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Subglacial clast behaviour and its implication for till fabric development: new results derived from wireless subglacial probe experiments

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A R T I C L E I N F O

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A B S T R A C T

This study has investigated the three-dimensional movement of clasts within deformation till, using embedded wireless probes. These probes were part of an environmental sensor network, which measured subglacial properties (temperature, water pressure, resistivity, case strain and tilt) six times a day, and relayed that data via radio to the glacier surface, where they were forwarded and broadcast on-line. The system was installed at Briksdalsbreen, Norway and operated from August 2004 until August 2006. Approximately 2000 probe days worth of data were collected, with an increase in performance (41% more readings) during the second year. The probes showed similar patterns of water pressure rises throughout the two years, but with slightly different magnitudes and timings. These changes in water pressure could be related to clast behaviour. The probes decreased their dip over the year, and the rate of change was related to an increase in glacier velocity. After initial changes in dip, the probes experienced changes in orientation, followed by rotation about the *a*-axis. This continuous rotation was similar to the motion suggested by Jeffery [1922. The motion of ellipsoidal particles immersed in a viscous fluid. Proceedings of the Royal Society of London, Series A 102, 161–179] for the behaviour of clasts within a viscous material. In addition, some probes also showed short, frequent dip oscillations in spring and autumn, which were interpreted to reflect stick-slip events, similar to lodging; and demonstrated how local conditions can interrupt the predicted rotation pattern.

Overall, it is demonstrated that when water pressures were high, decoupling occurred associated with basal sliding and dip oscillations; and when water pressures fell, the ice and sediment were coupled and till deformation occurred. These events happened during summer and autumn. It is this combination of "lodgement" and deformation that builds up both a complex (but predictable) fabric and a resultant composite till sedimentology.

1. Introduction

Over the last 30 years there has been a dramatic change in our understanding of both subglacial processes and their role in glacier dynamics (Boulton and Jones, 1979; Alley et al., 1986; Clarke, 1987). Knowledge of the subglacial environment needs to be reconstructed from the sedimentology of ancient and modern glaciers, as well as from *in situ* subglacial experiments (Hart and Rose, 2001). Investigations from modern glaciers have demonstrated the extent of temporal and spatial changes within the subglacial environment (e.g. Engelhardt and Kamb, 1998; Murray and Porter, 2001; Fischer and Clarke, 2001; Boulton et al., 2001); whilst sedimentology records the integration of these processes (van der Meer, 1993; Piostrowski et al., 2006; Hart, 2007).

It is important to use the results from subglacial experiments to understand till formation and its associated till fabric development, so that glacial processes can be reconstructed more accurately from ancient glacial sediments. Deformation associated with till, for example, was once thought to be unusual, but since the 1990s has been regarded as a ubiquitous part of till formation (Hart and Boulton, 1991; Brown et al., 1987; van der Meer et al., 2003; Evans et al., 2006). These researchers have argued that there is a continuum of till forming processes between "lodgement" and "ploughing" (high effective pressures) and "deformation" (low effective pressures); and that most subglacial tills will have undergone some deformation during deposition. It has been demonstrated that effective pressure can vary, causing the bed to be modelled as a mosaic of mobile (low effective pressure zones) and "sticky spots" (high effective pressure zones) that change over space and time (Alley, 1993; MacAyeal et al., 1995; Piotrowski et al., 2004; Stokes et al., 2007).

Associated with till genesis is the formation of a distinct till fabric (Andrews, 1971; Dowdeswell and Sharp, 1986; Hart, 1994;

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Benn, 1995; Carr and Rose, 2003). Most geologists have applied Jeffery's 1922 model for the rotation of a rigid ellipsoidal object in a Newtonian fluid to understand the formation of fabrics in shear zones (e.g. Gay, 1968; Ghosh and Ramberg, 1976; Arbaret et al., 2000; Schmid and Podladchikov, 2004) and this model has been applied to tills (Glen et al., 1957; Hart, 1994; Clark, 1997; Carr and Rose, 2003).

Field studies of deformation tills have shown a range of fabric strengths (defined as S1 eigenvalue, after Mark, 1973). Hart (1994) suggests that where the deforming layer is relatively constrained (as in the formation of flutes) then the fabric strength will be high (Benn, 1995; Hart, 2006), whilst where the deforming layer is thicker (greater than the scale of the obstacle), deformation till will tend to have a low fabric strength (Dowdeswell and Sharp, 1986; Hicock et al., 1996; Hart et al., 2004). The latter occurs because in Jeffrey's model, at high strains the clasts move to a transverse position (as this dissipates the least energy during rotation). As each clast has its own rotation pattern within the heterogeneous deforming layer, this leads to an overall weakening of the fabric.

In contrast, other researchers have suggested that the clasts will initially rotate into the shear plane and then remain there (Hooyer and Iverson, 2000; Larsen and Piotrowski, 2003; Thomason and Iverson, 2006; Iverson et al., 2008). Thus the March (1932) model, which treats clasts as passive strain markers, is more appropriate.

Consequently, not only is there a controversy as to the nature of clast behaviour within the deforming layer, but also data on the rate of clast movement is lacking. The instrumentation used in most current *in situ* experiments were designed to monitor changes in till properties (e.g. ploughmeter, Fischer and Clarke, 1994; tilt cells, Iverson et al., 1995; pressure transducers, Hodge, 1976). These instruments are inserted into the till or ice via boreholes, and are connected by wires to the glacier surface where the data is recorded by a logger. The presence of the wires means that they can not move "naturally", and so can not produce data on clast movement.

To overcome these problems, a new system was designed where the sensors are encased within a "probe", which sends its data back to the glacier surface by radio waves. This eliminated the need for wires, and enables the probe to behave as a "natural" clast in the subglacial environment (Glasweb project—Martinez et al., 2004; Hart et al., 2006). The probes were part of an environmental sensor network designed to monitor the glacial environment (Hart and Martinez, 2006).

This wireless system has been used to understand the nature of clast behaviour and thus depositional processes associated with the deforming bed. We are able to determine the rate and nature of clast movement, and demonstrate how these processes generate subglacial deformation till.

2. Glacsweb system and the study site

The Glacsweb system (Fig. 1) uses wireless polyester cylindrical probes (16 cm long with an axial ratio of 2.9:1) to measure tilt, water pressure, temperature, case strain and resistance. Data is recorded 6 times a day and relayed to a base station on the glacier surface using 433 MHz radios. The base station also has a weather station and dGPS recorder. Once a day all the data were forwarded to a mains-powered computer located 2.5 km away, where they were uploaded onto the internet (for specific details see Hart et al., 2006).

