8.10 Depositional Processes

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Glossary

Attenuation Stretching of sediment due to deformation.
Boudinage The extension of layered sediments, where the more competent sediment breaks up into sausage shapes.
Debris-rich basal ice Lower most part of a glacier with a high percentage of debris frozen into the ice. Normally appears as layers of ice and debris.
Rheology The study of the behaviour of sediment deformation.
Shear zone Thin layer which has undergone high deformation.
Skelsepic plasmic fabric Where the orientation of the long axes of the plasma (matrix) are orientated around larger bodies (grains).
Till Sediment deposited by a glacier, normally an unstratified diamicton with far travelled clast (erratics).

Abstract

The interaction of water and sediment at the glacier base controls glacier motion, and it is the resultant till that provides a dynamic record. These processes can change on a spatial (mobile and 'sticky spots') and temporal (annual and diurnal) scale. Deformation within the deforming layer occurs by simple shear, by rotation and longitudinal extension, as well as abrasion and fracture, of both clasts and grains. This produces a resultant till fabric, which can be used to interpret till genesis. Water flow in channelized forms either as 'fast' R-channels or 'slow' cavities, water films, and 'microcavities' will produce stratified sediments.

8.10.1 Introduction

Over the last 20 years, the study of glacial processes has been transformed by a combination of new techniques and technologies, and new theoretical ideas about the way in which glaciers move, deposit, and deform their sediments. Glacial till is not just a passive result of straightforward subglacial processes, but an active response to glacier dynamics. It is the interaction of water and sediment at the glacier base that controls glacier motion in many cases and it is the till that provides a dynamic record of the amalgamation of many processes. The next 20 years will witness further advances in these directions, which will continue to revolutionize our understanding of one of the least-explored areas on Earth – the subglacial environment.

These technological highlights include:

- *The development of wired and wireless instruments to monitor the subglacial environment*. Initial studies of the subglacial environment were via tunnels dug into glaciers (Fisher, 1963; Kamb and LaChapelle, 1964). These were difficult to construct, potentially dangerous to enter, and could only

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allow investigation of the glacier margin. The most significant recent study of this type was from Breiđamerkurjökull (Boulton, 1979), where the movement of strain markers placed within till at the base of such a tunnel led to the understanding of the significance of subglacial deformation in glacier motion and sedimentology. However, by the 1990s, many researchers were using a hot water drill to access the glacier bed and place a series of delicate instruments into the ice and till to measure glacial processes. These normally included tilt-cells (to measure the amount of till deformation), ploughmeters (to measure till strength), and drag spools (to measure relative deformation/sliding) (see reviews in Murray, 1997; Boulton et al., 2001; Fischer and Clarke, 2001). In more recent years, wireless techniques have been developed so that the instruments can behave more like natural clasts (Harrison et al., 2004; Hart et al., 2006, 2009).

- *The development of borehole video cameras*. These allowed the englacial and subglacial environment to be observed for the first time (Koerner et al., 1981; Harper and Humphrey, 1995; Copland et al., 1997). This has led to a re-evaluation of the role of crevassing in englacial hydrological pathways (Fountain et al., 2005) and the presence of debris within glacier (Carsey et al., 2002). In addition, Roberson and Hubbard (2010) have used borehole optical televiewing to investigate the 3D structure of glaciers.
- *The development of geophysical techniques (ground-penetrating radar (GPR) and seismic)*. These allowed the englacial and subglacial environment to be 'imaged' over a large spatial scale. Alley et al. (1986) were able to show the presence of a 6 m thick saturated deforming layer, whereas Smith and Murray (2009) used seismics and King et al. (2009) used GPR to show the development of subglacial bedforms beneath the Antarctic ice sheet.
- *The development of accurate glacier velocity measurements from dGPS and InSAR*. The use of dGPS to measure glacier surface ice velocities has revealed how glacier motion is not constant, but is commonly episodic and it has been proposed that this reflects stick–slip motion similar to the movements associated with earthquakes (Bahr and Rundle, 1996; Fischer and Clark, 1997; Bindschadler et al., 2003; Tsai and Ekstrom, 2007). Ice movements of up to 70 cm in approximately 25 min (equivalent to an earthquake magnitude (M_w) of 7) have been recorded from the West Antarctic Ice Sheet (Wiens et al., 2008). In addition, the processing of repeat radar and LiDAR measurements has allowed the quantification of glacier velocity changes over the entire glacier.

It is the integration of these techniques combined with sedimentology, from both modern and ancient glacial deposits, that allows us to understand the glacial environment. In this chapter, I briefly discuss glacial transport and then go on to discuss glacial deposition within the terrestrial environment.

8.10.2 Glacial Transport

Rock fragments carried within the glacier are known as debris, and can be carried in one of three transport paths (**Figure 1**): *supraglacial transport* over the top of the glacier, *englacial transport* through the glacier, and *subglacial transport* along the bed of the glacier, in both the ice (debris-rich basal ice layer) and any mobile saturated unconsolidated layer (the deforming layer). These transport processes will be discussed in detail in the following chapter.

Glacier flow ensures that supraglacial debris deposited on the glacier surface (via rock falls) in the accumulation area will soon be incorporated into the glacier and become englacial material, before being moved back onto the surface again in the ablation area (Boulton, 1978; Eyles and Rogerson, 1978; Boulton and Eyles, 1979; Small et al., 1979) (**Figure 1**). Material originating in the subglacial environment may also be thrust up at the margin (Boulton, 1970a; Bennett et al., 1996; Hambrey et al., 1996; Hambrey and Dowdeswell, 1997; Murray et al., 1997; Glasser et al., 1998) and become englacial and then supraglacial. Hambrey et al. (1999) illustrated three-dimensional aspects of debris paths within a valley glacier, which can produce the complex arrangement of debris commonly occurring on the surface of the glacier (**Figures 2(a)–2(c)**).

8.10.3 Glacial Deposition

Once debris is deposited onto the landscape; it is known as till. This is a diamicton comprising clasts resting in a finer

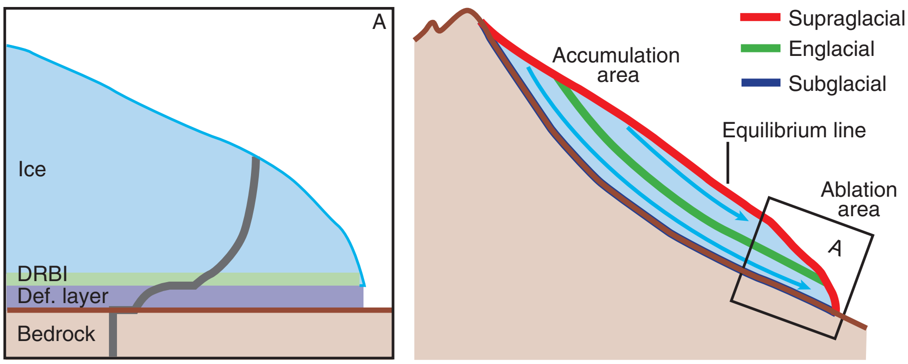

Figure 1 Glacial transport pathways (see the inset for detail of the bed, not to scale; the black line in A indicates the theoretical velocity profile). DRBI indicates debris-rich basal ice layer. Def. Layer is deforming layer.

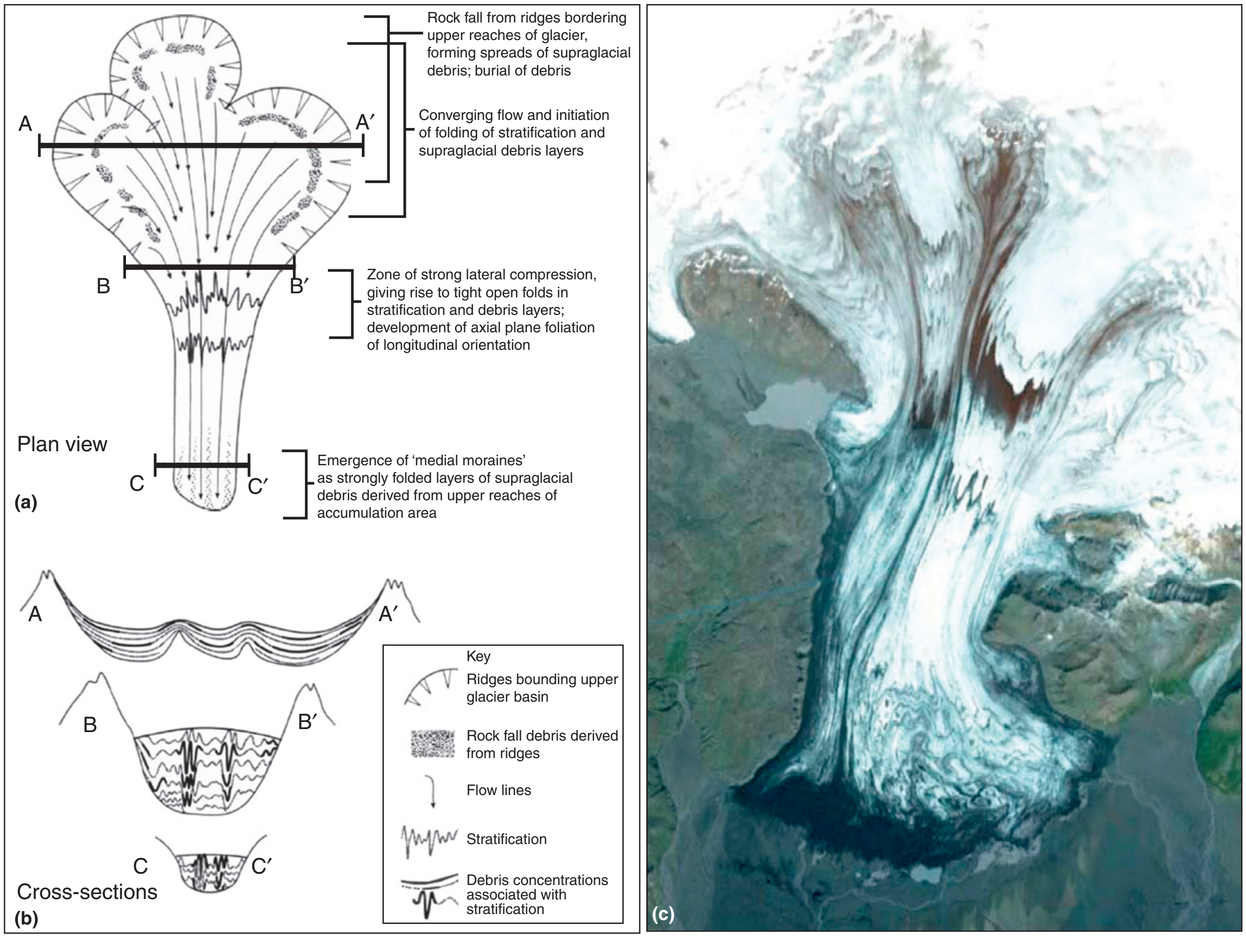

Figure 2 (a) and (b) Schematic diagram showing the three-dimensional debris pathways. (a) Reproduced from Hambrey, M.J., Bennett, M.R., Dowdeswell, J.A., Glasser, N.F., Huddart, D., 1999 with permission from IGS. Debris entrainment and transfer in polythermal valley glaciers. Journal of Glaciology 45(149), 69–86, with permission from IGS. (c) Outcropping of the ash debris layers at Skeiđararjökull, Iceland (Google Earth image 2002; the width of glacier at the narrowest point is 7.3 km).

matrix. Normally, these clasts may include erratics, they may have striae (striations), and may have a strong orientation (fabric) in the ice direction. In general, till is not stratified, although it can be under special circumstances that are discussed below.

8.10.3.1 Supraglacial Till

In theory, debris present on the glacier surface can melt out to form a supraglacial till. The clasts within this material should be oriented in a random manner.

Debris-mantled ice will not melt out evenly, due to changes in heat received on the glacier surface. This leads to a continuously changing glacier surface, which creates an irregular landscape. Till and debris will flow down slope (aided by the presence of abundant water supply from glacier melting), small lakes may form (with clay sedimentation), and rivers can flow around any irregular ice blocks, leading to sand and gravel deposition. This will result in a very complex landscape of hummocky moraines (Hoppe, 1952; Benn, 1992; Hambrey et al., 1997; Lukas, 2005) composed of an intricate arrangement of stratified clays, sand, gravels, and till (Boulton 1970b, 1972; Bennett et al., 1997; Hättestrand and Johansen, 2005).

8.10.3.2 Subglacial Till

The vast majority of till described in the literature from previously glaciated areas has been interpreted to have formed subglacially. Subglacial process studies have indicated that the subglacial environment comprises debris held directly in the ice (either in clear glacier ice or in the debris-rich basal ice layer) or in the deforming layer (**Figure 1**).

Till generated from the melt-out of debris from the base of the ice is known as *melt-out till* and some Quaternary tills have been interpreted to be the direct result of this process (Mickelson et al., 1983; Piotrowski, 1992). Till generated purely from the frictional retardation of clasts on a rigid bedrock directly from the ice is known as *lodgement till* (Boulton, 1978; Dreimanis, 1989; Krüger, 1993). However, both these scenarios probably reflect rare depositional conditions within the subglacial environment. Most studies since the 1990s (from sedimentology, fabric studies, and *in situ* monitoring) have demonstrated that a complex range of processes operate within the subglacial environment, and it is the interplay of sediment and water that controls both glacier dynamics and glacial sedimentology, and that this results in a *deformation till* (Boulton and Jones, 1979; Hicock and Dreimanis, 1992; Hart and Boulton, 1991a; van der Meer, 1997; van der Meer et al., 2003; Roberts and Hart, 2005; Evans et al., 2006).

Water is continually being released from the base of a temperate glacier into the underlying till, and if the flow of this water is restricted, porewater pressures will rise and the sediment strength will be reduced, allowing the subglacial sediment to deform and glacier effective pressure to decline. **Table 1** shows the typical thicknesses and amount of deformation associated with a series of instrumented deforming beds.

Deposition with the deforming layer can occur in a number of ways (Hart and Boulton, 1991a) (**Figure 3**):

a. Debris can be melted out from the ice or debris-rich basal ice layer.
b. Subglacial material will be moved along with the glacier (advection).
c. Changes in the thickness of the deforming layer (due to changes in basal shear stress and porewater pressures) will lead to the deforming layer thickening (erosion of weak bedrock) or thinning (deposition at the base of the deforming layer).

Numerous researchers have shown how there is a continuum of subglacial processes, from lodgement associated with low porewater pressure, and deformation associated with high porewater pressure, with ploughing (Brown et al., 1987) as an intermediate stage. *In situ* process studies (see **Table 1**) have demonstrated that changes in porewater pressure occur both spatially and temporally (**Figure 4**).

In contrast, some researchers have argued that ploughing is not an intermediate category between lodgement and deformation, but a dominant process producing the majority of deformation features occurring in till as well as subglacial bedforms (e.g., drumlins and megascale lineations) (Tulaczyk et al., 2000, 2001). They suggested that features within the till are produced by 'ice keels'. These are generated over rigid bedrock and carried passively onto the unconsolidated bedrock of the lowlands 'ploughing' into the sediment. In this model, geology becomes almost irrelevant, since it is the ice, rather than the saturated till, that generates and controls sediment and landform development.

8.10.3.3 Subglacial Shear Zone

Deformation within the deforming layer has been modeled as a shear zone (Hart and Boulton, 1991a) (**Figures 1** and **5**). Where a glacier moves over a heterogeneous bed rock, the styles of deformation can be clearly seen (**Figures 5(b)** and **5(c)**). Deformation within a shear zone is by simple shear, which is accompanied by rotation and longitudinal extension. Typical features on the field scale include the following:

- tectonic laminations (attenuated folds)
- rotational structures
- boudins
- basal décollement plane

These features also occur at the micro (thin-section) scale. Typical rotational structures include small grains displaying a parallel orientation to the edge of a larger

Table 1 Evidence for subglacial deformation and the relationship between subglacial water pressure and plough meter response from the literature

	Basal motion due to sediment deformation %	*Thickness of the deforming layer (m)*	*Yield stress (kPa)*	*Till viscosity (Pa s)*	*Till discharge per 1 m^3 section per year*[a] *(m^3 a^{-1})*
Trapridge Glacier (Fischer and Clarke, 1994)	24–45	0.3	48–57	3×10^9–1.5×10^{11}	314
Trapridge Glacier (Fischer et al., 1999)					
Storglaciaren (Fischer et al., 1998)	≈26	0.35 m	55	-	0.64
Unteraargletscher (Fischer et al., 2001)					
Bakaninbreen (Murray and Porter, 2001)		0.1–0.2	82	6×10^{10}–4.3×10^{11}	-
Breiðamerkurjökull (Boulton and Jones, 1979; Boulton and Hindmarsh, 1997; Boulton et al., 2001)	67–85	0.38–0.45 m	5.7–32.5	5×10^{10}–5×10^{11}	3.2–6.3
Black Rapids Glacier (Truffer et al., 2000)	100 below 2 m 0 above 2 m	>2 m			>60–80
Columbia Glacier (Humphrey et al., 1993)		0.65	5.5–13		315
Briksdalsbreen (Hart et al., 2011b)	56–64	≈0.3	35	3.6–7.3×10^9	1.3–5.6

[a]Boulton et al., 2001.

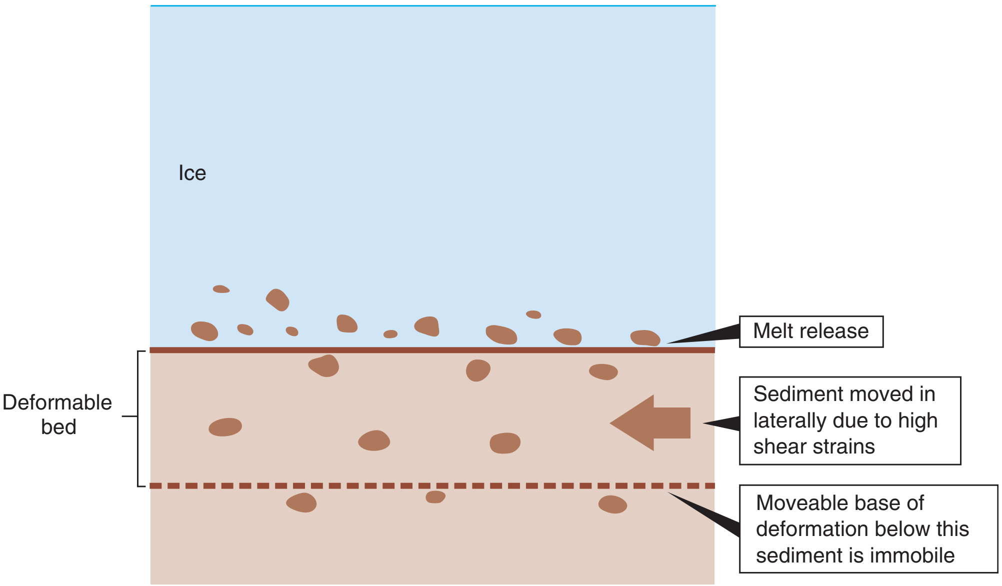

Figure 3 Deposition within the deforming layer. Adapted from Hart, J.K., Boulton, G.S., 1991a. The interrelationship between glaciotectonic deformation and glaciodeposition. Quaternary Science Reviews 10, 335–350

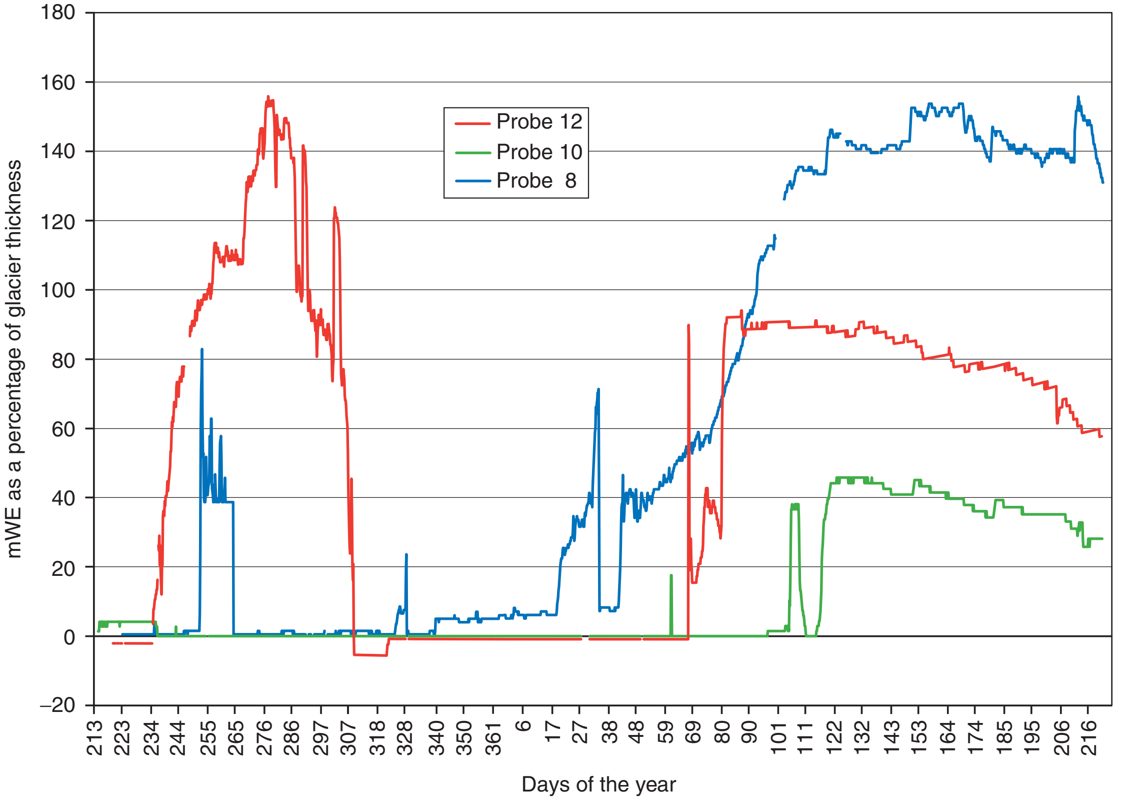

Figure 4 Graph of *in situ* changes in the porewater pressure from a Glacsweb probe embedded in subglacial till from Briksdalsbreen (probe 8 2004/5, probes 10 and 12 2005/6). Adapted from Hart, J.K., Rose, K.C., Waller, R.I., Vaughan-Hirsch, D., Martinez, K., 2011a. Assessing the catastrophic break up of Briksdalsbreen, Norway, associated with rapid climate change. Journal of the Geological Society of London 168, 1–16. doi: 10.1144/0016-76492010-024.

grain (turbates) (Figure 5(d)), attenuation and boudinage (Figure 5(e)) of laminations, skelsepic plasmic fabric, plastering around grains, grain lineations, and folds and faults (van der Meer, 1993; Menzies, 2000; Hart et al., 2004).

In situ studies have also shown that 'rafts' of material can move beneath the glacier. Truffer et al. (2000) demonstrated from Black Rapids glacier, Alaska, that a 2 m thick 'slice' of till with no internal deformation moved

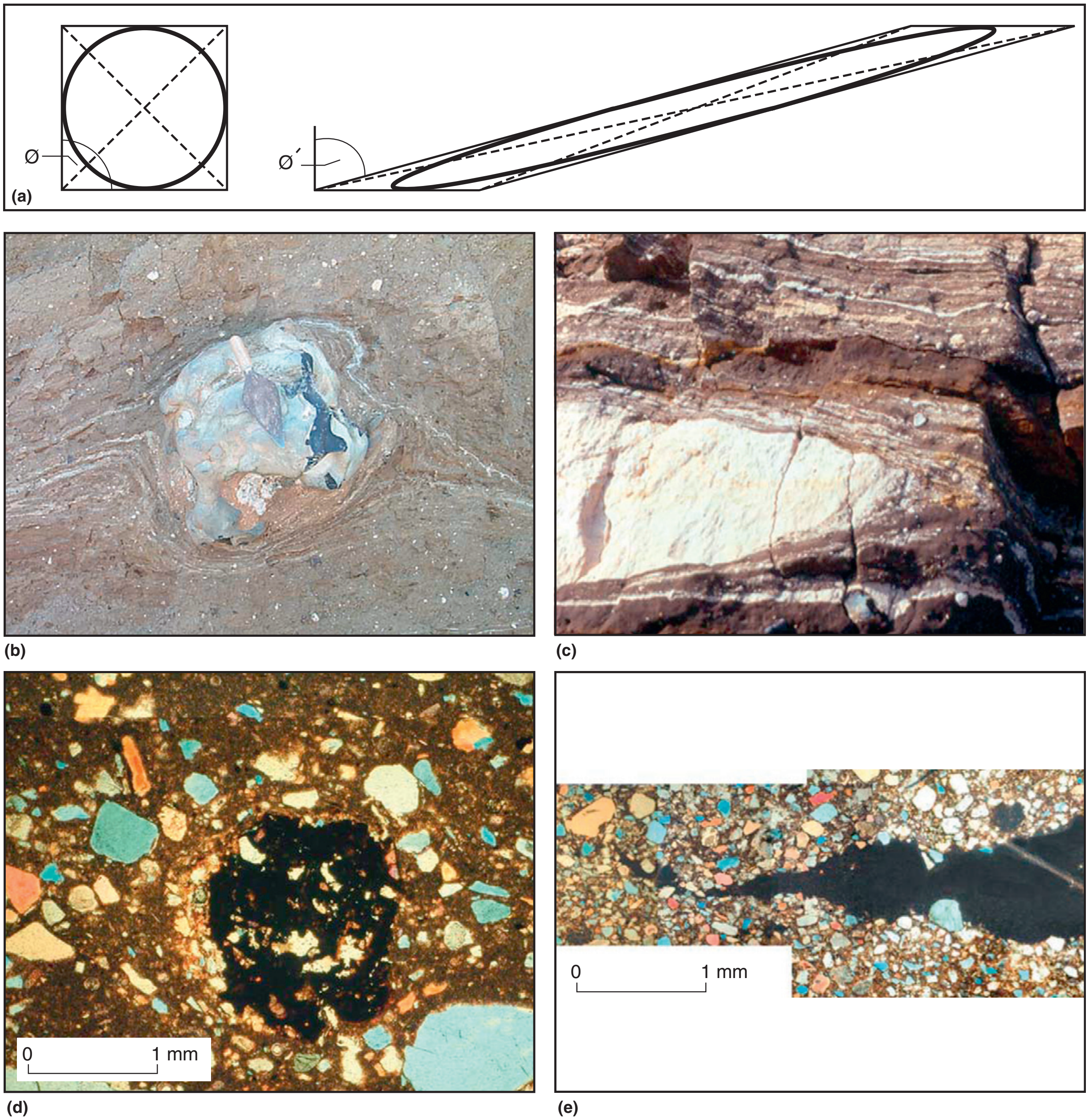

Figure 5 Subglacial shear zone: (a) theoretical pattern of rotation and extension that results from simple shear; (b) photograph of chalk tectonic laminations flowing around a flint obstacle (Weybourne, Norfolk); (c) photograph of chalk and sand tectonic laminations (West Runton, Norfolk – scale 0.5 m $\times$ 0.6 m); (d) thin section photograph showing smaller grains (turbates) flowing around a larger 'core' clast (Weybourne, Norfolk); (e) thin section photograph showing attenuation and boudinage of a chalk (dark) lamination. Adapted from Hart, J.K., 2007. An investigation of subglacial shear zone processes from Weybourne, Norfolk, UK. Quaternary Science Reviews 26, 2354–2374.

beneath the glacier, and similar scale 'rafts' of till were observed beneath Skalafellsjökull, Iceland (Figure 6). Comparable 'rafts' of material have been observed within Quaternary tills (Ruszczyńska-Szenajch, 1987; Hart, 1990; Hiemstra et al., 2007; Phillips and Merritt, 2008). Deformation by simple shear has also been observed in frozen deforming layers (Echelmeyer and Wang, 1987; Astakhov et al., 1996; Murton et al., 2004) and in the debris-rich basal ice layer (Hart, 1995a; Waller et al., 2000; Fitzsimons et al., 2001).

8.10.3.4 Changes in Subglacial Deformation Over Space and Time

Numerous researchers have argued that deformation patterns change over space and time. In particular, it has been suggested (Alley, 1993; MacAyeal et al., 1995; Fischer et al., 1999; Stokes et al., 2007) that the deforming bed comprises a mosaic of 'sticky spots' (undeforming) and mobile spots (deforming). Sticky spots may be permanent, representing bedrock elements, or temporary, reflecting changes of water

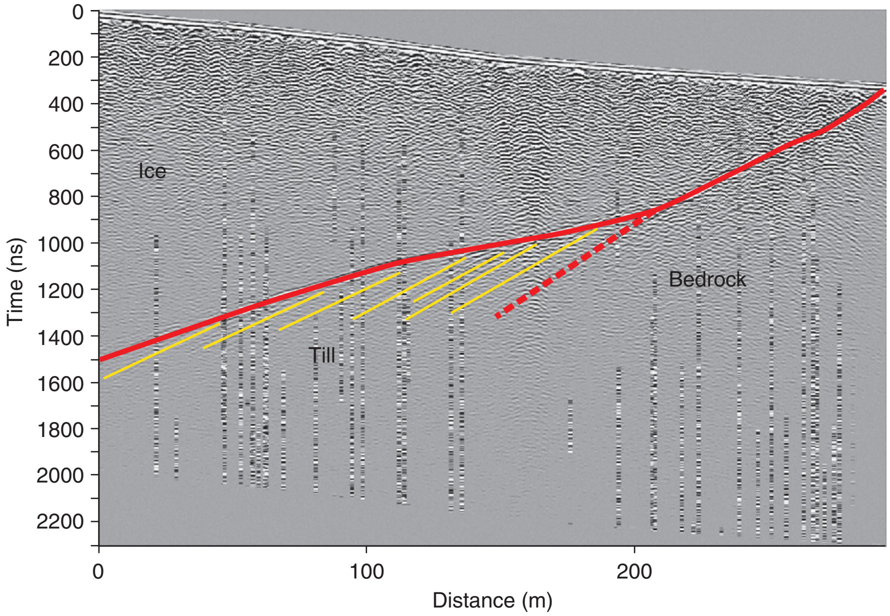

Figure 6 Ground-penetrating radar (GPR) radargram of subglacial 'rafts' of till at Skalafellsjökull (ice flowing left to right, maximum ice thickness 132 m, 'rafts' delimited by yellow lines).

pressure in the till. Seismic studies in particular (Smith, 1997; Anandakrishnan et al., 1998) as well as GPR studies have shown these changes (Copland and Sharp, 2001; Catania et al., 2003; Pattyn et al., 2003; Hart et al., 2011a).

Since the glacier mass balance is always changing, predictable deforming bed sequences can be produced. Typically, as a glacier first advances over an area, it will either erode or deform the bedrock. The resultant till will be dominated by local material and may show evidence of a low shear strain. Overlying this will be the 'mature' till comprising local and far-traveled material, usually with evidence of high shear strain. This may form a two-layer sequence ('local' till and 'far-traveled' till) over rigid bedrock or a three-layer sequence (deformed bedrock, 'local' till, and far-traveled till over unconsolidated bedrock) (**Figure 7**). In the past, the 'local' till may have been interpreted as a till from a different glaciation because of its different lithology, rather than the evolution of subglacial processes. This style of stratigraphy is known as constructional deformation (Hart et al., 1990) and typically occurs at the glacier margin where the deforming bed is relatively thin, accretion is high, and so a sequence can accumulate (Hiemstra et al., 2007; Ó Cofaigh et al., 2007; Davies et al., 2009).

In contrast, where the deforming bed thickens over time, at a faster rate than till accretion, the deforming bed will erode into the bedrock and the previous stages of deformation will not be preserved. This is known as excavational deformation; it typically occurs up-glacier and has a distinct basal décollement layer (Hart et al., 1990).

8.10.3.5 Rheological Processes Within the Deforming Layer

Till deformation involves the movement and reorientation of particles at both microscopic (clast and matrix scale) and macroscopic (bulk rheology) scales. However, until recently, these two elements have been investigated separately, with conflicting results. Initial research by Boulton and Hindmarsh (1987) on a till flow law proposed a viscous rheology. Experimental research by Kamb (1991) and Tulaczyk et al. (2000) proposed plastic deformation. However, most *in situ* experiments and sedimentological evidence also indicated viscous behavior. 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) argued that as a material deforms, disturbed zones develop that are distributed throughout the material. As deformation continues, these elements coalesce. Alternative to the Mohr–Coulomb model (Iverson et al., 1998; Tulaczyk et al., 2000), they show that 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 an overall viscous flow.

Hart et al. (2011b) showed from *in situ* experiments that the sand-rich till at Briksdalsbreen in Norway underwent deformation throughout the year. On the bulk rheology scale, till deformation exhibited elastic behavior during the winter, when water pressures are low, and linear viscous behavior after a critical yield stress of 35 kPa, when water pressures are high during the spring and summer. On the clast and matrix scale, during the winter, meltwater-driven, stick–slip, glacier velocity increases were transmitted through a relatively strong till grain network, causing brittle deformation. During the summer, the ductile till absorbed any stick–slip velocity increases.

8.10.3.6 Erosion Within the Deforming Layer

Erosion, deposition, and deformation within the subglacial environment are interrelated. This occurs in two main areas:

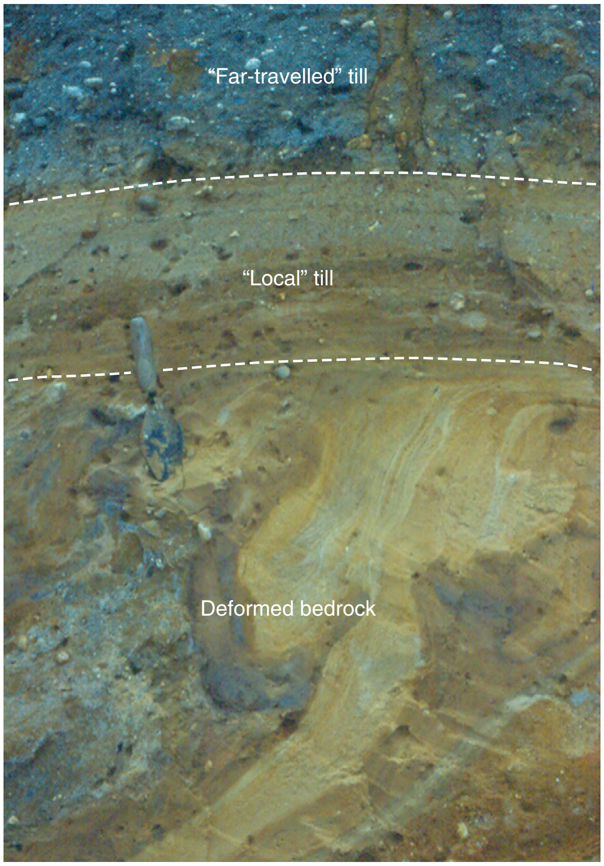

Figure 7 Constructional deformation from Great Blakenham, Suffolk.

a. Within the deforming layer – It has been shown on the microscale that abrasion and fracturing of grains and clasts can take place (Hart, 2006a; **Figures 8(a)** and **8(b)**). It has also been suggested that the vibrational energy released during stick–slip processes can cause exceptionally high subglacial temperatures (Bestmann et al., 2006) and cause grain fracture (Cuffey and Alley, 1996; Van Hoesen and Orndorff, 2004; Mahaney, 2008), although it is not clear how this would be identified.
b. At the base of the deforming layer, numerous researchers have argued for 'till abrasion' (Gjessing, 1965; Hart, 1995b, 2006b; Evans et al., 1998), by direct processes of abrasion and fracture. However, if the deforming layer thickens and more of the underlying substrate is incorporated into the deforming layer, then this can also be considered as erosion.

Additional erosional features of the deforming bed are stoss-and-lee clasts (**Figures 8(c)** and **8(d)**). These are large clasts with an abraded stoss side and fractured lee side (mobile miniature roches moutonnées) (Boulton, 1978; Sharp, 1982). They commonly have evidence of rotation, such as reversed stoss-and-lee clasts or double stoss-and-lee features (Krüger, 1984; Benn and Evans, 1996), and commonly occur alongside flutes (formed by subglacial deformation, Boulton, 1976; Sharp, 1982; Hart, 2006b). Benn and Evans (1996) concluded that the large stoss-and-lee boulders were lodged into the till, commonly into a consolidated bed below the deforming layer (b-layer, Boulton and Jones, 1979), as they were larger than the depth of the deforming layer. The smaller clasts were more mobile wholly within the deforming layer and were able to rotate. Thus, stoss-and-lee forms can be formed within the till or at the ice/sediment interface.

8.10.3.7 Hydrological Processes Within the Deforming Layer

The subglacial hydrological system is a vital component in understanding both glacier dynamics and till behavior (Duval, 1977; Mair et al., 2002; Copland et al., 2003; Clarke, 2005). Fountain and Walder (1998) argued that subglacial hydrology can be divided into two components and can be described as 'fast' and 'slow' (Raymond et al., 1995). The fast system is essentially a converging channelized Rothlishberger (r)-channel system, whereas the slow system is more complicated, covers a much larger area of the bed, and comprises cavities, water films, canals (Walder and Fowler, 1994), and 'microcavities' (Kamb, 1991), as well as water flowing within the till. It is well documented how these systems commonly evolve over a season (Seaberg et al., 1988; Hock and Hooke, 1993), changing from a distributed system in the spring to a channelized system in the summer.

Clark and Walder (1994) have argued that wide, thin channels ('canals') are more likely associated with a deforming bed system than traditional r-channels. Although canal deposits have been recorded from Quaternary deforming bed tills (Hart, 1996; Davies et al., 2009; Ó Cofaigh et al., 2010), esker deposits and r-channels also occur in association with deformation till (e.g., Blakeney Esker, Norfolk – Hart and Boulton, 1991b; Breiđamerkurjökull – Boulton and Hindmarsh, 1987; Briksdalsbreen – Hart et al., 2011a). Thus, it is clear that subglacial hydrology changes both spatially and temporally related to water content and sediment behavior, and this will be reflected in the resultant sedimentology.

Modern-day glacier observations, dGPS studies, and *in situ* subglacial studies have recorded subglacial high water pressure events causing the glacier to lift off its bed ('bed separation') on both a diurnal and a seasonal scale. It has been proposed that this process may lead to the deposition of thin stratified layers within till (Hoffmann and Piotrowski, 2001; Fuller and Murray, 2002; Munro-Stasiuk, 2000; Nelson et al., 2005).

These stratified sediments deposited at the ice/sediment interface may undergo subsequent deformation. They may behave as obstacles within the deforming layer, become attenuated and boudinaged, and thus contribute to a complex deformational pattern. Another common feature in till associated with high water pressure events are hydrofractures (Rijsdijk et al., 1999; Kjær et al., 2006; Phillips and Merritt, 2008). These form associated with high water pressures either within or below the till, and may allow sediments from beneath the deforming layer to be injected into the till (till dykes) (Humlum, 1978; Fitzsimons and Colhoun, 1989; Boulton and Caban, 1995).

8.10.3.8 Clast Movement and Till Fabric

The Glacsweb wireless probe has provided the only *in situ* data of the rate of clast rotation within the deforming layer

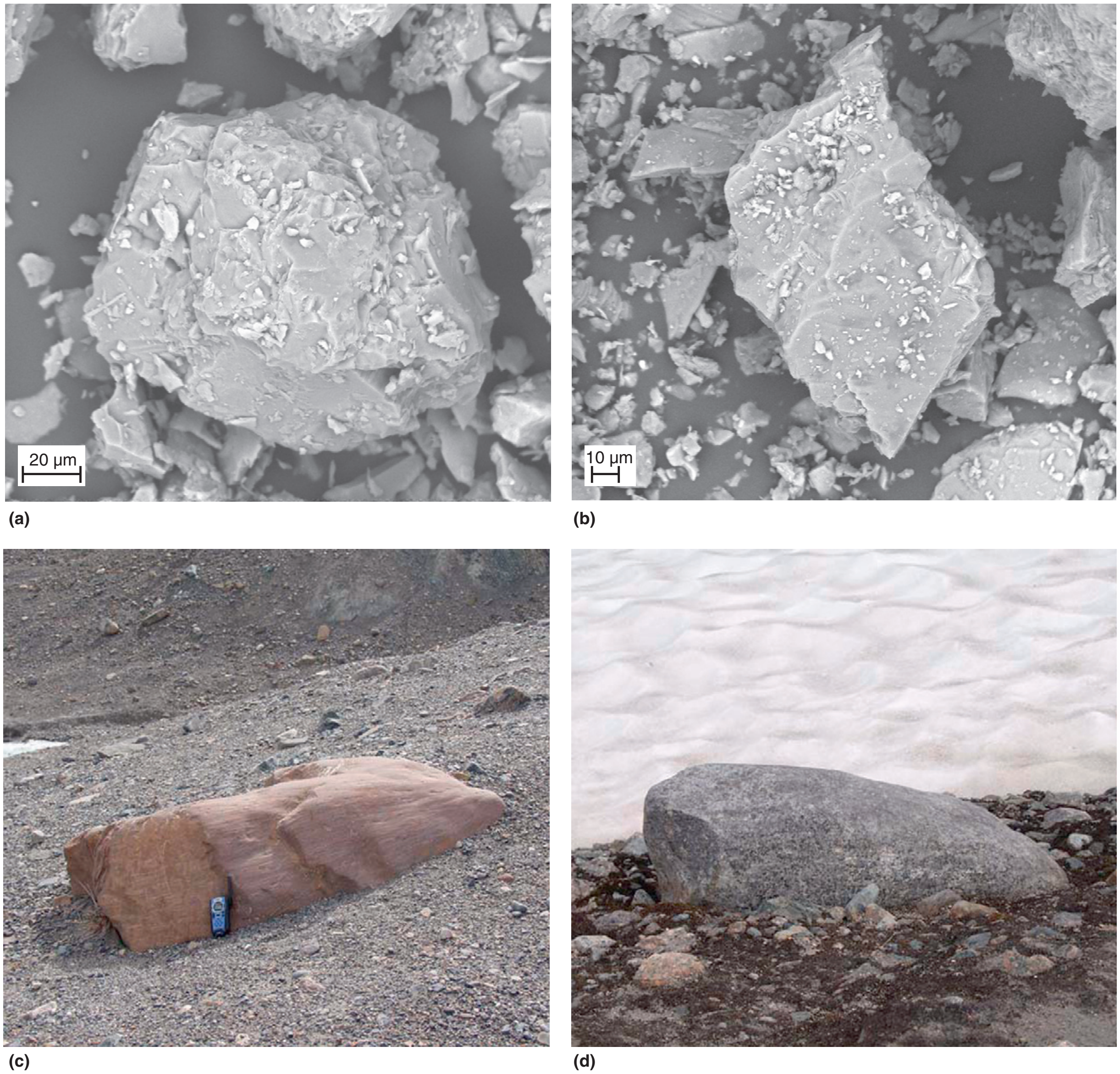

Figure 8 Erosion within the deforming layer: (a) SEM image of abrasion dominated rotation from Bødalsbreen, Norway. (b) SEM image of percussion dominated, Nigardsbreen, Norway. (c) Stoss-and-lee clast, Athabasca Glacier, Canada. (d) stoss-and-lee clast, Boverbreen, Norway. (Ice flow for both stoss-and-lee clasts from right to left.)

(Hart et al., 2009). On an annual scale, it could be seen that the dominant mechanism of movement was a change in dip from autumn to mid-July. The rate of change increased from 0.06° per day (in 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 and late-July, there was also a change in orientation (0.62° per day in late July). In August, the dominant mechanism changed and the probe began to rotate about its a-axis (anticlockwise), at 0.88° per day. 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).

Researchers have also shown diurnal patterns of sliding and deformation throughout the day. At Breiðamerkurjökull (Boulton and Hindmarsh, 1987) and Trapridge Glacier (Blake et al., 1994), maximum sliding occurred during the evening. At Breiðamerkurjökull, the sliding peak occurred after a peak in water pressure, whereas at Trapridge Glacier, this occurred as water pressure increased. However, at Briksdalsbreen, sliding initially occurred in the morning, followed by deformation (initially with probes rotating 'forward' and then 'backward'). This antithetical rotation has also been reported from tethered *in situ* tilt cells (Fischer and Clarke, 2001; Iverson et al., 1995; Boulton and Dobbie, 1998), and both laboratory- and field-based shear zone studies (Ghosh and Ramberg, 1976; Marques et al., 2007). These results indicate that both bed separation and possibly lodgement (associated with sliding) and deformation can occur each day.

Once clasts are deposited within the deforming layer, till fabric provides a useful (but contested) method to reconstruct ice direction and subglacial processes (Andrews, 1971; Glen et al., 1957; Hart, 1994; Bennett et al., 1999). The eigenvalue technique developed by Mark (1973) and pioneered by Dowdeswell and Sharp (1986) quantifies the fabric strength and is a valuable technique to identify till types (**Table 2**), but needs to be used alongside other sedimentary techniques.

Most geologists have applied the Jeffrey (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). In contrast, other researchers have suggested that the clasts will initially rotate into the shear plane and then remain there if there is a weak layer between the matrix and the clast, allowing inclusion/matrix slippage (March, 1932; Ildefonse and Mancktelow, 1993; Hooyer and Iverson, 2000; Larsen and Piotrowski, 2003; Schmid and Podladchikov, 2004; Thomason and Iverson, 2006; Iverson et al., 2008).

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), the fabric strength will be high (Benn, 1995; Kjaer and Kruger, 1998; Hart, 2006b), whereas 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). This is because the factors promoting continuous rotation (weak fabric) are the interaction between inclusions and a higher inclusion concentration, whereas the factors conferring stability (strong fabric) would be a thin shear zone, inclusion/matrix slippage, elongation of inclusions, and preexisting matrix isotropy (Hart et al., 2009).

These processes also affect the microfabric of a till (grain alignment). Most studies determine orientation strength statistics from the two-dimensional thin section slides, including two-dimensional vector analysis (Curray, 1956), resultant of the mean vectors (*r-mag* calculated in the RockWorks geological statistics package, Hart et al., 2004), chi-squared (Harrison, 1957); Degree of Orientation method (Chiou et al., 1991). There have also been attempts to obtain three-dimensional ice direction data from thin sections (Stroeven et al., 2002).

Table 2 Till fabric characteristics of different terrestrial tills

Till Type		*Oriented with the ice direction?*	*Fabric strength*
Supra glacial		No	Weak
Subglacial	Melt-out	No	Weak
	Lodgement	Yes	Strong
	Deformation	Yes	Thin def. layer-strong Thick def. layer-weak
Flow		No – oriented with the dominant slope direction	Weak to strong

A number of researchers (Stroeven et al., 2001; Carr and Rose; 2003; Hart et al., 2004; Hart, 2006a; Carr and Goddard, 2007) have shown how fabric strength varies with the grain size. The interaction of the clasts with the grains (matrix) occurs on all scales and produces complex fabric strengths on a local scale.

8.10.4 Concluding Remarks

8.10.4.1 Subglacial Till

Till is the resultant sediment from the wide range of processes that have been described above, in particular, temporal and spatial changes in porewater pressure. A typical annual scenario can be illustrated from **Figure 4**, which shows the water pressure recorded from the till from the Glacsweb probes over two years (Hart et al., 2011a). During the winter (day 310–17), little occurs in the subglacial environment. However, as the snow melts in the spring, this leads to the opening of the subglacial hydrological system (Iken et al., 1983; Mair et al., 2002; Rose et al., 2009), subglacial water pressures rise (day 17–120), and bed separation occurs with the potential for stratified sediments deposition and/or hydrofracture. One probe (probe 12 – day 235–310) showed an autumn high-pressure event that would produce a similar depositional sequence. In summer, water pressures remain high or intermediate (day 120–216) and deformation occurs. However, superimposed on this annual trend is a diurnal pattern of sliding (bed separation/lodgement) and deformation. These processes are superimposed upon one another, and depending on the net sediment budget, the till may incrementally build up (if the deforming layer thickness remains the same) or 'erode' down into the underlying till or bedrock (if the deforming bed thickens). These conditions can change depending on the local bedrock, topography, subglacial channel location, as well as glacier thickness and velocity.

8.10.4.2 The Future

Technology improvements will allow easier and more sophisticated monitoring of subglacial processes, which will allow better interpretations of tills. Miniaturization and developments in communications will lead to wireless probes that can be smaller, cheaper, and inserted into till beneath deeper ice. Improvements in geophysical techniques will allow a better understanding of the bed; examples include: (1) the DELORES (DEep-LOok Radar Echo Sounder), which is an oversnow, deep-penetrating radar system developed at the British Antarctic Survey to investigate englacial and subglacial processes (Bingham et al., 2008); (2) high-frequency passive seismometers to monitor microseismicity and slip–stick events (Wiens et al., 2008; Walter et al., 2009). In addition, the development of three-dimensional analysis of till at the microscale with X-ray microtomography has great potential (Kilfeather and van der Meer, 2008; Fasano et al., 2009).

The combination of geophysical and *in situ* experiments on modern glacier with the sedimentological investigations of modern and till provides a set of powerful tools to understand glacial processes and reconstruct modern and ancient glacier dynamics. Over the last twenty years, explorations of the subglacial environment have led to new till interpretations. Most of these ideas have led to lively debates within the subject that have led to new directions of research. The next twenty years will continue the exciting exploration of the subglacial environment, and a further understanding of till genesis.

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.

Anandakrishnan, S., Blankenship, D.D., Alley, R.B., Stoffa, P.L., 1998. Influence of subglacial geology on the position of a West Antarctica ice stream from seismic measurements. Nature 394, 62–65.

Andrews, J.T., 1971. Techniques of till fabric analysis. BGRG Technical Bulletin 6, 43.

Arbaret, L., Fernandez, A., Ježek, J., Ildefonse, B., Launeau, P., Diot, H., 2000. Analogue and numerical modelling of shape fabrics: application to strain and flow determination in magmas. Transactions of the Royal Society of Edinburgh. Earth Sciences 91, 97–109.

Astakhov, F., Kaplyanskaya, A., Tarnogradsky, V.D., 1996. Pleistocene permafrost of West Siberia as a deformable glacier bed. Permafrost and Periglacial Processes 7, 165–191.

Bahr, D.B., Rundle, J.B., 1996. Stick-slip statistical mechanics at the bed of a glacier. Geophysical Research Letters 23(16), 2073–2076.

Benn, D.I., 1992. The genesis and significance of 'hummocky moraine': evidence from the Isle of Skye, Scotland. Quaternary Science Reviews 11, 781–799.

Benn, D.I., 1995. Fabric signature of subglacial till deformation, Breiđamerkurjökull, Iceland. Sedimentology 42, 735–747.

Benn, D.I., Evans, D.J.A., 1996. The interpretation and classification of subglacially deformed materials. Quaternary Science Reviews 15(1), 23–52.

Bennett, M.R., Hambrey, M.J., Huddart, D., 1997. Modification of clast shape in high-Arctic glacial environments. Journal of Sedimentary Research 67, 550–559.

Bennett, M.R., Huddart, D., Hambrey, M.J., Ghienne, J.F., 1996. Moraine development at the high-Arctic valley glacier Pedersenbreen, Svalbard. Geografiska Annaler 78A, 209–222.

Bennett, M.R., Waller, R.I., Glasser, N.F., Hambrey, M.J., Huddart, D., 1999. Glacigenic clast fabrics: genetic fingerprint or wishful thinking? Journal of Quaternary Science 14, 125–135.

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.

Bindschadler, R.A., King, M.A., Alley, R.B., Anandakrishnan, S., Padman, L., 2003. Tidally controlled stick-slip discharge of a West Antarctic Ice Stream. Science 301, 1087–1089.

Bingham, R.G., Scott, J.B.T., Smith A.M., Hindmarsh, R.C.A., 2008. Basal conditions at Pine Island Glacier imaged using deep-looking radar. EGU abstract http://www.abdn.ac.uk/~geo572/posters/vienna08poster.pdf

Blake, E.W., Fischer, U.H., Clarke, G.K.C., 1994. Direct measurement of sliding at the glacier bed. Journal of Glaciology 40(136), 595–599.

Boulton, G.S., 1970a. On the origin and transport of englacial debris in Svalbard glaciers. Journal of Glaciology 9(56), 213–229.

Boulton, G.S., 1970b. On the deposition of subglacial and melt-out tills at the margins of certain Svalbard glaciers. Journal of Glaciology 9(56), 231–245.

Boulton, G.S., 1972. Modern Arctic glaciers as depositional models for former ice sheets. Journal of the Geological Society 128, 361–393.

Boulton, G.S., 1976. The origin of glacially fluted surfaces: observations and theory. Journal of Glaciology 17, 287–309.

Boulton, G.S., 1978. Boulder shapes and grain-size distributions of debris as indicators of transport paths through a glacier and till genesis. Sedimentology 25, 773–799.

Boulton, G.S., 1979. Processes of glacier erosion on different substrata. Journal of Glaciology 23, 15–38.

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., Dobbie, K.E., Zatsepin, S., 2001. Sediment deformation beneath glaciers and its coupling to the subglacial hydraulic system. Quaternary International 86, 3–28.

Boulton, G.S., Eyles, N., 1979. Sedimentation by valley glaciers; a model and genetic classification. In: Schlüchter, C. (Ed.), Moraines and Varves. Balkema, Rotterdam, pp. 11–23.

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.

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.

Carr, S.J., Goddard, M.A., 2007. Role of particle size in till-fabric characteristics: systematic variation in till fabric from Vestari-Hagafellsjökull, Iceland. Boreas 36, 371–385.

Carr, S.J., Rose, J., 2003. Till fabric patterns and significance: particle response to subglacial stress. Quaternary Science Reviews 22, 1415–1426.

Carsey, F., Behar, A., Lane, A.L., Realmuto, V., Engelhardt, H., 2002. A borehole camera system for imaging the deep interior of ice sheets. Journal of Glaciology 48(163), 622–628.

Catania, G.A., Conway, H.B., Gades, A.M., Raymond, C.F., Engelhardt, H., 2003. Bed reflectivity beneath inactive ice streams in West Antarctica. Annals of Glaciology 36, 287–291.

Chiou, W.A., Bryant, W.R., Bennett, R.H., 1991. Quantification of clay fabric: a simple technique. In: Bennett, R.H., Bryant, W.R., Hulbert, M.H. (Eds.), Microstructure of Fine Grained Sediments. Springer-Verlag, New York, pp. 379–388.

Clark, C.D., 1997. Reconstructing the evolutionary dynamics of former ice sheets using multi-temporal evidence, remote sensing and GIS. Quaternary Science Reviews 16, 1067–1092.

Clark, P.U., Walder, J.S., 1994. Subglacial drainage, eskers, and deforming beds beneath the Laurentide and Eurasian ice sheets. Geological Society of America Bulletin 106, 304–314.

Clarke, G.K.C., 2005. Subglacial processes. Annual Review of Earth and Planetary Sciences 33, 247–276.

Copland, L., Harbor, J., Gordon, S., Sharp, M., 1997. The use of borehole video in investigating the hydrology of a temperate glacier. Hydrological Processes 11, 211–224.

Copland, L., Sharp, M., 2001. Mapping thermal and hydrological conditions beneath a polythermal glacier with radio-echo sounding. Journal of Glaciology 47(15), 232–242.

Copland, L., Sharp, M.J., Nienow, P.W., 2003. Links between short-term velocity variations and the subglacial hydrology of a predominantly cold polythermal glacier. Journal of Glaciology 49(166), 337–348.

Cuffey, K., Alley, R.B., 1996. Is erosion by deforming subglacial sediments significant? Annals of Glaciology 22, 17–24.

Curray, J.R., 1956. The analysis of two-dimensional orientation data. Journal of Geology 64, 117–131.

Davies, B.J., Roberts, D.H., Cofaigh, O, Bridgland, D.R., C., 2009. Subglacial and ice marginal controls on sediment deposition during the last glacial maximum: interlobate ice sheet dynamics at Whitburn Bay, County Durham, England. Boreas 38, 555–578.

Desai, C.S., 1974. A consistent finite element technique for work-softening behavior. Proc., Int. Conf. on Comp. Meth. in Nonlinear Mechs. University of Texas, Austin.

Desai, C.S., 2001. Mechanics of Materials and Interfaces: The Disturbed State Concept. CRC Press, Boca Raton, FL, 712 pp.

Dowdeswell, J.A., Sharp, M., 1986. Characterisation of pebble fabrics in modern terrestrial glacigenic sediments. Sedimentology 33, 699–710.

Dreimanis, A., 1989. Tills: their genetic terminology and classification. In: Goldthwait, R.P., Matsch, C.L. (Eds.), Genetic Classification of Glaciogenic Deposits. A.A. Balkema, Rotterdam, pp. 17–83.
Duval, P., 1977. The role of water content on the creep rate of polycrystalline ice. IAHS 118, 29–33.
Echelmeyer, K., Wang, Z., 1987. Direct observation of basal sliding and deformation of basal drift at sub-freezing temperatures. Journal of Glaciology 33(113), 83–98.
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.
Evans, D.J.A., Rea, B.R., Benn, D.I., 1998. Subglacial deformation and bedrock plucking in areas of hard bedrock. Glacial Geology and Geomorphology 4, 1–22.
Eyles, N., Rogerson, R.J., 1978. A framework for the investigation of medial moraine formation: Austerdalsbreen, Norway, and Berendon Glacier, British Columbia, Canada. Journal of Glaciology 20(82), 99–113.
Fasano, F., Baroni, C., Talarico, F.M., Bettuzzi, M., Pasini, A., 2009. Glacial Stress Field Orientation Reconstructed through Micromorphology and μX-Ray Computed Tomography of Till. In: Hambrey, M.J., Christoffersen, P., Glasser, N.F., Hubbard, B. (Eds.), Glacial Sedimentary Processes and Products. Blackwell, Oxford, UK. http://dx.doi.org/10.1002/9781444304435.ch16.
Fisher, J.E., 1963. Two tunnels in cold ice at 4000 m. on the Breithorn. Journal of Glaciology 4(35), 513–520.
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., Clarke, G.K.C., 1994. Ploughing of subglacial sediment. Journal of Glaciology 40(134), 97–106.
Fischer, U.H., Clarke, G.K.C., 1997. Stick-slip sliding behaviour at the base of a glacier. Ann. Glaciol. 24, 390–396.
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.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., 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.
Fitzsimons, S.J., Colhoun, E.A., 1989. Pleistocene clastic dykes in the King Valley, western Tasmania. Australian Journal of Earth Sciences 36, 351–363.
Fitzsimons, S.J., McManus, K.J., Sirota, P., Lorrain, R.D., 2001. Direct shear tests of material from a cold glacier: implications for landform development. Quaternary International 86, 129–137.
Fountain, A.G., Schlicting, R.B., Jacobel, R.W., