from a combination of *in situ* subglacial experiments (e.g. Hooke et al., 1997; Engelhardt and Kamb, 1998; Murray and Porter, 2001; Fischer and Clarke, 2001), geotechnical experiments (Kamb, 1991; Boulton and Dobbie, 1998; Tulaczyk et al., 2001) and sedimentological investigations (Hart and Rose, 2001; van der Meer et al., 2003; Menzies et al., 2006; Evans et al., 2006). This research has demonstrated the complexity of subglacial processes and the prevalence of subglacial deformation, with 20–85% of glacier motion occurring within the subglacial sediment layer (till) rather than the ice (Boulton et al., 2001).

This has important implications for glacial sedimentology. Prior to the 1980s, most subglacial tills were assumed to be formed by lodgement, a frictional process. However, once the importance of pore-water pressure on subglacial processes was demonstrated (Boulton and Jones, 1979; Alley et al., 1986; Clarke, 1987), it was suggested that lodgement and deformation till were actually part of a pore-water pressure continuum (Brown et al., 1987; Hart and Boulton, 1991; Hicock, 1992; Hicock and Dreimanis, 1992; Iverson et al., 1995), which varies temporally and spatially in the form of mobile beds and sticky spots (Alley, 1993; Piotrowski et al., 2004; Stokes et al., 2007, 2009; Smith and Murray, 2009). Deformation within this layer has been modelled as a shear zone (Hart and Boulton, 1991; Scherer et al., 2004; van der Meer et al., 2003; Lee and Phillips, 2008).

Till deformation involves movement and reorientation of particles at both microscopic (clast and matrix scale) and macroscopic (bulk rheology) scales. Recent experiments using the Disturbed State Concept (Desai, 1974, 2001; Sane et al., 2008) and the critical state response model (Roscoe et al., 1958; Altuhafi et al., 2009) have attempted to model these two elements. Sane et al. (2008) argue that as a material deforms, disturbed zones develop which are distributed throughout the material. As deformation continues, so these elements coalesce. Alternative to the Mohr–Coulomb model (Iverson et al., 1998; Tulaczyk et al., 2000),

* Corresponding author. Tel.: +44 2380594615.
E-mail address: j.hart@soton.ac.uk (J.K. Hart).

0277-3791/$ – see front matter
doi:10.1016/j.quascirev.2010.11.001

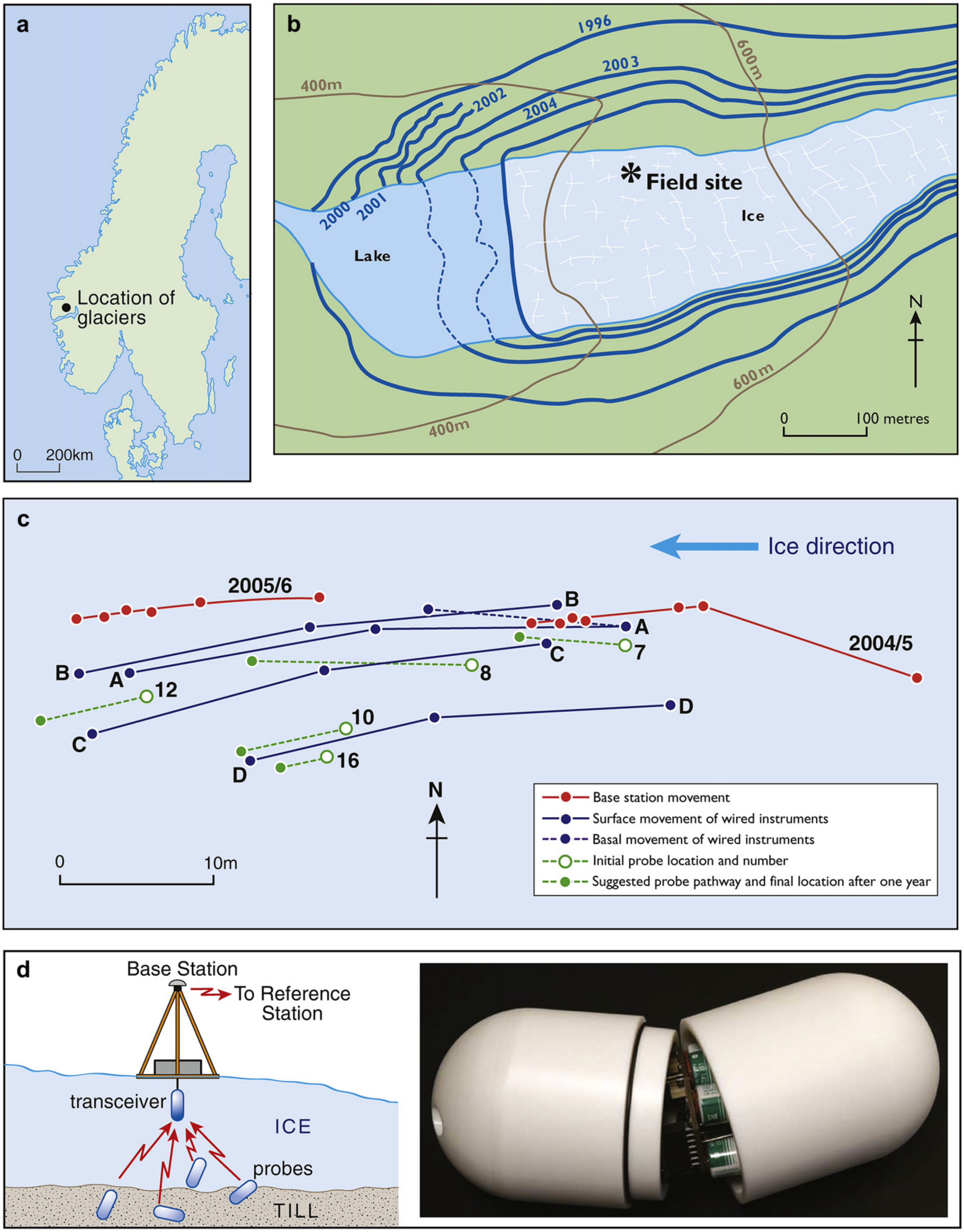

Fig. 1. Briksdalsbreen: a) location of the glacier in Norway; b) map of the lower part of the glacier showing the dated ice limits; c) glacier surface flow paths mapped using Topcon dGPS, A = ploughmeter; B = camera; C = transceiver; D = tilt cells; d) Glacsweb system with a photograph of a probe (0.16 m in length, axial ratio 2.9:1).

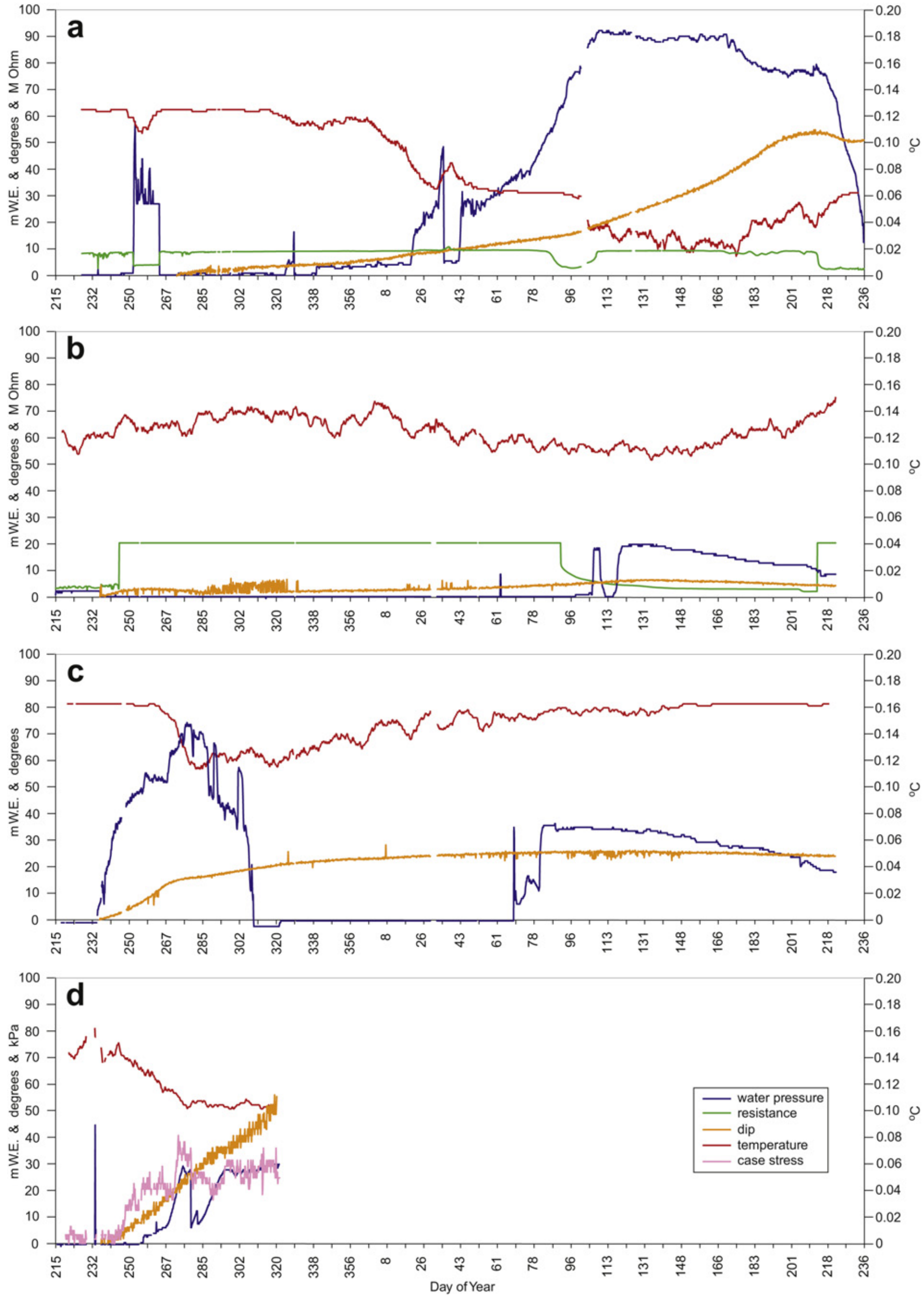

Fig. 2. Sensor readings: a) probe 8 (2004/5); b) probe 10 (2005/6); c) probe 12 (2005/6); and d) probe 16 (2004/5). Sensor readings are omitted where sensors failed to function.

they show failure and motion occur when 85% of the material reaches critical disturbance. Similarly, Hindmarsh (1997) and Fowler (2003) have argued that multiple small areas of weak till may fail, which combine to produce overall viscous flow.

Traditionally, field experiments to examine *in situ* till deformation have been limited by the inaccessibility of the basal zone. We have developed a new *in situ* wireless Glacsweb probe (Martinez et al., 2004; Hart et al., 2006) to examine the subglacial environment and sand-rich till from beneath Briksdalsbreen, a small, rapidly retreating Norwegian glacier with an aquatic margin. Here we use the probes to investigate the two scales of deformation, rheology and hydro-mechanical interactions at the ice–bed interface. In the latter, we focus on the relationship between water pressure (hydrology), case stress and till temperature (mechanical properties). We discuss how these findings can help us to understand the process of deformation and the development of till, which will consequently have implications for the interpretation of till sedimentology.

1.1. Methodology

The study was undertaken at Briksdalsbreen, an outlet glacier from Jostedalsbreen, in Southern Norway, underlain by Precambrian gneiss bedrock (Fig. 1). This glacier advanced 390 m between 1987 and 1996, over its proglacial lake and into a birch forest (Winkler, 1996; Kjøllmoen, 2007). This dramatic readvance is thought to have resulted from a precipitation increase associated with a positive phase of the North Atlantic Oscillation (NAO) (Nesje and Dahl, 2003). However, since 1997 the glacier has retreated approximately 460 m (measured April 2007), associated with

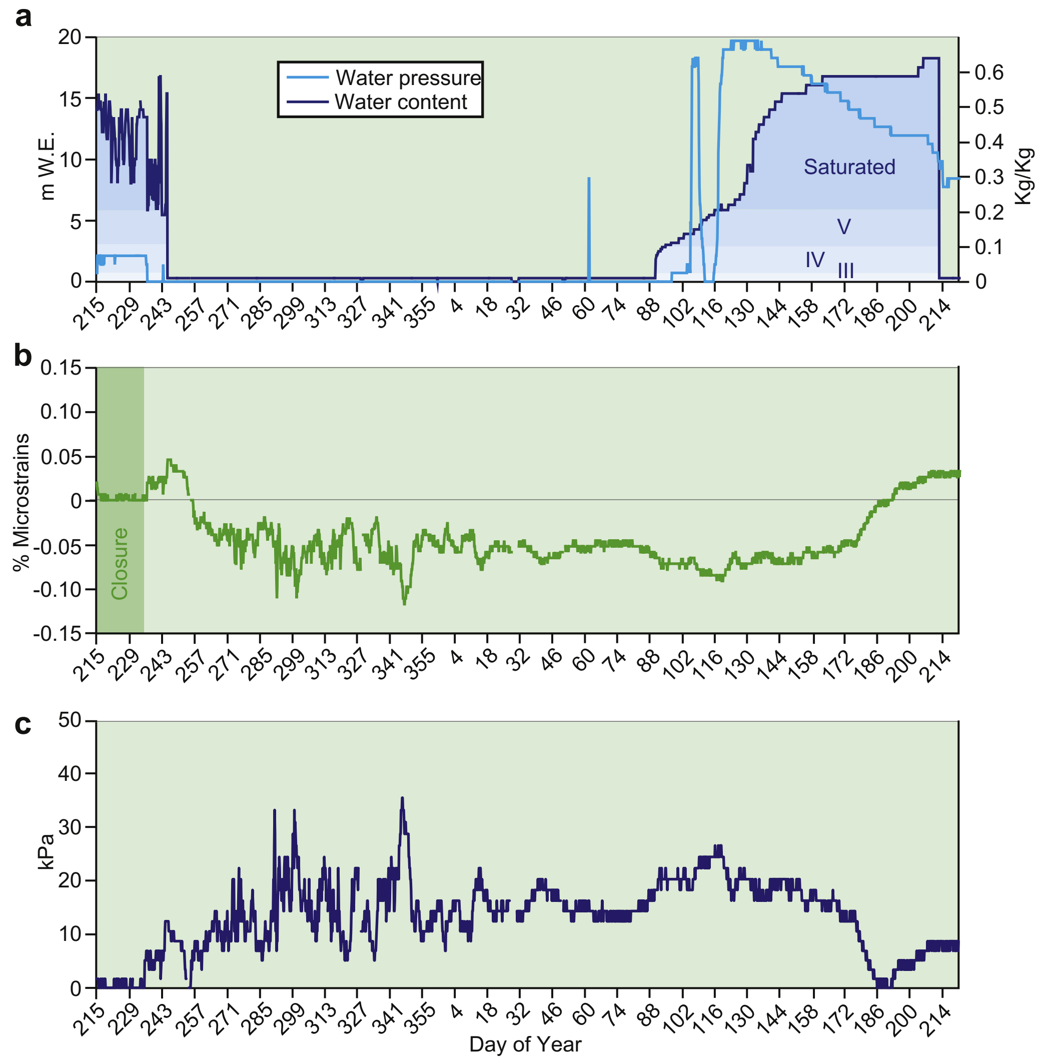

Fig. 3. Probe 10 a) water pressure and calibrated water content (derived from resistance, see text for details, water regimes I, II and III have such low water contents that they have been shown as 'III' in the diagram; b) case strain (measured as % microstrains), c) calibrated case stress.

a combination of a negative phase of the NAO and global climate change (Winkler et al., 2009; Laumann and Nesje, 2009).

The post – 1996 foreland comprises push moraines (1–7 m in height) and a preserved subglacial surface of flutes and lineations (Winkler and Nesje, 1999; Hart, 2006). Thin section and SEM studies of the subglacial till provide evidence for subglacial deformation and erosion within an approximately 0.3 m thick deforming layer (Hart, 2006; Rose and Hart, 2008). The Glacsweb system ran from August 2004 to August 2006 and was installed on the glacier where it was flat and crevasse-free with safe access (Fig. 1d). Micro-sensors, housed within a probe (0.16 m long, axial ratio 2.9:1), measured water pressure, probe deformation, resistance, tilt and probe temperature within the ice or till. These data were recorded six times a day, and transmitted to a base station located on the glacier surface. Probe data, along with differential GPS (dGPS) and meteorological data, were sent once a day to a mains powered computer (2.5 km away), where it was forwarded to a web server in the UK. The specific details of the system are explained in Hart et al. (2006).

Probes were deployed in the summers of 2004 and 2005, in a series of boreholes, which were drilled with a Kärcher HDS1000DE jet wash system. Once the boreholes were made, the glacier and till were examined using a custom made CCD video camera. This used infra red (900 nm) illumination in 2004 and a white LED illumination colour camera in 2005. The video was captured using Digital Video camera. The thickness of the glacier was determined from the measured borehole depths and a 50 MHz Ground Penetrating Radar survey. The glacier limits, boreholes, base station and radar grids were mapped with a Topcon dGPS system.

In order to insert probes into the till, the boreholes were drilled to the base of the glacier, and the presence of till checked with the video camera. If till was present it was hydraulically excavated (Blake et al., 1992) by maintaining the jet at the bottom for an extended period of time. The probes were then lowered into this space, enabling the till to subsequently close in around them.

1.2. Summary of results

Overall, from the probes deployed, four lasted more than one month during 2004/5 (859 days of probe data; 36,078 sensor readings) and a further four survived during 2005/6 (1208 days of probe data; 50,715 sensor readings). This paper will focus on probe 8 (2004/5), and probes 10, 12 and 16 (2005/6), all of which were held solely within the till (Hart et al., 2009). The depth of the probes within the till is not known, but is approximated at 0.2 m beneath the glacier base, estimated from video footage of the ice–till interface. Precipitation and air temperature data were collected by the base station and the closest Norwegian meteorological station.

Observations from the ice margin and boreholes showed that the glacier's basal ice is free from debris. Instead, there was an abrupt ice/till boundary. The till had a mean grain size of 1600 μm and the less than 4 mm fraction comprised 93% very fine gravel and sand, 7% silt and 0% clay (Rose and Hart, 2008). We were only able to derive a quasi − monthly glacier velocity record because of power loss of the Topcon unit and intermittent satellite reception due to obstructions from the steep sided valley walls. The record showed high summer velocities that decreased to a minimum in December, followed by a spring peak in March, a subsequent decline in April, and a rise in early summer (see Hart et al., 2009). The internal angle of friction (φ) was measured at 35°. The surface slope angle of the on ice study area was measured to be 14° in 2004 and 16° in 2005.

1.2.1. Water pressure

This is measured as meters water equivalent (hereafter referred to as mW.E.) and records for the probes show similar patterns over the year (Figs. 2 and 3). We have categorised water pressure into three relative classes: high, intermediate and low. Most probes experienced low pressure during the winter (apart from some short high water pressure events during autumn) (probe 8: day of year [D] 213–8; probe 10: D244–88; probe 12: D213–229, 304–63; probe 16: D213–251), high water pressure in spring and early summer (mostly associated with rising water pressures) (probe 8: D8–176; probe 10: D89–176; probe 12: D229–304, 63–176; probe 16: D263–316), and intermediate water pressure during late summer (associated with failing water pressures) (all probes approximately D176 onwards). It has been argued that the spring high water pressure events relate to the opening of the hydrological system and are discussed in detail in Rose et al. (2009).

1.2.2. Resistance

The electrical resistance of the material outside the probe was measured across two bolts. Different sensors were used in 2004 and 2005 (hence the different data ranges in Fig. 2) and were calibrated in the laboratory. High resistance indicates dry or frozen material, low values indicate wet sediments. For water contents of 0–35%, there was a relationship between water content (w) and resistance (R). The resistance sensor did not function in probes 12 or 16. Probe 8 recorded an inverse relationship between resistance and water pressure whilst the borehole was still open (D212–277). Following this resistance remained mostly high during the winter, with a low resistance event during the spring and a slow fall in resistance into the summer (Fig. 2a). Probe 10 generally showed an inverse relationship between resistance and water pressure (Fig. 2b). Till water contents derived from readings of resistance (Fig. 3a), may also be classified into six classes of till water storage, as defined by Helsey and Levine (1998). In water content regimes I, II and III the water within the till will be stored as liquid bridges. Water regime IV reflects coalesced bridges, which form liquid clusters in water regime V. Finally, water regime VI reflects till saturation at approximately 0.25 kg/kg.

1.2.3. Case stress

Strain gauges measure relative compression and extension of the probe case in two perpendicular planes, which are expressed as relative positive and negative values (microstrain as a %) (Fig. 3b). This data can also be expressed as case stress, i.e. the force applied to the probes per unit area (Figs. 2d and 3c). The applied force was calibrated using an Instron 5560 tension/compression machine attached to a nitrogen cooled chamber, where the average chamber temperature was 1.3 °C. The case strain sensors were very delicate and only remained active in probes 10 and 16, which both showed a pattern of high annual and daily variation.

Table 1
Estimation of subglacial deformation as a percentage of basal motion.

Year	Probe	% 2× resolution of the tilt sensor	3× resolution of the tilt sensor	4× resolution of the tilt sensor	Mean (s.d.)
2004/5	7	65	62	59	64 (5.7)
	8	73	68	58	
2005/6	10	66	54	45	56 (7.9)
	12	70	58	48	
	16	55	54	54	

1.2.4. Tilt

The Glacsweb probes measure tilt with two dual axis 180° MEMS accelerometers. Values of 0° x-tilt and 0° y-tilt represent the probe standing vertically. Dip is calculated by trigonometry (for details see Hart et al., 2009). The tilt data indicated that the probes were generally inserted in a vertical position. Their dip then decreased over time (e.g. in probe 8, 0.06° per day in December, to 0.4° per day in June) (Fig. 2). There was a systematic temporal pattern in the style of movement recorded by the probes. After initial changes in dip, the probes experienced changes in orientation, followed by rotation about the longest (a) axis during late summer. All the probes showed significant overall rotation (probe 7: 46°; probe 8: 54°; probe 10: 6°, probe 12: 26°; probe 16: 52°) (Fig. 2). In addition, large dip oscillations occurred during periods of high water pressure, and typically comprised short, frequent dip oscillations, averaging a dip change of 3.32° over a 7 h period (Hart et al., 2009).

Glacier motion is composed of ice flow, basal sliding and subglacial deformation. Due to the exposure of buried ploughmeter, whose cable had snapped 75 days after deployment in a borehole, it was calculated that basal movement accounted for 70% of net surface glacier velocity (measured by dGPS). Relative measurements of till deformation were made by assuming that deformation will produce significant changes in probe dip, whilst sliding will produce little change. A sensitivity study was made to determine the threshold for "sliding". Two to four times the resolution (0.048°) of the tilt readings was taken, in order to estimate the

Table 2
Parameters used for the calculation of rheological properties.

$\tau_b = F\rho gh \sin\alpha$	F = shape factor derived from Nye (1965) for a parabolic shaped valley glacier ρ = density of ice g = acceleration due to gravity h = thickness of the glacier α = glacier slope angle
$p_e = p_i - p_w$ $\tau_o = C + (p_i - p_w)\tan\varphi$ We have ignored any component strength from cohesion in line with Clarke (1987); Fischer and Clarke (1994); Hooke et al. (1997); Boulton and Dobbie (1998) and Tulaczyk et al. (2000).	p = pressure of ice and water C = cohesion φ = angle of friction
γ = displacement/depth	
$\dot{\varepsilon} = d\gamma/dt$	
$\eta = \tau_b/\dot{\varepsilon}$	
d_s = annual till movement × depth × width	

Table 3
Evidence for subglacial deformation and the relationship between subglacial water pressure and ploughmeter response from the literature.

	Basal motion due to sediment deformation %	Thickness of deforming layer (m)	Yield stress (kPa)	Till Viscosity (Pa s)	Till discharge per m^3 section per year[a] ($m^3\ a^{-1}$)	No of records presented	Length of record	Depth (m)	Located in the same hole as pressure transducer	Connected (C) or unconnected (U)	Diurnal changes	Relationship between water pressure and ploughmeter
Trapridge glacier Fischer and Clarke, 1994	24–45	0.3	48–57	3×10^9–1.5×10^{11}	314	2	13 days	0.1–0.4	No (1 m away)	U	Yes and no	Inverse and weakly positive
Trapridge glacier Fischer et al., 1999						2	16 days	0.1–0.2	No (within 10 m)	C	Yes	Inverse and positive
Storglaciaren Fischer et al., 1998	≈26	0.35	55	–	0.64	1	70 days	0.13	Yes	U	No	Inverse
Unteraargletscher Fischer et al., 2001						1	26 days	0.1	Yes	C	No	Inverse
Bakaninbreen Murray and Porter, 2001		0.1–0.2	82	6×10^{10} to 4.3×10^{11}	–	9	1–4 years	0.08–0.55	No	U and C	No	Mostly none, positive and inverse
Breiðamerkurjökull Boulton and Jones, 1979; Boulton and Hindmarsh, 1987; Boulton et al., 2001	67–85	0.38–0.45	5.7–32.5	5×10^{10} to 5×10^{11}	3.2–6.3							
Black rapids glacier Truffer et al., 2000	100 below 2 m, 0 above 2 m	>2			>60–80							
Columbia glacier Humphrey et al., 1993		0.65	5.5–13		315							
Briksdalsbreen	56–64	≈0.3	35	3.6–7.3×10^9	1.3–5.6	4	1 year	≈0.2	Yes	?	No	Positive and inverse

[a] From Boulton et al., 2001.

amount of time during which "deformation" occurred. This was then used as a proxy for the percentage of basal movement due to deformation. The mean basal motion due to deformation was 64% (±9%) in 2004/5 and 56% (±14%) in 2005/6 (Table 1).

1.2.5. Temperature

This was recorded in all of the probes and provides one of the few continuous records of till temperature. Readings were always positive, with a maximum value of 0.25 °C (Fig. 2).

2. Discussion

2.1. Rheology

Sediments such as soil or till undergo mixed behaviours of elasticity, viscosity and plasticity during deformation (Ghezzehei and Or, 2001). At low stresses material deforms elastically and when the stress is removed, the original shape is restored. However, above a critical stress value (yield stress), the material may deform in a viscous manner, i.e. stress is proportional to strain rate, and the original shape is unrecoverable (Bingham material). This relationship may be linear or it can be described by a non-Newtonian power law (Wilkinson, 1960):

$$\dot{\varepsilon} = k(\tau - \tau_o)^n \tag{1}$$

where $\dot{\varepsilon}$ = strain rate and τ = shear stress, k and n are constants. Alternatively, in a plastic-Coulomb model, deformation of an ideal plastic body only occurs at the yield stress, which is also the maximum stress.

At Briksdalsbreen, we have used the field results to inform us about the rheology by calculating: i) shear stress (τ_b), ii) effective pressure (p_e), iii) Coulomb yield strength (τ_o),iv) shear strain (γ), v) strain rate ($\dot{\varepsilon}$), vi) viscosity (η) and vii) sediment discharge per 1 m^3 transverse section per year (d_s) (see Table 2 for equations and explanation of symbols).

Since till deformation comprises both matrix and clast (probe) movement, the displacement was estimated by assuming that the till movement (bulk rheology) was proportional to the changes in probe dip. Three estimates were made of shear zone depth, a maximum depth of 0.4 m, an intermediate depth of 0.3 m (based on the average flute thickness), and a minimum value of 0.2 m (since probe length was 0.16 m). These thicknesses are comparable with those recorded from other valley glaciers (Table 3).

Fig. 4 shows a plot of tilt per day against excess shear stress ($\tau_b - \tau_o$) for five periods throughout the year that were delimited by the recorded surface velocity measurements and had similar water pressure readings. This indicates that a small amount of movement occurs in the till when the Coulomb yield stress has not been exceeded. This occurred during times of low water pressure during the winter and probably reflects the elastic behaviour. The relationship between shear stress and strain rate was examined for the high water pressures periods in the till and plotted for three values of deformation and three shear zone depths (Fig. 5). Although with increasing depth of the shear zone there is decreasing strain, it can be seen that the results are very similar. There is a distinct increase in shear stress with shear strain (with an average r^2 value of 0.75) above a critical yield stress of 35 kPa (s.d. = 0.35). This behaviour is indicative of linear Bingham viscoplastic flow with an n value of 1.

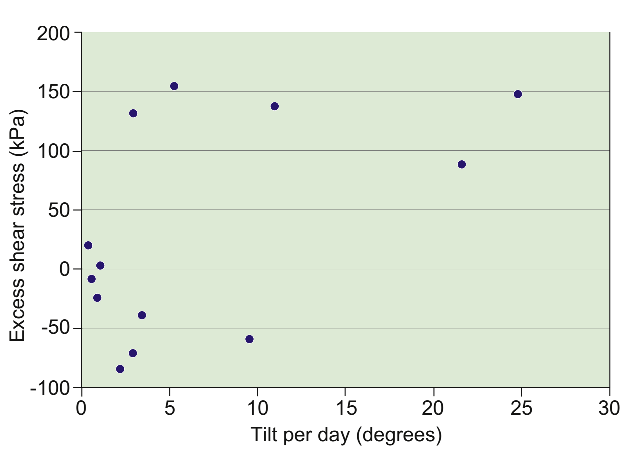

Fig. 4. Tilt per day against excess shear stress.

The yield strength, viscosity and till discharge results are very similar to examples from other valley glaciers with deforming beds (Table 3). In line with Porter and Murray (2001), we argue that, although our results do not support the Breiðamerkurjökull flow relations (Boulton and Hindmarsh, 1987), neither did we find a consistent relationship between effective pressure and shear strain, which is crucial to a plastic model of rheology (Tulaczyk et al., 2000).

2.2. Hydro-mechanical interactions

Hydro-mechanical interactions at the ice–till interface can be assessed in terms of probe water pressures (hydrology), and case stress and temperature (mechanical properties). The relationship between sediment strength (case stress) and variations in subglacial hydrology (water pressure) can reflect changes in till behaviour. This may affect the proportional contribution of sediment deformation to basal motion and consequently influence the overall formation, and make-up, of the till.

Our water pressure results are unusual as we measured generally low water pressures in the winter and high water pressures in the spring and summer. Most *in situ* studies have shown high water pressures throughout the year. Porter and Murray (2001) show winter water pressures of approximately 20 mW.E. associated with the Bakaninbreen surge, which was approximately a third of summer water pressures. Willis et al. (2003) have shown from the Haut d'Arolla glacier, that water pressures remain between 45% and 115% of ice over burden throughout the autumn and winter. At Briksdalsbreen, such low winter water pressures may be partly an effect of the high porosity till, or more likely due to the aquatic margin.

Our results have also indicated that water contents within the till during the winter were very low, and rose to saturation in the summer (Fig. 2). Although it is often assumed that the subglacial environment is always saturated, there have been very few studies of till water contents during the winter (Porter and Murray, 2001). Clarke (2005) states that beneath temperate glaciers, free water can exist at the ice–bed contact and interstitially in subglacial sediment. Nolan and Echelmeyer (1999) have argued that it was possible for tills adjacent to conduits during high pressure events to become temporarily unsaturated.

2.2.1. Water pressure and deformation

Overall, it can be seen from probe 10 (Fig. 3) that there are two distinct patterns of case stress. During the winter (D244–88) when the water pressure was very low, the case strain showed very high variation, whilst during the spring and summer as water pressure rose, the variation in case strain decreased (Table 4). Both daily and long term trends were observed in these records.

During periods of low water pressure in the winter, case stress values fluctuated within a range of 30 kPa, over 6–21 days (mean 12 days, s.d. 6.3). An example with the largest range was from

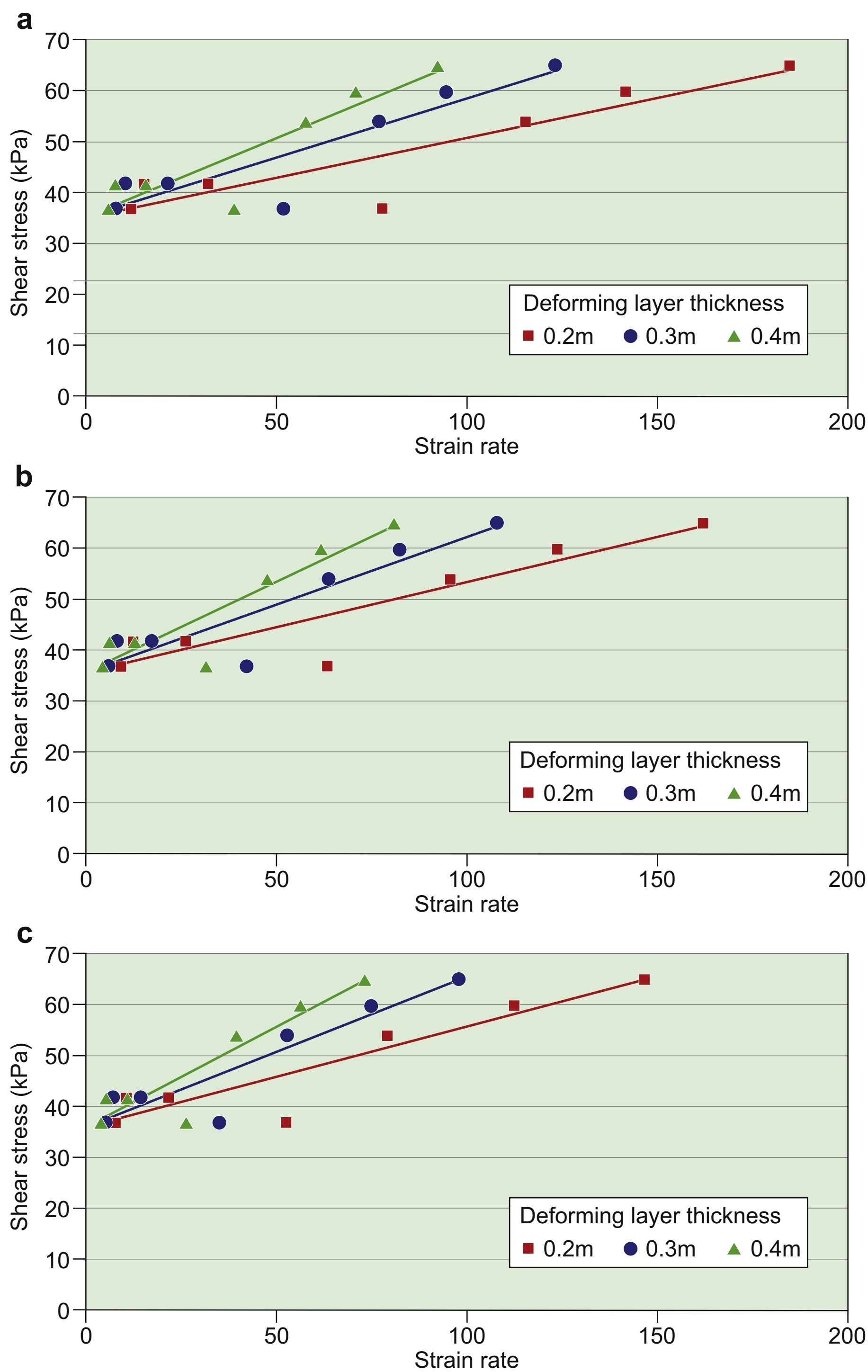

Fig. 5. Strain rate against basal shear stress for three possible deforming bed thicknesses and amount of basal motion due to subglacial deformation, see text for details.

D335–356. The case stress maxima occurred within 4 days of a precipitation or high temperature (over 10 °C) event, with a mean lag of 2 days. Typical daily stress changes comprised a pattern of low case stress in the morning, with stresses rising through the day.

During the high and intermediate water pressure events in the summer (after D105) there were low range, irregular length oscillations (average 19 days, s.d. 15) (range 5–10 kPa). A typical example is D140–156. When the case stress maxima were compared with high rainfall and temperature events it was found that there was also an average lag time of 2 days. However, many rainfall or high temperature events had no effect on the case stress.

In probe 10 during the early summer, water pressure rose in a three day peak (D106–109), and was followed by a high pressure event which fell to intermediate pressure towards the end of the summer (Fig. 2). Case strain initially decreased slightly as pressure rose (D98–134), but as water pressure slowly began to fall (D135–221), there was a positive relationship between water pressure and case stress (Fig. 6).

Table 4
The relationship between water pressure and case strain and temperature.

	Case strain (% microstrain)				Mean probe temperature (°)			
	Probe 10		Probe 16		Probe 8	Probe 10	Probe 12	Probe 16
	Range	Mean (abs)	Range	Mean (abs)				
Low water pressure	0.116	0.051	0.013	0.072	0.161	0.027	0.041	0.34
Intermediate water pressure	0.065	0.018	–	–	0.111	0.026	0.061	–
High water pressure (summer)	0.032	0.064	0.072	0.093	0.097	0.009	0.056	–
High water pressure (autumn)							0.021	0.318

Probe 16 only recorded readings of water pressure and case stress during autumn 2005 (Fig. 3d), but showed a similar response to probe 10. As water pressure began to increase, case stress initially decreased (D256–270). This continued until a critical value of water pressure was reached; 10 mW.E. during the first water pressure rise, and 21 mW.E. during the second pressure rise. Once this threshold had been exceeded, case stress then generally increased with increasing water pressure. This highlights that, over time, a higher water pressure threshold was required for the same response in case stress.

At Briksdalsbreen, we have observed during the winter that there are dramatic changes in case stress (Fig. 3). The largest case stress maxima relate (within a 2 day lag period) to variations in external weather conditions. We suggest that, during the winter, surface water, generated from rainfall or surface melt, takes a long time to pass through the glacier since the majority of englacial pathways have closed and the glacier is snow covered (Roberts et al., 2006; Purdie et al., 2008). The water that does reach the subglacial environment may cause an increase in glacier velocity (Iken et al., 1983; Mair et al., 2001; Bartholomaus et al., 2008; Walter et al., 2008). This may be particularly relevant during the winter when the subglacial drainage system will be poorly developed and of a low capacity (Willis, 1995; Rose et al., 2009). Consequently, this may result in a series of short-lived, meltwater driven, 'slip' events (Bahr and Rundle, 1996; Fischer and Clark, 1997). Superimposed on these longer term meltwater driven changes are daily case stress changes, which may reflect daily variations in water generated from frictional heating, as a result of high basal drag at the ice–bed interface.

Previous research on the relationship between subglacial water pressure (at the ice–bed interface) and force (recorded by ploughmeters) provides contradictory responses. Most studies have found both positive and inverse relationships (Table 3), attributing these findings to a variety of till behaviour (e.g. Hooke et al., 1997; Fischer et al., 1999; Murray and Porter, 2001). Similarly, laboratory studies to investigate the relationship between water pressure and till strength associated with the ploughing of an instrument through till have also been contradictory. Thomason and Iverson (2008) argue that resistance to ploughing can decrease with increasing ploughing velocity (velocity weakening) in clay-rich tills. They suggest that the till on the lee-side of ploughing particles is compacted and sheared as particles move through it. The porosity reduction during compaction increases till pore-water pressures. In contrast, Rousselot and Fischer (2007) argue that the degree of sediment weakening in front of ploughing clasts depends on the relative magnitudes of excess pore pressure generated by sediment compression, as opposed to strengthening by dilatant shearing. They discuss how, according to critical state theory, a sediment may increase or reduce its volume during shearing depending on its initial porosity (Lambe and Whitman, 1979).

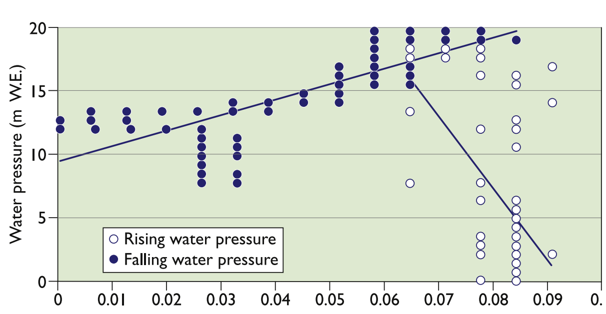

Fig. 6. Relationship between probe 10 case strain and water pressure associated with water pressure rise (D98–134) (negative relationship) and water pressure fall (D135–221) (positive relationship).

Granular materials behave very differently depending on their water content and numerous researchers (e.g. Schiffer, 2005; Nowak et al., 2005) have argued that even a very small percentage of water can affect its physical behaviour, because capillary action can produce interstitial liquid bridges between grains. This acts to strengthen the material at low water contents (Helsey and Levine, 1998; Herminghaus, 2005) (water content regimes I, II and III) and results in a granular regime, dominated by the motion of individual grains. However, as the water content, and thus connectivity between the grains, in sediments increases, so the yield strength decreases (water content regimes IV and V). Eventually, with high water contents (saturation; water content regime VI), the type of deformation changes from a granular regime, to cohesive flow (Tegzes et al., 2003).

At Briksdalsbreen, when the water content in the till is low and the till is relatively strong (due to interstitial bridges), we suggest that stick-slip motion at the glacier base will transmit changes in glacier shear stress directly to the probe via the grain structure. This is represented by a reduction in case stress during the slip event, and a subsequent increase in stress as the ice reconnects with its bed and basal drag increases.

Once the pore-water pressure and water content of the till rise, the pattern of case stress changes. Initially, as water pressure rises, the sediment is weakened. Fischer and Clarke (2001) explain this negative relationship as a process of *elastic relaxation*. As a result, the variation in case stress is reduced, and becomes much less dependent on meltwater generated events. Conversely, above a certain critical threshold a positive relationship occurs, and each time this occurs a greater critical pressure is required to trigger the same response. This may reflect initial excess pore-water pressure (generated by sediment compression), followed by strengthening (increase in case stress) once deformation by grain shear, dilation and rolling has occurred (*dilatancy hardening* – Kavanaugh and Clarke, 2001). This results in an increase in case stress with water pressure, as sediment strength increases, despite a reduction in the applied shear stress of the ice above.

2.2.2. Till temperature

In addition to case stress, till temperature may also provide an indication as to the mechanical properties of the till and how they relate to variations in subglacial hydrology. There have been very few previous studies of till temperature and so there is little comparative literature. The relationship between water content and till temperature at Briksdalsbreen can be seen in Fig. 2. Overall,

Table 5
Parameters and values used for temperature calculations.

Symbol	Parameters and unit	Values
G	Daily geothermal flux (J/m^2)	3888[a]
I	Daily ice flux (J/m^2)	191808[b]
H_t	Till thickness (m)	2[c]
H_d	Deforming bed thickness (m)	0.3[c]
ρ	Till bulk density (kg m^{-3})	2100
c_t	Specific heat capacity of till (J kg^{-1} K^{-1})	1150[b]
c_w	Specific heat capacity of water (J kg^{-1} K^{-1})	4180[b]
m_t	Mass of 1 kg till (kg)	1[b]
μ	Coefficient of friction (dimensionless)	0.5[b]
p_m	Yield strength of material (N m^{-2})	100,000[c]
W	Normal load (N)	2940–5520[c]
K	Thermal conductivity of till (W (m °C)$^{-1}$)	3[b]
V	Till velocity (m s^{-1})	3.35×10^{-8} to 9.27×10^{-7}[c]
l	Length of till (m)	1
w	Width of till (m)	100

[a] Estimate based on the Pollack et al. (1993).
[b] http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html.
[c] Measured at Briksdalsbreen.

probe temperature showed an inverse relationship with water pressure and positive relationship with case stress. A summary of the temperature values associated with water pressure is shown in Table 4.

Heat within the deforming layer will be estimated by:

$$\text{frictional heat}\left(T_f\right) + \text{geothermal heat}\left(T_g\right) - \text{heat from the ice}\left(T_i\right) - \text{meltwater}\left(T_w\right) \quad (2)$$

Table 5 shows the values and units used to calculate these different components. It can be assumed that geothermal heat and heat from the ice remain constant over the year, and the main differences between the low water pressure regimes and the higher levels must be due to heating from friction and cooling from meltwater inputs. Using probe 8 as an example it can be seen that there was a 0.85 K reduction in temperature between the low water pressure (winter) and high water pressure regimes (spring and early summer), followed by a rise in temperature of 0.023 K between the high water pressure regimes and the intermediate water pressure regimes (late summer).

Using equation (3), we can estimate the temperature of the water draining from the ice (0.061 K), assuming a water content of the till of 25% (saturation). This would result in a predicted cooling of 0.07 K. This is very close to the fall in temperature seen in probe 8.

$$\Delta T_w = \frac{m_t c_t 0.025}{m_w c_w} \quad (3)$$

Table 6
Summary of till behaviour.

	Water pressure		
	Low	Intermediate	High
Rheology	Elastic	Viscous	Viscous
Case stress variability	High	Intermediate	Low
Probe temperature	Moderate	High	Low
Probe tilt	Slow changes in dip	a-axis rotation	Dip oscillations
Water content	Low	Saturated	Saturated
Till strength	Strong	Dilation strengthening	Dilation strengthening
Deformation	Brittle	Ductile	Ductile
Season	Autumn, winter	Late summer	Autumn, spring, early summer

In order to calculate frictional heat, we have used equation (4) (Bestmann et al., 2006; adapted from Archard, 1958):

$$\Delta T_f = \mu \frac{(\pi p_m)^{\frac{1}{2}}}{(8K)} W^{\frac{1}{2}} V \quad (4)$$

This gives a predicted temperature rise of 0.0007 K.

The predicted fall in temperature due to meltwater is very similar to the measured values from probe 8 during the spring high water pressure rise. However, during the late summer intermediate water pressure regime, we would assume the cooling due to meltwater inputs to be the same, so the only difference to account for the measured till temperature rise would be an increase in friction. This could be due to the increased deformation measured by increased probe movements (Fig. 2). However, the theoretical temperature changes due to friction as discussed above are very small.

An explanation for the additional frictional heating in the till, may be the result of 'flash' temperatures. These are described by Bestmann et al. (2006), in association with stick-slip motion. Similarly, Archard (1958), using both empirical and experimental data, argues that the aggregate resistance of a large number of small, closely grouped particles is similar to the resistance of one large particle. Archard (1958) suggests that there is a difference in behaviour between low and high pebble velocities. At low velocities the heat can be diffused, whilst at higher velocities there is insufficient time for heat diffusion and so temperatures can rise. In the latter scenario the following relationship applies:

$$\Delta T_f = \mu \frac{1}{3.25} \frac{(\pi p_m)^{\frac{3}{4}}}{(K \rho c_t)^{\frac{1}{2}}} W^{\frac{1}{4}} V^{\frac{1}{2}} \quad (5)$$

Archard (1958) argue that equation (4) can be used where the Peclet number (L) is less than 0.1 and equation (5) is used where the Peclet number is greater than 100. The Peclet number (equation (6)) measures the relative importance of advection (high L) and conduction (low L).

$$L = \frac{lV}{\left(\frac{K}{\rho c_t}\right)} \quad (6)$$

At Briksdalsbreen this would result in a Peclet number of 32 during the intermediate water pressure regime. Assuming a linear relationship between Peclet number and temperature rise, this would result in a temperature increase of 0.027 K. This is very similar to our probe 8 results which show a rise of 0.023 K. Consequently, we associate the elevated probe temperatures with additional frictional heating resulting from deformation.

2.2.3. Summary of till behaviour

In Table 6 we summarise the different till behaviours associated with different water pressures. We were able to show that during low water pressures elastic behaviour was observed, followed by linear viscous behaviour associated with high water pressure. On the microscale, we suggested that as water pressures initially rose this related to elastic relaxation, and once water pressures were high there was a positive relationship between water pressure and case stress due to dilatancy hardening. This suggests that the rheology of till is readily variable and strongly dependent on localised conditions. Thus, any modelling of till rheology needs to take this into account. The *in situ* probe provides data (on both the macro and micro scale) to enable us to begin to constrain the conditions under which the mode (rheology) of deformation changes with subglacial conditions.

2.3. Till formational processes

In this section, we discuss how the different types of subglacial behaviour observed from the probes can be related to the resultant till sedimentology both at Briksdalsbreen and to tills in general.

2.3.1. Low water pressure

During low water pressure, the till had relatively low water content, and deformation was imparted through the till as a result of velocity stick-slip events. In terms of till sedimentology, these conditions would result in brittle deformation of the sediment. Numerous researchers have suggested this process would cause grain fracture (Cuffey and Alley, 1996; Van Hoesen and Orndorff, 2004; Mahaney, 2008). At Briksdalsbreen, SEM studies showed that grain fracture and abrasion occurred together associated with subglacial deformation. However there were till samples where the dominant erosional form was grain fracture (Hart, 2006; Rose and Hart, 2008; Fig. 7a), which may reflect deformation of a strong

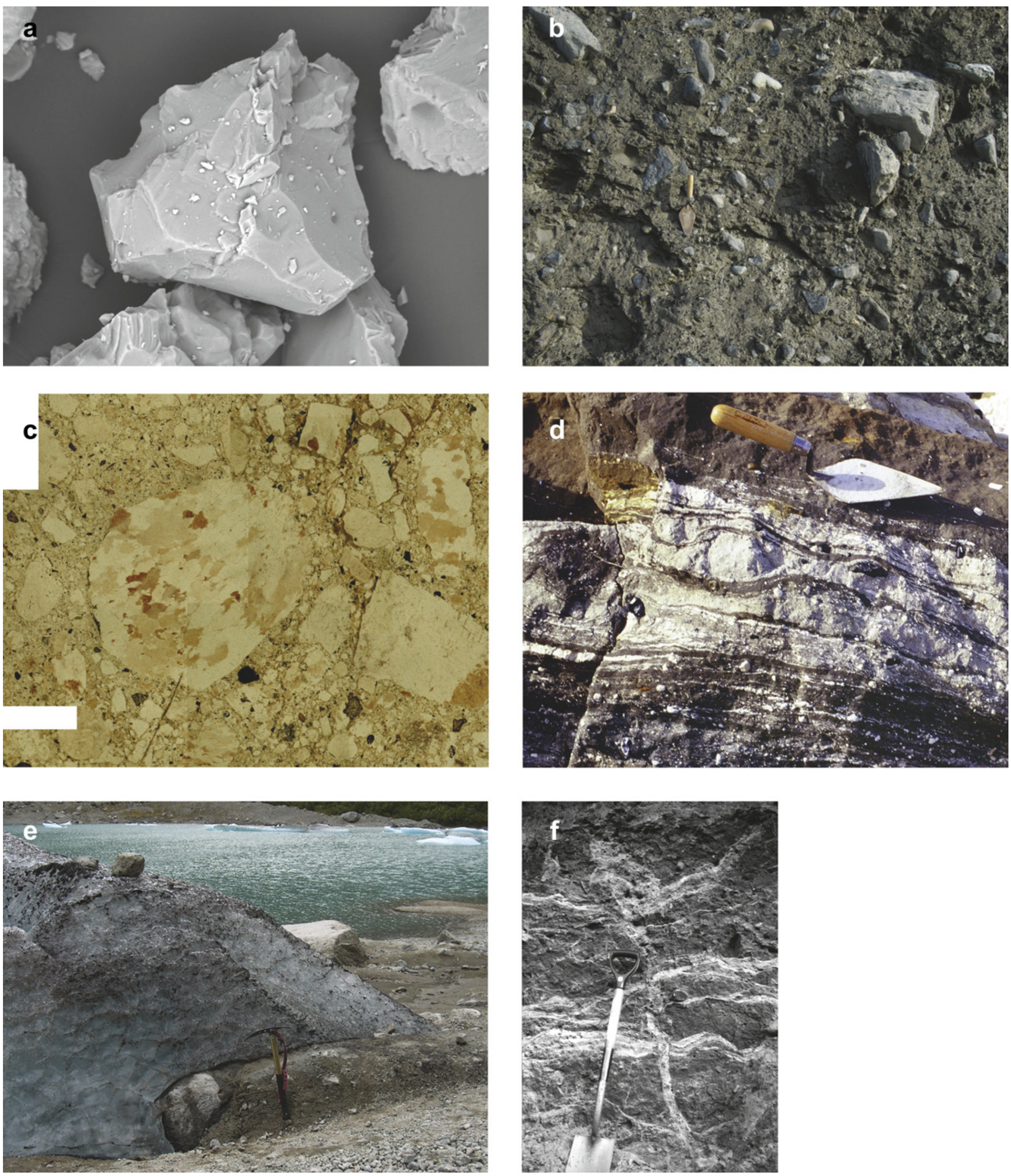

Fig. 7. Sedimentary products: a) percussion erosion from low water pressures (Briksdalsbreen subglacial sample (collected from base of a borehole); b) brittle deformation associated with low water pressures (Thornhill, Ireland); c) microscale deformation (Briksdalsbreen); d) ductile deformation (West Runton, England); e) flute emerging from glacier terminus (Briksdalsbreen); f) subvertical and horizontal hydrofractures infilled with laminated silt sand and clay, associated with high water pressures (Clava, Scotland – Philips and Merrit, 2006).

grain till network. Other examples of brittle deformation that are typically seen within till include faulting (e.g. Benn, 1995; Hart et al., 1996; Ruszczyńska-Szenajch et al., 2003; van der Meer et al., 2009; Fig. 7b) and large 'rafts' of material that may be fractured from the bed (e.g. Hart, 1990; Boulton and Caban, 1995; Phillips and Merritt, 2008).

2.3.2. Intermediate water pressure

During intermediate pressures, the till was saturated and there was viscous and significant probe (clast) rotation (Hart et al., 2009). This produces a typical deformation till, associated with ductile deformation and till advection (Hart et al., 1990; van der Meer et al., 2003; Roberts and Hart, 2005; Evans et al., 2006). At the microscale, dependent on till texture, there may be signs of attenuation and rotational structures (e.g. skelsepic plasmic fabric [fine-grained particles displaying parallel orientation to the grain edge], thin plastering around grains and turbates [small clasts orientated around larger clasts associated]), as well as abrasion within the deforming layer (van der Meer, 1997; Menzies, 2000; Hiemstra and Rijsdijk, 2003). These features were seen in SEM and thin section studies from Briksdalsbreen (Hart, 2006; Rose and Hart, 2008; Fig. 7b).

On the field scale, where differences in lithology exist, the characteristics of the till will include deformation structures such as folds and laminations (Fig. 7c). Till will be deposited from the combined processes of subglacial meltout, till advection, and changes in the thickness of the deforming layer (till accretion) (Hart and Boulton, 1991). At Briksdalsbreen the maximum depth of till recorded from GPR was 12 m, although only the top 0.3 m is deforming. Very little debris (if any) is carried within the ice. Instead the till must have been generated by subglacial erosion of the bedrock, which is then moved along with the glacier (advection), combined with proglacial lake sediments (as the glacier was advancing) and finally accreted by the stabilisation of the till immediately below the deforming layer. During ductile deformation, it is also likely that flutes (observed at Briksdalsbreen) (Fig. 7e) and drumlins could form, as till flows around obstacles within the deforming layer (Boulton, 1987; Benn, 1995; Hart, 1997).

2.3.3. High water pressure

High water pressure events typically occurred as short duration peaks in autumn and/or spring, and as sustained events in early summer. Iverson et al. (1995), Fischer and Clark (1997) and Boulton et al. (2001) have argued that when (and where) water pressure in till is high, ice–bed coupling is weak and basal sliding dominates. It has also been suggested that high basal water pressures may lead to hydraulic separation between the glacier and the bed. This could lead to the deposition of thin bedded sand-beds (Hoffmann and Piotrowski, 2001; Fuller and Murray, 2002; Munro-Stasiuk, 2000; Nelson et al., 2005), and/or hydrofracture (Rijsdijk et al., 1999; Kjær et al., 2006; Phillips and Merritt, 2008) (Fig. 7f).

At Briksdalsbreen, abrupt oscillations in the dip of clasts (probes) were reported during high pressure events (Hart et al., 2009), but this process would be unlikely to be preserved in the till. Similarly, if sediments associated with bed separation had been deposited at Briksdalsbreen, they would probably have been deformed during the later ductile deformation events. Thus, although high water pressure events were common at Briksdalsbreen, they probably had the least effect on till formation, both at this site, and in till sedimentation in general.

2.3.4. Summary

The probes have demonstrated that variations in subglacial water pressure can result in both daily and long term annual trends in till deformation. We suggest that 'normal' viscous deformation will occur at intermediate water pressures, and although there are both ductile and brittle elements associated with this deformation, the former will be dominant. Brittle deformation will dominate at low water pressures, and sliding, bed separation and till hydrofracture will occur at high water pressures. These latter features, may then all deform during subsequent intermediate water pressure events, and so not be preserved in the till. Small scale daily changes would also be superimposed on the larger scale annual changes in till formation processes, and these may change over a small spatial scale. The resultant till will be a combination of these processes, reflecting the accretion of numerous thin deforming layers that have built up over time.

3. Conclusion

This study has shown how results from the Glacsweb wireless subglacial probes can help us to characterise subglacial processes and thus, further our understanding of glacier dynamics and how these processes may be reflected in till sedimentology. By examining the relationship between water pressure, case stress and till temperature, along with changes in probe dip, we were able to characterise three distinct styles of subglacial behaviour that occur on both a diurnal and annual scale.

Low water pressures are associated with high case stress variability and till temperatures. We suggest that this reflects velocity driven stick-slip events, directly transmitted via the grain structure through a relatively strong till (due to liquid grain bridges). Intermediate water pressures are associated with intermediate case stress variability and high till temperatures, reflecting the importance of friction associated with high deformation under these conditions. High water pressures are associated with low case stress variability and low meltwater controlled till temperatures.

It was also shown that as water pressure rose, the till weakened, but as pressures continued to rise and the till reached saturation, it also strengthened in association with dilation. On the microscale, we were able to show that the stress imparted by velocity driven stick-slip events at low water pressures, causes brittle deformation of the till. In contrast, during high water pressures the ductile nature of the saturated till absorbs, rather than transmits, any velocity driven events. However, high 'flash' temperatures generated by stick-slip motion produced the high temperatures recorded in the till.

The formation and sedimentology of till at Briksdalsbreen reflects a combination of these differing processes operating on both diurnal and annual time scales. These findings reiterate the complexities of till sedimentology and the care that should be taken when interpreting sequences. However, it is through the application of such *in situ* studies that we can start to link past deposits with active subglacial processes with more confidence. This will also aid reconstructions of past glacier behaviour.

Acknowledgements

The authors would like to thank Inge and Gro Melkvoll for their help with logistics and all the members of the Glasweb team: Royan Ong, Alistair Riddoch, Ahmed Elsaify, Gang Zou, Paritosh Padhy, Richard Waller, Daniel Miles, Hannah Brown, Sarita Ward, Kim Dowset, John Hunt, Sarah Stafford, Natalie Jarman, Elisa Anderson, Celine Ragault, David Vaughan-Hirsch, and Mathew Westoby. Thanks also go to Bob Smith in the Cartographic Unit, School of Geography for cartography. We would like to thank Dave Beckett, George Crammond and Thom Bostock, School of Engineering Sciences, University of Southampton for their help with probe case stress calibration. Also thanks to Prof. Steve Darby for his helpful advice concerning geothermal heating and Dr Emrys Phillips for the use of his photograph. We would like to thank the referees for their very helpful reviews, which lead to a much improved version of an earlier manuscript. This research was funded by the Royal Society, DTI NextWave programme and ESPRC.

References

Alley, R.B., 1993. In search of ice-stream sticky spots. Journal of Glaciology 39 (133), 447–454.
Alley, R.B., Blankenship, D.D., Bentley, C.R., Rooney, S.T., 1986. Deformation of till beneath ice stream B, West Antarctica. Nature 322, 57–59.
Altuhafi, F.N., Baudet, B.A., Sammonds, P., 2009. On the time-dependent behaviour of glacial sediments: a geotechnical approach. Quaternary Science Reviews 28, 693–707.
Archard, J.F., 1958. The temperature of rubbing surfaces. Wear 2, 438–455.
Bahr, D.B., Rundle, J.B., 1996. Stick-slip statistical mechanics at the bed of a glacier. Geophysical Research Letters 23 (16), 2073–2076.
Bartholomaus, T.C., Anderson, R.S., Anderson, S.P., 2008. Glacier sliding response to transient. water storage. Nature Geoscience 1, 33–37.
Benn, D.I., 1995. Fabric signature of subglacial till deformation, Breiðamerkurjökull, Iceland. Sedimentology 42, 735–747.
Bestmann, M., Grasemann, B., Heidelbach, F., Langenhorst, F., Rice, A.H.N., 2006. Subglacial bedrock welding associated with glacial earthquakes. Journal of the Geological Society 163, 417–420.
Blake, E.W., Clarke, G.K.C., Gerrin, M.C., 1992. Tools for examining subglacial bed deformation. Journal of Glaciology 38, 388–396.
Boulton, G.S., 1987. A Theory of Drumlin Formation by Subglacial Deformation. In: Menzies, J., Rose, J. (Eds.), Drumlin Symposium. Balkema, Rotterdam, pp. 25–80.
Boulton, G.S., Caban, P., 1995. Groundwater flow beneath icesheets, Part II. Its impact on glacier tectonic structures and moraine formation. Quaternary Science Reviews 14, 563–587.
Boulton, G.S., Dobbie, K.E., 1998. Slow flow of granular aggregates: the deformation of sediments beneath glaciers. Philosophical Transaction of the Royal Society A 356, 2713–2745.
Boulton, G.S., Hindmarsh, R.C.A., 1987. Sediment deformation beneath glaciers: rheology and geological consequences. Journal of Geophysical Research 92 (B9), 9059–9082.
Boulton, G.S., Jones, A.S., 1979. Stability of temperate ice caps and ice sheets resting on beds of deformable sediment. Journal of Glaciology 24, 29–44.
Boulton, G.S., Dobbie, K.E., Zatsepin, S., 2001. Sediment deformation beneath glaciers and its coupling to the subglacial hydraulic system. Quaternary International 86, 3–28.
Brown, N.E., Hallet, B., Booth, D.B., 1987. Rapid soft bed sliding of the Puget glacial lobe. Journal of Geophysical Research 92 (B9), 8985–8997.
Clarke, G.K.C., 1987. Subglacial till: a physical framework for its properties and processes. Journal of Geophysical Research 92 (B9), 8942–8984.
Clarke, G.K.C., 2005. Subglacial processes. Annual Review of Earth and Planetary Sciences 33, 247–276.
Cuffey, K., Alley, R.B., 1996. Is erosion by deforming subglacial sediments significant? Ann. Glac 22, 17–24.
Desai, C.S., 1974. A consistent finite element technique for work-softening behavior. In: Proc., Int. Conf. on Comp. Meth. in Nonlinear Mechs. University of Texas, Austin.
Desai, C.S., 2001. Mechanics of Materials and Interfaces: The DisturbedState Concept. CRC Press, Boca Raton, FL, 712 pp.
Engelhardt, H., Kamb, B., 1998. Basal sliding of ice stream B, West Antarctica. Journal of Glaciology 44 (147), 223–230.
Evans, D.J.A., Phillips, E.R., Hiemstra, J.F., Auton, C.A., 2006. Subglacial till: formation, sedimentary characteristics and classification. Earth-Science Reviews 78 (1–2), 115–176.
Fischer, U.H., Clarke, G.K.C., Blatter, H., 1999. Evidence for temporally varying “sticky spots” at the base of Trapridge Glacier, Yukon Territory, Canada. Journal of Glaciology 45 (150), 352–360.
Fischer, U.H., Clark, G.K.C., 1997. Stick-slip sliding behaviour at the base of a glacier. Annals of Glaciology 24, 390–396.
Fischer, U.H., Clarke, G.K.C., 1994. Ploughing of subglacial sediment. Journal of Glaciology 40 (134), 97–106.
Fischer, U.H., Clarke, G.K.C., 2001. Review of subglacial hydro-mechanical coupling: Trapridge glacier, Yukon Territory, Canada. Quaternary International 86, 29–44.
Fischer, U., Iverson, N.R., Hanson, B., Hooke, R., Le, B., Jansson, P., 1998. Estimation of hydraulic properties of the subglacial till layer from ploughmeter measurements. Journal of Glaciology 44 (148), 517–522.
Fischer, U.H., Porter, P.R., Schuler, T., Evans, A.J., Gudmundsson, G.H., 2001. Hydraulic and mechanical properties of glacial sediments beneath Unteraargletscher, Switzerland: implications for glacier basal motion. Hydrological Processes 15, 3525–3540.
Fowler, A.C., 2003. On the rheology of till. Annals of Glaciology 37, 55–59.
Fuller, S., Murray, T., 2002. Sedimentological investigations in the forefield of an Icelandic surge-type glacier: implications for the surge mechanism. Quaternary Science Reviews 21, 1503–1520.
Ghezzehei, T.A., Or, D., 2001. Rheological properties of wet soils and clays under steady and oscillatory stresses. Soil Science Society of America Journal 65 (3), 624–637.
Hart, J.K., 1990. Proglacial glaciotectonic deformation and the origin of the Cromer Ridge push moraine complex, North Norfolk, UK. Boreas 19, 165–180.
Hart, J.K., 1997. The relationship between drumlins and other forms of subglacial deformation. Quaternary Science Reviews 16, 93–108.
Hart, J.K., 2006. An investigation of subglacial processes at the microscale from Briksdalsbreen, Norway. Sedimentology 53, 125–146.
Hart, J.K., Boulton, G.S., 1991. The interrelationship between glaciotectonic deformation and glaciodeposition. Quaternary Science Reviews 10, 335–350.
Hart, J.K., Rose, J., 2001. Approaches to the study of glacier bed deformation. Quaternary International 86, 45–58.
Hart, J.K., Hindmarsh, R.C.A., Boulton, G.S., 1990. Different styles of subglacial glaciotectonic deformation in the context of the Anglian ice sheet. Earth Surface Processes and Landforms 15, 227–242.
Hart, J.K., Gane, F., Watts, R., 1996. Evidence for deforming bed conditions on the Dänischer Wohld peninsula, northern Germany. Boreas 25, 101–113.
Hart, J.K., Martinez, K., Ong, R., Riddoch, A., Rose, K.C., Padhy, P.A., 2006. A wireless multi-sensor subglacial probe: design and preliminary results. Journal of Glaciology 52 (178), 389–397.
Hart, J.K., Rose, K.C., Martinez, K., Ong, R., 2009. Subglacial clast behaviour and its implication for till fabric development: new results derived from wireless subglacial probe experiments. Quaternary Science Reviews 28, 597–607.
Helsey, T.C., Levine, A.J., 1998. How sandcastles fall. Physical Review letters 80, 3141–3144.
Herminghaus, S., 2005. Dynamics of wet granular matter. Advances in Physics 54, 221–245.
Hicock, S.R., 1992. Lobal interactions and rheologic superposition in subglacial till near Bradtville, Ontario, Canada. Boreas 21, 73–88.
Hicock, S.R., Dreimanis, A., 1992. Deformation till in the Great Lakes region: implications for rapid flow along the south-central margin of the Laurentide Ice Sheet. Canadian Journal of Earth Sciences 29, 1565–1579.
Hiemstra, J.F., Rijsdijk, K.F., 2003. Observing artificially induced strain: implications for subglacial deformation. Journal of Quaternary Science 18, 373–383.
Hindmarsh, R., 1997. Deforming beds: viscous and plastic scales of deformation. Quaternary Science Reviews 16 (9), 1039–1056.
Hoffmann, K., Piotrowski, J.A., 2001. Till mélange at Amsdorf, central Germany: sediment erosion, transport and deposition in a complex, soft-bedded subglacial system. Sedimentary Geology 140, 215–234.
Hooke, R.L., Hanson, B., Iverson, N.R., Jansson, P., Fischer, U., 1997. Rheology of subglacial till, Storglaciären, Sweden. Journal of Glaciology 43, 172–179.
Humphrey, N.F., Kamb, B., Fahnestock, M., Engelhardt, H., 1993. Characteristics of the bed of the lower Columbia glacier, Alaska. Journal of Geophysical Research 98 (B1), 837–846.
Iken, A., Röthlisberger, H., Flotron, A., Haeberli, W., 1983. The uplift of Unteraargletscher at the beginning of the melt season—a consequence of water storage at the bed? Journal of Glaciology 29, 28–47.
Iverson, N.R., Hanson, B., Hooke, R.L., Jansson, P., 1995. Flow mechanisms of glaciers on soft beds. Science 267, 80–81.
Iverson, N.R., Baker, R.W., Hooyer, T.S., 1998. Ring-shear studies of till deformation: Coulomb-plastic behavior and distributed strain in glacier beds. Journal of Glaciology 44, 634–642.
Kamb, B., 1991. Rheological nonlinearity and flow instability in the deforming-bed mechanism of ice stream motion. Journal of Geophysical Research 96, 16585–16595.
Kavanaugh, J.L., Clarke, G.K.C., 2001. Abrupt glacier motion and reorganization of basal shear stress following the establishment of a connected drainage system. Journal of Glaciology 47 (158), 472–480.
Kjær, K.H., Larsen, E., van der Meer, J., Ingólfsson, Ó, Krüger, J., Örn Benediktsson, Í, Knudsen, C.G., Schomacker, A., 2006. Subglacial decoupling at the sediment/bedrock interface: a new mechanism for rapid flowing ice. Quaternary Science Reviews 25, 2704–2712.
Kjøllmoen, B., 2007. Glaciological investigations in Norway in 2006. Report 1. Norwegian Water Resources and Energy Directorate.
Lambe, T.W., Whitman, R.V., 1979. Soil Mechanics. John Wiley and Sons, New York.
Laumann, T., Nesje, A., 2009. The impact of climate change on future frontal variations of Briksdalsbreen, western Norway. Journal of Glaciology 55 (193), 789–796.
Lee, J., Phillips, E., 2008. Progressive soft sediment deformation within a subglacial shear zone: a hybrid mosaic-pervasive deformation model for middle Pleistocene glaciotectonised sediments from Eastern England. Quaternary Science Reviews 27, 1350–1362.
Mahaney, W.C., 2008. Pleistocene and Holocene glacier thicknesses, transport histories and dynamics inferred from SEM microtextures on quartz particles. Boreas 24, 293–304.
Mair, D., Nienow, P., Willis, I., Sharp, M., 2001. Spatial patterns of glacier motion during a high-velocity event: Haut Glacier d'Arolla, Switzerland. Journal of Glaciology 47, 9–20.
Martinez, K., Hart, J.K., Ong, R., 2004. Environmental sensor networks. Computing 37 (8), 50–56.
van der Meer, J.J.M., 1997. Particle and aggregate mobility in till: microscopic evidence of subglacial processes. Quaternary Science Reviews 16, 827–831.
van der Meer, J.J.M., Menzies, J., Rose, J., 2003. Subglacial till: the deforming glacier bed. Quaternary Science Reviews 22, 1659–1685.
van der Meer, J.J.M., Kjær, K., Krüger, J., Rabassa, J., Kilfeather, A.A., 2009. Under pressure: clastic dykes in glacial settings. Quaternary Science Reviews 28, 708–720.
Menzies, J., 2000. Micromorphological analyses of microfabrics and microstructures indicative of deformation processes in glacial sediments. In: Maltman, A.J.,

Hubbard, B., Hambrey, M.J. (Eds.), Deformation of Glacial Materials. Geol. Soc. Spec. Publ., vol. 176, pp. 245–258.
Menzies, J., van der Meer, J.J.M., Rose, J., 2006. Till-as a glacial "tectomict", its internal architecture, and the development of a "typing" method for till differentiation. Geomorphology 75, 172–200.
Munro-Stasiuk, M.J., 2000. Rhythmic till sedimentation: evidence for repeated hydraulic lifting of a stagnant ice mass. Journal of Sedimentary Research 70, 94–106.
Murray, T., Porter, P.R., 2001. Basal conditions beneath a soft-bedded polythermal surge-type glacier: Bakaninbreen, Svalbard. Quaternary International 86, 103–116.
Nelson, A.E., Willis, I.C., ÓCofaigh, C., 2005. Till genesis and glacier motion inferred from sedimentological evidence associated with the surge-type glacier, Brúarjökull, Iceland. Annals of Glaciology 42, 14–22.
Nesje, A., Dahl, S.O., 2003. The "Little Ice Age"-only temperature? Holocene 13, 171–177.
Nolan, M., Echelmeyer, K., 1999. Seismic detection of transient changes beneath Black Rapids glacier, Alaska, USA: II. Basal morphology and processes. Journal of Glaciology 45 (149), 132–146.
Nowak, S., Samadani, A., Kudrolli, A., 2005. Maximum angle of stability of a wet granular pile. Nature Physics 1, 50–52.
Nye, J.F., 1965. The flow of a glacier in a channel of rectangular, elliptic or parabolic cross-section. Journal of Glaciology 40, 661–690.
Phillips, E., Merritt, J., 2008. Evidence for multiphase water-escape during rafting of shelly marine sediments at Clava, Inverness-shire, NE Scotland. Quaternary Science Reviews 27 (9–10), 988–1011. doi:10.1016/j.quascirev.2008.01.012.
Piotrowski, J.A., Larsen, N.K., Junge, F.W., 2004. Reflections on soft subglacial beds as a mosaic of deforming and stable spots. Quaternary Science Reviews 23, 993–1000.
Pollack, H.N., Hurter, S.J., Johnson, J.R., 1993. Heat flow from the earth's interior: analysis of the global dataset. Reviews of Geophysics 31 (3), 267–280.
Porter, P.R., Murray, T., 2001. Mechanical and hydraulic properties of till beneath Bakaninbreen, Svalbard. Journal of Glaciology 47 (157), 167–175.
Purdie, H.L., Brook, M.S., Fuller, I.C., 2008. Seasonal variation in ablation and surface velocity on a temperate maritime glacier: Fox glacier, New Zealand. Arctic, Antarctic and Alpine Research 40, 140–147.
Rijsdijk, K.F., Owen, G., Warren, W.P., McCarroll, D., van der Meer, J.J.M., 1999. Clastic dykes in over-consolidated tills: evidence for subglacial hydrofracturing at Killiney Bay, eastern Ireland. Sedimentary Geology 129, 111–126.
Roberts, D.H., Hart, J.K., 2005. The deforming bed characteristics of a stratified till assemblage in north East Anglia, UK: investigating controls on sediment rheology and strain signatures. Quaternary Science Reviews 24, 123–140.
Roberts, M.J., Magnusson, E., Bennett, R., Geirsson, H., Sturkell, E., Bjornsson, H., Rott, H., 2006. Meltwater dynamics beneath Skeiðararjökull From continuous GPS measurements and seismic observations. EOS Transactions of the AGU 87 (52) Fall Meeting Supplementary Abstracts C31A-1232.
Roscoe, K.H., Schofield, A.N., Wroth, C.P., 1958. On the yielding of soils. Géotechnique 8, 22–53.
Rose, K.C., Hart, J.K., 2008. Subglacial comminution in the deforming bed: inferences from SEM analysis. Sedimentary Geology 203, 87–97.
Rose, K.C., Hart, J.K., Martinez, K., 2009. Seasonal changes in basal conditions at Briksdalsbreen Norway: the winter–spring transition. Boreas 38, 579–590.
Rousselot, M., Fischer, U.H., 2007. A laboratory study of ploughing. Journal of Glaciology 53 (181), 225–231.
Ruszczyńska-Szenajch, H., Trzciński, J., Jarosińska, U., 2003. Lodgement till deposition and deformation investigated by macroscopic observation, thin-section analysis and electron microscope study at site Dębe, central Poland. Boreas 32, 399–415.
Sane, S.M., Desai, C.S., Jenson, J.W., Contractor, D.N., Carlson, A.E., Clark, P.U., 2008. Disturbed state constitutive modeling of two Pleistocene tills. Quaternary Science.
Scherer, R.P., Sjunneskog, C.M., Iverson, N.R., Hooyer, T.S., 2004. Assessing subglacial processes from diatom fragmentation patterns. Geology 32, 557–560.
Schiffer, P., 2005. Granular physics: a bridge to sandpile stability. Nature Physics 1, 21–22.
Smith, A.M., Murray, T., 2009. Bedform topography and basal conditions beneath a fast-flowing west Antarctic ice stream. Quaternary Science Reviews 28, 584–596.
Stokes, C.R., Clark, C.D., Lian, O.B., Tulaczyk, S., 2007. Ice stream sticky spots: a review of their identification and influence beneath contemporary and palaeo-ice streams. Earth-Science Reviews 81, 217–249.
Stokes, C.R., Clark, C.D., Storrar, R., 2009. Major changes in ice stream dynamics during deglaciation of the north-western margin of the Laurentide Ice Sheet. Quaternary Science Reviews 28, 721–738.
Tegzes, P., Vicsek, T., Schiffer, P., 2003. Development of correlations in the dynamics of wet granular avalanches. Physical Review 67, 051303.
Thomason, J.F., Iverson, N.R., 2008. A laboratory study of particle ploughing and pore-pressure feedback: a velocity-weakening mechanism for soft glacier beds. Journal of Glaciology 54 (184), 169–181.
Truffer, M., Harrison, W.D., Echelmeyer, K.A., 2000. Glacier motion dominated by processes deep in underlying till. Journal of Glaciology 46 (153), 213–221.
Tulaczyk, S., Kamb, W.B., Engelhardt, H.F., 2000. Basal mechanics of ice stream B, West Antarctica 1. Till mechanics. Journal of Geophysical Research 105 (B1), 463–482.
Tulaczyk, S.M., Scherer, R.P., Clark, C.D., 2001. A ploughing model for the origin of weak tills beneath ice streams: a qualitative treatment. Quaternary International 86, 59–70.
Van Hoesen, J.G., Orndorff, R.L., 2004. A comparative SEM study on the micromorphology of glacial and nonglacial clasts with varying age and lithology. Canadian Journal of Earth Sciences 41, 1123–1139.
Walter, F., Deichmann, N., Funk, M., 2008. Basal icequakes during changing subglacial water pressures beneath Gornergletscher, Switzerland. Journal of Glaciology 54 (186), 511–521.
Wilkinson, W.L., 1960. Non-Newtonian Fluids. Pergamon Press.
Willis, I.C., 1995. Intra-annual variations in glacier motion: a review. Progress in Physical Geography 19, 61–106.
Willis, I., Mair, D., Hubbard, B., Nienow, P., Fischer, U.H., Hubbard, A., 2003. Seasonal variations in ice deformation and basal motion across the tongue of Haut Glacier d'Arolla, Switzerland. Annals of Glaciology 36, 157–167.
Winkler, S., 1996. Front variations of outlet glaciers from Jostedalsbreen, western Norway, during the twentieth century. Norges Geologiske Undersøkelse Bulletin 431, 33–47.
Winkler, S., Nesje, A., 1999. Moraine formation at an advancing temperate Glacier: Brigsdalsbreen, western Norway. Geografiska Annaler 81A, 17–30.
Winkler, S., Elvehøy, H., Nesje, A., 2009. Glacier fluctuations of Jostedalsbreen, western Norway, during the past 20 years: the sensitive response of maritime mountain glaciers. The Holocene 19, 395–414.