The system was installed at Briksdalsbreen, an outlet glacier from the Jostedalsbreen ice cap, in southern Norway (Fig. 2). This glacier advanced 305 m between 1988 to 1996, over its proglacial lake into a birch forest (NVE; Winkler, 1996). This dramatic re-advance is thought to result from a precipitation increase associated with a positive phase of the North Atlantic Oscillation (NAO) (Nesje and Dahl, 2003). However, between 1997 and 2007 (April), the glacier has retreated approximately 439 m, associated with a combination of a negative phase of the NAO and "global warming".

The underlying bedrock at Briksdalsbreen is Precambrian gneiss, which is mostly covered by till and proglacial lake sediments. The post-1996 foreland comprises push moraines (1–7 m in height) and an exposed subglacial surface comprising flutes and lineations (Winkler and Nesje, 1999; Hart, 2006). Investigations of the subglacial till have indicated the presence of deformation from thin section and SEM evidence of rotation, attenuation and fracture associated with subglacial erosion (Hart, 2006; Rose and Hart, 2008). It is estimated from the average height of the flutes and comparisons with other instrumented valley glaciers that the deforming layer is approximately 0.3 m thick.

The Glacsweb system was installed in summer 2004 on the northern side of the glacier, where there was safe access and the glacier was flat and crevasse-free (Fig. 2b). This system lasted until November 2006, when an exceptionally warm autumn resulted in approximately 100 m of glacier retreat in three months. The ice on which the base station was sited calved into the lake, terminating the experiment.

3. Methodology

The field site (including glacier limits, boreholes, base station and radar grids) was annually surveyed with a Topcon differential GPS (dGPS) system and a grid was marked out on the glacier surface with bamboo poles. In addition, the dGPS was mounted on the top of the base station to record glacier movement throughout the year.

Boreholes were drilled with a Kärcher HD1000DE jet wash system, and the glacier and till were examined using a custom

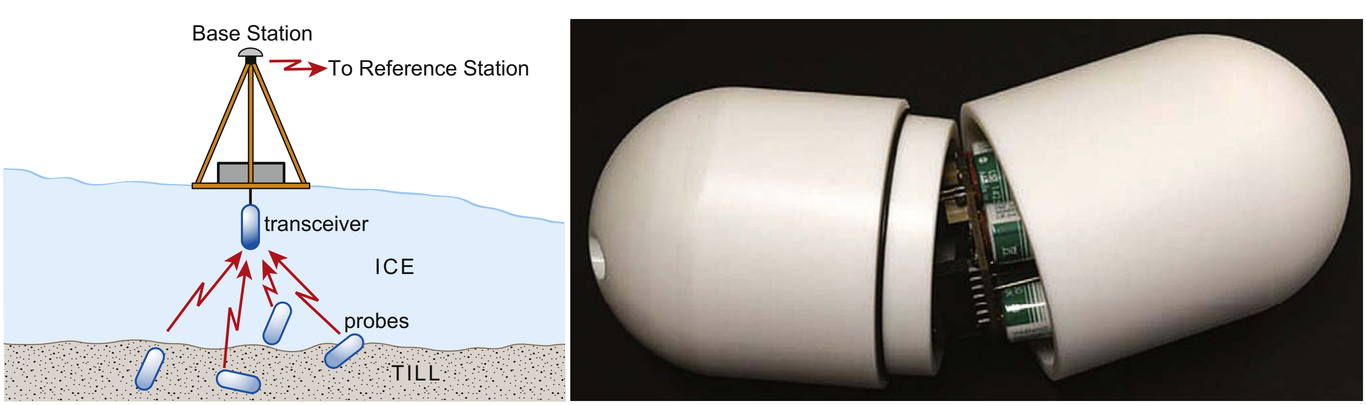

Fig. 1. Glacsweb system with probe inset. The probes are powered by Lithium Thionyl Chloride cells, potentially for 36 months. The Base Station is mounted on a pyramidal tripod and tethered to the ice with an anchor (15 m down a borehole) and rocks on the base. It was powered by two large 12 V lead–acid batteries with 96 Ah of capacity in total, as well as a 15 W solar panel and a 60 W wind generator (Rutland 503).

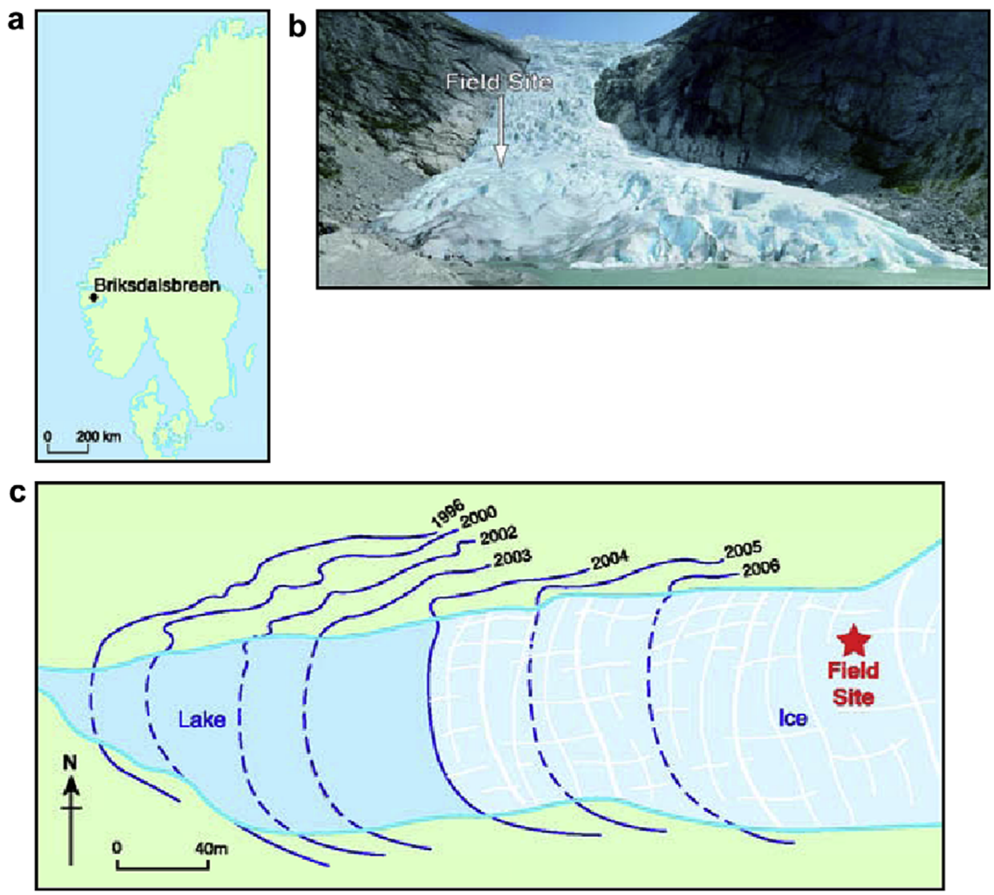

Fig. 2. Briksdalsbreen: (a) location of the glacier; (b) photograph of the glacier with field site shown; (c) map of the glacier with field site marked with a star.

made CCD video camera, which used infra red (900 nm) in 2004 and a white LED illumination colour camera in 2005. The video was captured using a hand-held digital video camera.

The thickness of the glacier was determined from the measured borehole depths and a Ground Penetrating Radar (GPR) survey. For the latter, a pulse EKKO 100 GPR with a 1000 volt transmitter was used. A common offset survey was performed on the marked grid, using 50 MHz antennas with a 2 m antenna spacing and a 0.5 m sampling interval. Because the glacier was relatively thin and debris-free the glacier bed could easily be detected (Hart et al., 2006).

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 observed, then the hydraulic excavation method of Blake (1992) was used (i.e. drilling was continued at the bottom of the borehole for a further fifteen minutes). The probes were lowered into this space, and it was assumed that the till would subsequently close in around them.

4. Results

The GPR and measured boreholes showed that the average depth of the glacier in the study area was 68 m in 2004, 51 m in 2005 and 30 m in 2006. The glacier velocity (Fig. 3a) and change in glacier thickness (Fig. 3b) over the two-year period was calculated from the dGPS readings.

The probe data collection was very successful. During 2004/5, eight probes were inserted into the glacier, of which seven responded and one of these, probe 8, lasted a whole year. A total of 859 days of probe data (36,078 sensor readings) were received. During 2005/6, another seven probes were inserted into the ice, of which four responded, and two of these lasted a whole year. These yielded a total of 1208 days of probe data (50,715 sensor readings). This reflects a 41% increase in sensor readings during the second year. Unfortunately, due to power failures at the base station it was difficult to pinpoint the causes of probe failures over the course of the year. It is strongly believed, however, that the dominant cause of failure was the result of the probes moving out of communication range. Table 1 records the length of time the probes sent back data and Table 2 the success of the different sensors within the probes.

In this study the results from the three till probes that responded for a whole year (probes 8—2004/5, 10 and 12—2005/6) will be discussed, as well as probes 5, 7 (2004/5) and 16 (2005/6) that only responded during the autumn. A summary of their data are shown in Table 3, alongside data from englacial probes. The data presented in this study reflects the whole data series, except for singular outliers which were considered to be sensor failures. Data reliability was considered to be high, because there appeared to be a general continuity in data trends, and the sensor failures were less than 1% of the overall sensor readings.

It has been argued by Hart et al. (2006) that the probe data can be used to confirm whether they are located in the ice or the till (Table 3). Englacial probes (those deployed in holes which did not reach the bed) record high temperatures, low pressures and low case strain and high movement rates prior to being frozen into the ice. Once frozen in, they have low temperatures, the highest case strain and lowest movement. In contrast, probes in the till have, low temperatures, and intermediate case strains and rates of movement. The latter will be discussed in detail.

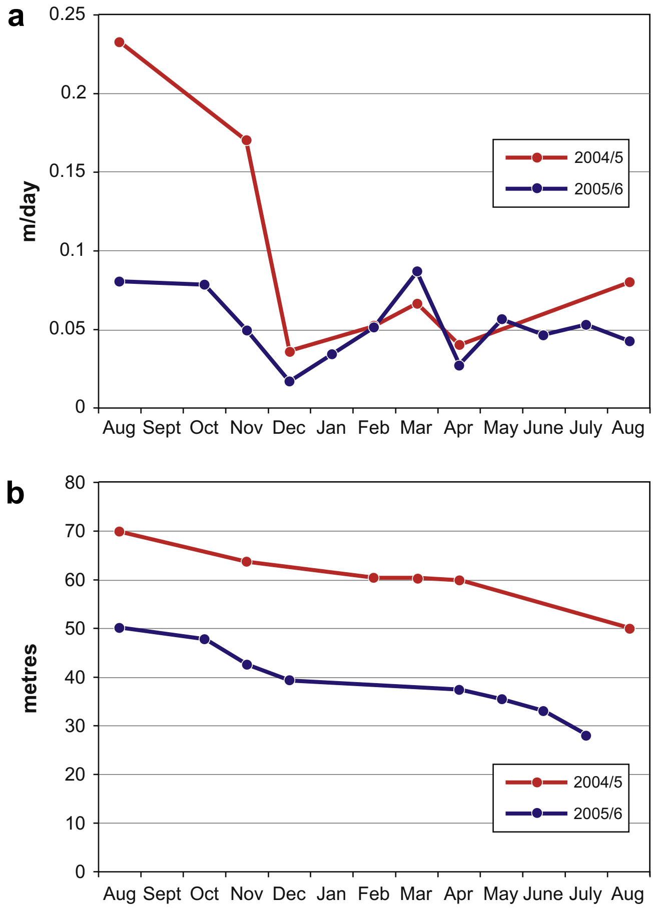

Fig. 3. Changes 2004–6 in: (a) glacier velocity, (b) glacier thickness.

4.1. Water pressure and yield strength

Fig. 4 shows the weather and water pressure data (measured as meters water equivalent, referred to as mW.E.) for 2004/5 and 2005/6. From this, we have divided the year into three glaciological periods: "autumn" (day 244 to day 365—generally low water pressures, except for some high water pressure events), "spring" (day 0 to day 120—short high water pressure events recorded in all the probes) and "summer" (day 120 to 243—continuously high water pressures). During autumn the probes become embedded into the till as the glacier advances over the probe location and the boreholes slowly close. This season is characterised by mild temperatures (4.5 °C, compared with summer temperatures of 10.28 °C, average over two ce:hsp sp="0.25"/>years) and high precipitation (56% of the annual total) (Fig. 4a and c). Once settled in the subglacial environment, most of the probes recorded low water pressures during autumn, except probes 7, 12 and 16, which recorded a high water pressure event (Fig. 4b and d). We suggest that these high pressure events occurred where the till was "connected" to the subglacial drainage system (Röthlisberger et al., 1979; Fischer and Clarke, 2001), reflecting mobile zones. In contrast, till which was "unconnected" with the subglacial drainage system did not show high water pressure events in the autumn and may reflect "sticky spots".

The spring was dominated by a series of high water pressure events which are associated with the "Spring Event". This occurred because the basal drainage system (which shuts down over the winter) could not immediately evacuate the increased meltwater generated from rising temperatures (Iken et al., 1983; Willis et al., 1991). Details of this event are discussed elsewhere.

During the late spring and summer, all three till probes had a similar water pressure pattern, comprising of an initial sharp rise, followed by a sustained period of high pore water pressure before a slow decrease. However, the amount and timing of the water pressure changes varied between the probes. In probe 8, there was a rise from 40 mW.E. to over 90 mW.E. during March, reaching a peak on day 110. This was followed by high water pressures (89.86 mW.E., s.d. 1.14) until mid June (day 171). Water pressures then began to decrease, slowly at first (0.2 mW.E./day) until early August (day 219), and then more rapidly (3.29 mW.E./day) until late August (day 235). Probes 12 and 10 experienced sudden water pressure rises during March (day 82) and April (day 119), respectively. These rises occurred more abruptly, but were of a lower magnitude, than probe 8. This was followed by a slow decrease in water pressure over the summer of 0.13 mW.E./day and 0.1 mW.E./day, respectively.

It has been argued by numerous researchers that deformation of till will occur when the driving stress imparted by the glacier is greater than the till yield strength (derived from the Mohr Coulomb criterion).The driving stress (τ_b) is as follows:

$$\tau_b = \rho g h \sin\alpha \tag{1}$$

and the strength of the till (τ_o) is calculated by:

$$\tau_o = C + (p_i - p_w)\tan\varphi \tag{2}$$

where C is the cohesion of the till, φ is the angle of friction, and $p_i - p_w$ represents effective pressure.

The slope angle of the study area was measured to be 16° in 2004 and 20° in 2005, the height was taken from Fig. 3b. Table 4 shows the values of C and φ described in the literature. The values from Storglaciären were used as the till was closest in terms of sedimentology to Briksdalsbreen. Using these values, and probe readings of water pressure, τ_b and τ_o were calculated (Fig. 5). The results indicated that the applied stress exceeded till yield strength (values greater than 0 kPa) for all the probes during the summer, and during the autumn for probes 7, 12 and 16.

Table 1
Probe success (only those that sent back data for longer than one day are displayed).

Year	2004					2005												2006							
Month	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A
Probe 3	✓																								
Probe 4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓															
Probe 5	✓	✓	✓	✓	✓																				
Probe 7	✓	✓	✓																						
Probe 8	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓												
Probe 10													✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Probe 12													✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Probe 15													✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Probe 16													✓	✓	✓	✓									

Table 2
Sensor success.

Probes	Temperature	Water pressure	Case strain	Resistance	*X*-tilt	*Y*-tilt
Probe 3	✓	✓	✓	✓	✓	✓
Probe 4	✓	✓	✓	✓	✓	✓
Probe 5	✓	✓	✓	✓	✓	✓
Probe 7	✓	✓	×	✓	✓	✓
Probe 8	✓	✓	×	✓	✓	✓
Probe 10	✓	✓	✓	✓	✓	✓
Probe 12	✓	✓	×	×	×	✓
Probe 15	✓	✓	✓	✓	✓	✓
Probe 16	✓	✓	✓	×	✓	✓

4.2. Three-dimensional probe movement

Probe movement was measured with x and y tilt sensors that measure the angle of tilt from the vertical (0° x-tilt, 0° y-tilt represents the probe standing vertically) (Fig. 6a). The high level of metals within the probes meant that they could not contain a compass so the measurements are relative rather than absolute. Where one tilt measurement has high variation, and the other little variation, this indicates a change in dip (Fig. 6b). When the probe rotates about its (longest) a-axis (Fig. 6c), the x and y tilts abide by the following relationship:

$$y = X\sin\theta \tag{3}$$

and

$$x = X\cos\theta \tag{4}$$

where X is the dip and θ is the rotation angle. A change in orientation, if the tilt remains the same, can not be detected. However, if measurements show a switch over from high variation in one tilt measurement (and low variation in the other) to high variation in the other, this would reflect a relative change in orientation perpendicular to the a-axis (combined with a change in dip) (Fig. 6d).

On deployment, probe 8 was in a vertical position (Fig. 7a). The dominant mechanism of movement was a change in dip from November (2004) to mid-July (2005). The rate of change increased from 0.06° per day (December), to 0.1° per day in February, 0.28° per day in May and 0.4° per day in mid-July. However, between April to late–July there was also a change in orientation (0.62° per day in late July). In August (2005), the dominant mechanism changed and the probe began to rotate about its a-axis (anticlockwise), at 0.88° per day. In addition, there were a series of oscillations in dip during October and December (2004), the details of which are shown in Table 5.

Probe 12 recorded a similar pattern but with some significant differences (Fig. 7b). The probe was initially resting with a dip of 30° at the bottom of the borehole and after an initial settling-in period; the probe lessened its dip (Fig. 7b). This occurred at 0.38° per day at the beginning of the autumn high water pressure event (until the end of September, day 273), and then 0.09° per day until the end of the event (day 309). There were also 6 short-lived dip oscillation events (Table 5). There was also anticlockwise rotation of the probe along its a-axis, during the high pressure event, at a rate of 0.73° per day in September, 0.32° per day in October and 0.16° per day in November. From January to May, there was a change in orientation, and then other change in the opposite direction occurred after June. During July, rotation about the a-axis occurred at 0.2° per day (anti-clockwise).

In addition, for probe 12, between February and May there, were over 90 small oscillations (from the general trend) in dip. The duration, frequency and magnitude of these events are shown in Table 5, with April having the most events of the highest magnitude. These events are very short, with most events (66%) only recorded in one reading (one 4-hour period). The maximum length of an event was 20 h. These events did not show a temporal trend. Slightly more (24%) occurred at 12.00 (midday), but this is not statistically significant (chi-squared test).

Probe 10 showed a similar pattern to probe 8 but with variation on a smaller scale. The probe began at a high dip, which slowly decreased (Fig. 7c), with some change in orientation in June, and in July and August (2006) there was a-axis rotation at a rate of 0.25° per day (clockwise). Probe 10 was the only probe with a functional case strain sensor at this time of the year, and results show that during July and August there was also a change in case strain from positive to negative values, reflecting the a axis rotation of the probe (Fig. 7d). Probe 10 also showed some short term dip changes (Table 5) during the autumn and spring. In particular, those in October and November (2005), showed the dip continuously varying over a longer duration (typically four, 4-hour periods).

Of the probes that only survived during Autumn, probe 5 showed the least changes (Fig. 8a). In contrast, probe 7 experienced significant tilt changes associated with an autumn high water pressure event (Fig. 8b). Once the probe had settled in there was an initial flattening of dip and a change in orientation, and a series of long duration, continuously variable dip events. Then during the early phase of the water pressure rise (days 264–281), there was another change in orientation and 9 dip oscillation events (Table 5). During the second part of the high water pressure event (days 281–293), the oscillation events ceased and the probe began to rotate on its a-axis at a rate of 8° per day (clockwise).

Table 3
Summary of mean sensor values in the ice and till.

	Ice			Till					
	4[a] (11/08–05/03)	4[b] (06/03–24/05)	15[a] (05/08–09/09)	5 (13/03–6/12)	7 (01/09–20/10)	8	10	12	16 (05/08–17/11)
Temp. (°C)	1.07	0.11	1.2	0.08	0.14	0.12	0.09	0.11	0.08
Water pressure (m)	2.23	28.93	−1.85	5.24	35.96	73.7	4.55	21.31	16.47
Case strain (% micro strain)	0.68	1.29	0.03	–	–	–	0.05	–	0.08
Standard deviation x and y tilt (°)	33.3	0.9	34.21	3.6	15.5	13.5	3.1	8.4	8.03

Data for probes 8, 10, 12: whole year; others as shown.
[a] Not frozen in.
[b] Frozen in.

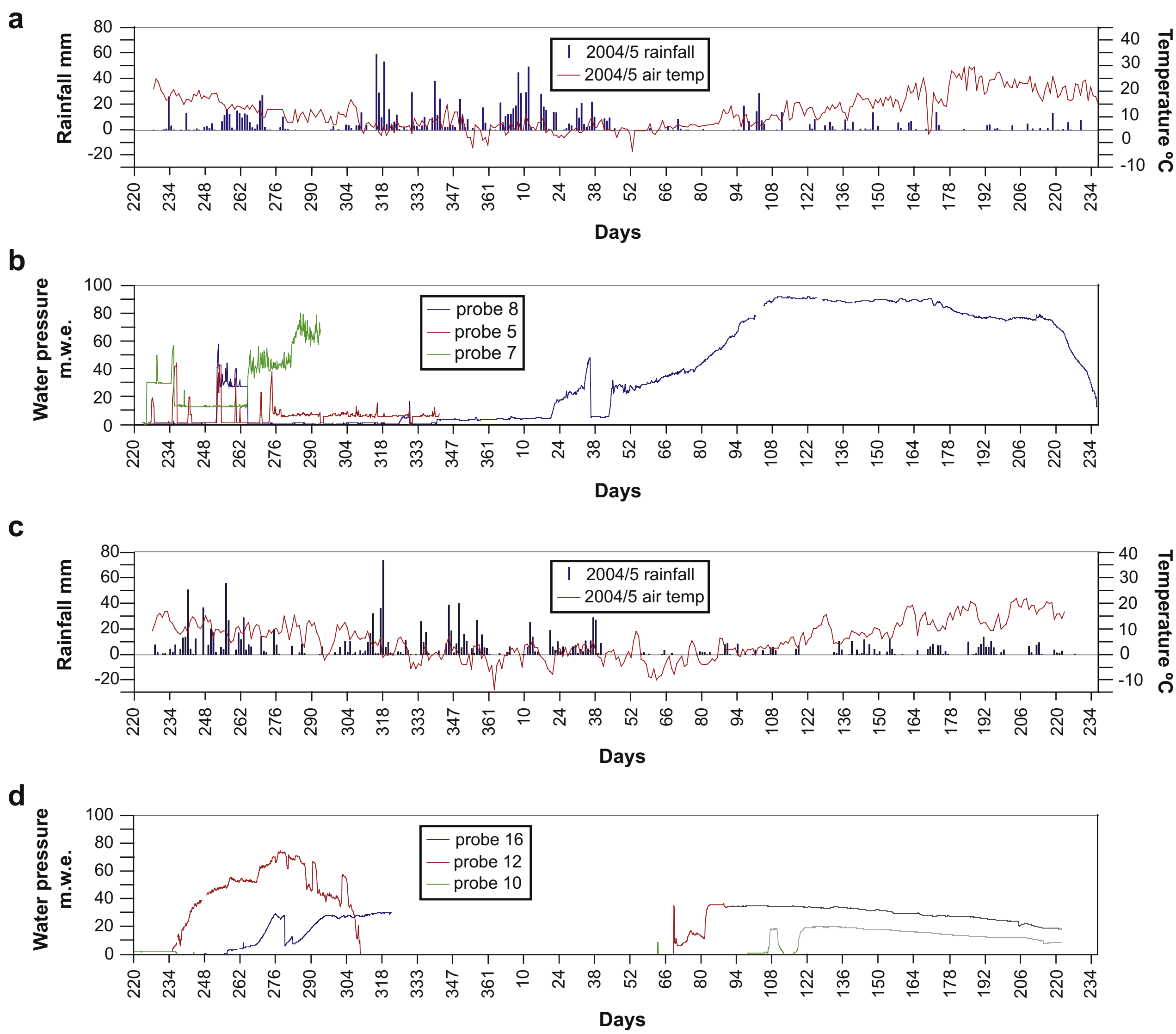

Fig. 4. (a) Air temperature and rainfall 2004–5; (b) water pressure data from probes 5, 7 and 8 (2004/5); (c) air temperature and rainfall 2005–6; (d) water pressure data from probes 10, 12 and 16 (2005/6);.

Probe 16 also showed a flattening of dip, with changes in orientation associated with the water pressure rise (Fig. 8c). During the first rise in water pressure (days 265–274) the probe rotated on its *a*-axis at 0.33° per day (clockwise).

Overall, the probes showed a flattening of dip over the year, with some changes in orientation, and rotation about the *a*-axis. The scale of the changes was related to glacier velocity. The greatest changes occurred in 2004/5 when the glacier was thicker and flowed faster. There was a consistent increase in dip changes (especially in probe 8) from November to July as the glacier velocity increased and *a*-axis rotation occurred during the high water pressure events of autumn and late summer.

Superimposed on these tilt trends were short term dip oscillations. These events are probably more common than we have recorded, as we only sampled once every four hour and 66% of these events were only one recording long. The relationship

Table 4
Average component of till movement to glacier motion, cohesion (C) and angle of friction (φ) from selected glaciers.

Glacier	Basal motion due to sediment deformation	C (kPa)	φ (°)	References
Black Rapids Glacier, Alaska	100% below 2 m, 0% above 2 m	1.3	40	Truffer et al., 2000
Breiðamerkurjökull, Iceland	67–85%	4	27/28	Boulton et al., 1974, 2001; Boulton, 1979; Boulton and Hindmarsh, 1987
Storglaciären, Sweden	Approx. 26%	5	25.5	Iverson et al., 1995
		0	25.5	Hooke et al., 1997
Whillians Ice Stream, Antarctica	17% or 31%	0	24	Engelhardt and Kamb, 1998; Tulaczyk et al., 2000
		2	22	Christoffersen and Tulaczyk, 2003
Trapridge, Yukon, Canada	24–45%	0	18.6	Clarke, 1987; Fischer and Clarke, 1994; Blake, 1992; Kavanaugh, 1994 (based on Iverson et al., 1995)

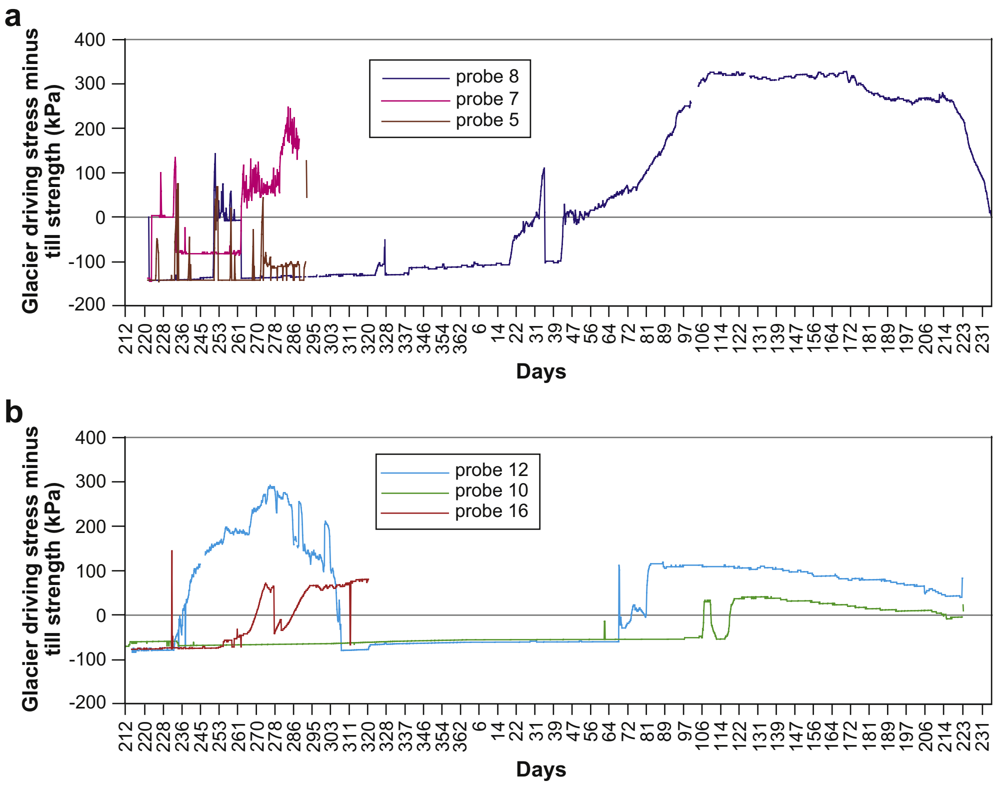

Fig. 5. Residual stress (driving stress minus till strength) for the probes: (a) 2004/5, (b) 2005/6. Till deformation can potentially occur when the glacier driving stress minus till strength is positive.

between water pressure and velocity is best illustrated from probe 12. With reference to Table 5 and Figs. 3a and 4d, it can be seen that in February and March, the number of oscillations were low, the glacier velocity medium to high, and the water pressure low. However, during the last week of March, when the water pressure rose dramatically and the glacier velocity began to decrease, the oscillations stopped. After this, the oscillation events were very frequent, whilst water pressure remained high. As water pressure fell in May, the number of oscillations also declined.

Similar dip oscillations occurred during the autumn high pressure event (Table 5). In 2004, although a water pressure rise was only recorded in probe 7, from late September to late October (days 264–293, end of probe record), dip oscillations are recorded during the beginning of this period in probe 7 and throughout the period in probe 8 (Table 5). A very small water pressure rise was recorded in probe 8 in early December (day 340), and similarly dip oscillations are recorded in this probe. In 2005, one water pressure rise was recorded in probe 12 from early September to early November (days 246–309), and two in probe 16 from mid September to the end of probe data in mid-November (days 256–281 and days 281–321). Dip oscillations occurred at the beginning of the water pressure rise in September (days 259–265) in probe 12 and throughout the pressure

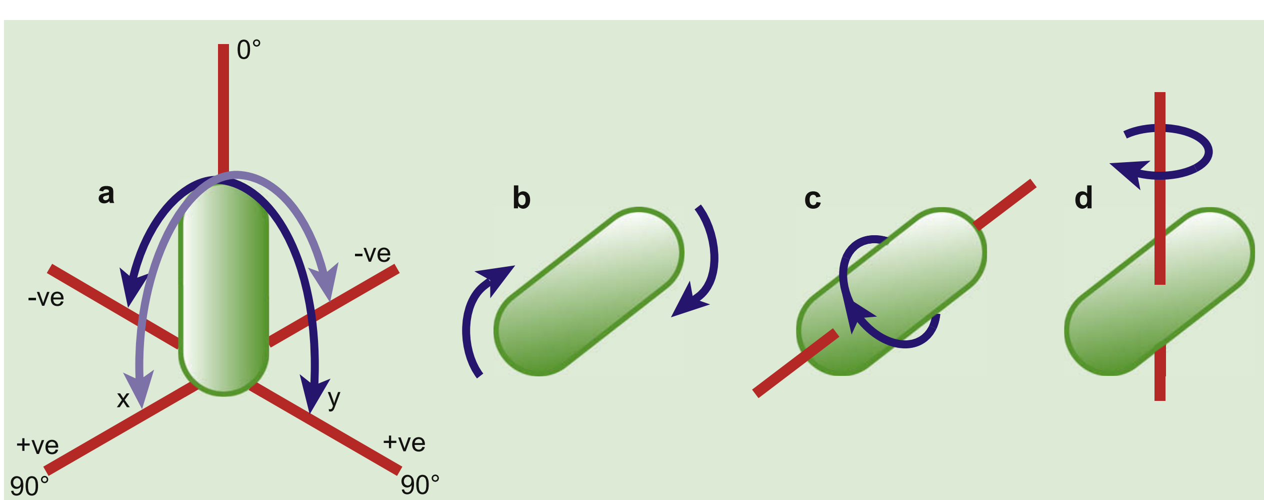

Fig. 6. Schematic diagram to show three-dimensional probe movement: (a) relative tilt angle axes; (b) theoretical change in dip; (c) theoretical rotation about its [longest] *a*-axis; (d) theoretical change in orientation (in practice this will be accompanied by a change in dip and/or rotation).

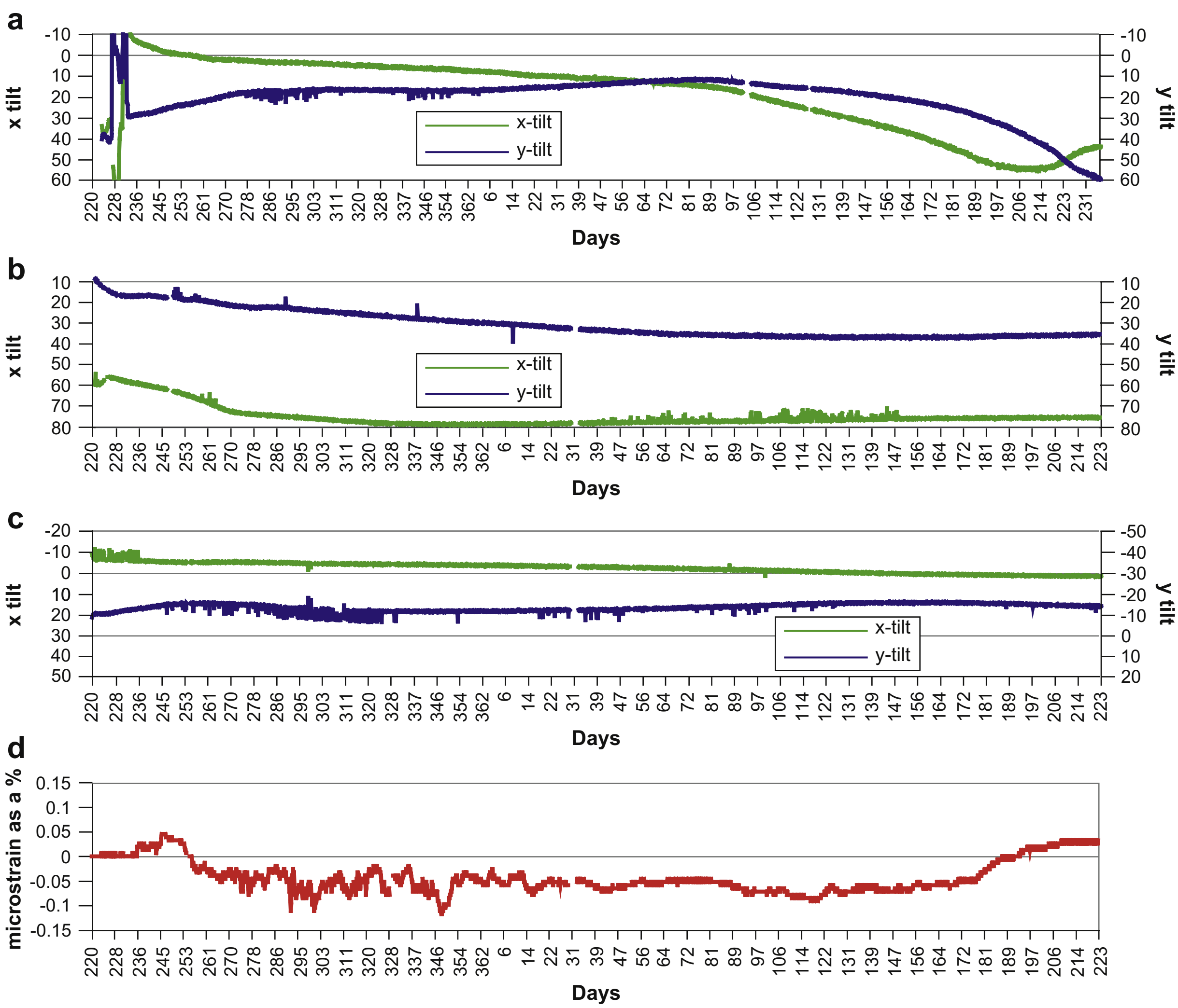

Fig. 7. Data from the three till probes that recorded data the whole year: (a) probe 8 tilt angle (2004/5); (b) probe 12 tilt angle (2005/6); (c) probe 10 tilt angle (2005/6); (d) probe 10 case strain.

rise in probe 10 (days 245–325), although none were seen in probe 16. Thus, it seems that there is a link between subglacial high water pressure (particularly rising water pressure) and dip oscillations, even at sites where the local water pressure was low. It can also be seen by a comparison between Fig. 7c and d that the times of dip oscillations occurred during periods of high case strain.

5. Discussion

5.1. Water pressure and till behaviour

Iverson et al. (1995), Fischer and Clarke (1997) and Boulton et al. (2001) have argued that when (and where) water pressure in till is

Table 5
Frequency and magnitude of the probe dip oscillations.

Probe	Dates			No. of dip oscillations	Average duration (h)	Average dip variation (°)
	Year	Calendar	Day of year			
7	2004	14–20 Sept	257–263	8	8.5	4.73
		23 Sept–10 Oct	266–281	9	7.52	4.37
8	2004	5–31 Oct	278–309	23	9.59	3.44
		6–21 Dec	340–355	9	8.44	3.04
10	2005	4 Sept–11 Oct	247–284	21	5.32	3.26
		12 Oct–6 Nov	268–310	38	15.28	4.76
		17–21 Nov	321–325	5	4.88	4.58
	2006	17 Jan–17 Feb	17–48	14	6.86	3.2
		28 Mar–10 Apr	87–100	11	5.76	2.73
12	2005	16–22 Sept	259–265	6	4.64	2.87
	2006	9–28 Feb	40–59	9	5.32	1.79
		1–21 Mar	60–81	14	4	2.64
		1–30 April	91–120	34	6.68	2.77
		1–31 May	121–151	23	6.6	2.33

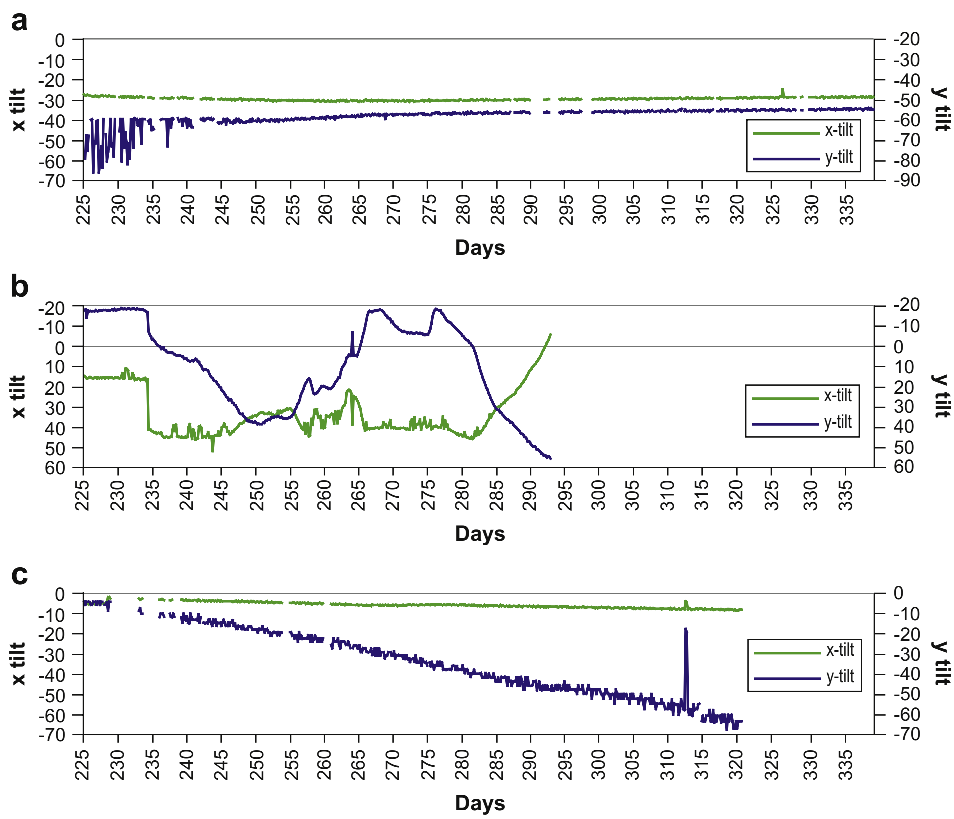

Fig. 8. Data from the three probes in the till that only responded during autumn: (a) probe 5 tilt angle (2004/5); (b) probe 7 tilt angle (2004/5); (c) probe 16 tilt angle (2005/6).

high, the ice-bed coupling is weak and basal sliding occurs. However, when water pressures are lower, ice-bed coupling is strong and till deformation occurs. We suggest that the probe data from Briksdalsbreen fits this model and demonstrates the relationship between clast behaviour and changes in water pressure.

During the early summer, there was a clear pattern of dramatic water pressure rise, followed by a period of high sustained pressures. This indicates that basal sliding must have been dominant. Later in the summer, water pressures decreased and the basal drag increased providing excellent conditions for subglacial deformation. This was associated with a change in dominant motion from dip variations, to changes in orientation and then *a*-axis rotation.

In addition, most probes displayed dip oscillations. These occurred in both autumn and spring associated with dramatic water pressure rises and high case strain. These events were even recorded when there were no local water pressure rises. This suggests that the dip oscillations were due to increases in glacier velocity and reflect stick-slip motion. Since the probe was relatively large (because of technological constraints), these movements may reflect the "lodging" type movement described by Benn and Evans (1996). In this instance, a clast is lodged into the till, often into a consolidated bed below the deforming layer, or has "bridged" the deforming bed between the ice and the bedrock.

5.2. Till fabric

Ghosh and Ramberg (1976) and Ježek et al. (1994, 1996) argued that, based on the Jeffery (1922) model, a population of prolate spheroidal rigid inclusions within a viscous material, would undergo either continuous rotation, creating a weak fabric, or develop a stable strong fabric. They suggested that the former occurs where simple shear dominates, whilst the latter is associated with pure shear. However, numerous workers have suggested constraints on the theoretical continuous rotation model (Jiang, 2007).

Marques and Coelho (2001) show that where the inclusion is large relative to the shear zone thickness, a pressure-gradient-driven rotation can overcome the normal Jeffrey rotation, leading to a stable fabric. Ildefonse et al. (1992a, b) describe the effect of interactions between inclusions. For equally sized particles, the interaction effects become significant if the distance between individual clasts is smaller than their length. Mandal et al. (2005a) have shown that the greater the concentration of inclusions the greater the rotation. Many researchers (e.g. Ghosh and Ramberg, 1976; Mancktelow et al., 2002; Ceriani et al., 2003) have argued that the more elongate the particle, the slower the particle rotates and it is more likely to develop a stable position. Mandal et al. (2005b) argues that decreasing the degree of isotropy in the matrix decreases inclusion rotation.

Finally, Ildefonse and Mancktelow (1993) and Schmid and Podladchikov (2004) argue that intrusions in shear zones can have stable positions associated with simple shear without the pure shear element, if there is a weak layer between the matrix and the clast allowing inclusion/matrix slippage.

In summary, the factors encouraging continuous rotation (weak fabric) would be simple shear, interaction between inclusions and a higher inclusion concentration; whilst the factors acting for the stable (strong fabric) would be a thin shear zone, inclusion/matrix slippage, pure strain, elongation of inclusions and pre-existing matrix isotropy.

Many of these factors have been considered within the subglacial shear zone. Numerous researchers have shown that greater size and elongation (Benn and Evans, 1996; Kjaer and Kruger, 1998; Carr and Rose, 2003; Carr and Goddard; 2007) leads to a stronger fabric. Hart (1994) has suggested that a thin shear zone leads to strong fabric, and Hooyer and Iverson (2000) and

Iverson et al. (2008) have discussed the effects of inclusion/matrix slippage. However, it must be noted that a subglacial shear zone varies from an experimental one, in that the thickness of the shear zone can change and the applied stress (glacier velocity) and water pressure (matrix strength) can vary dramatically on short time scales.

Thus, it can be concluded that in a subglacial shear zone, continuous rotation (weak fabric) is expected, however, local conditions may lead to a stable strong fabric. Our experimental study showed two types of behaviour. There was long-term (over the year) continuous rotation, in the form of a flattening of dip, change in orientation, and rotation about the *a*-axis. Probe 8, which provides the best record (as the glacier was flowing relatively fast during 2004/5), reached a final dip of approximately 45°. However, it could be argued that one year was not long enough for the inclusion to reach a stable position, and if the probe had survived for longer it may have moved to a low dip and remained there.

Superimposed on the long-term rotation were the short-term dip oscillations. These provide a good example of the local conditions within the shear zone affecting the rotation pattern.

5.3. Summary

The results from Briksdalsbreen illustrate the composite nature of deformation till, and it could be suggested that there is a lodging/deformation cycle associated with water pressure changes and the evolution of the subglacial drainage system. Increases in water pressure are associated with basal sliding and "lodgement"/dip oscillations. Then as water pressures fall, deformation occurs, with changes in dip, orientation and rotation about the *a*-axis. This cycle was relatively long over the summer (5 months), and related to the evolution of summer glacier hydrology. It was much shorter over the autumn (2 months) where high autumn rainfall delayed the shutting down of the glacier hydrological system.

6. Conclusion

This study has demonstrated, for the first time, the amount and nature of clast rotation within the deforming layer. The probes underwent continuous rotation (in dip, orientation and about the *a*-axis) throughout the year. The probes decreased their dip over the season, at a rate related to an increase in glacier velocity. Some probes showed additional short and frequent dip oscillations in spring and autumn. These were interpreted to reflect the stick-slip motion of clasts lodged within the deforming layer.

When water pressures were high, basal sliding and stick-slip of the probe occurs and when the water pressures fall, the ice and sediment were coupled causing till deformation. It is this combination of subglacial processes, with associated clast movement, that builds up a complex (but predictable) fabric and till sedimentology.

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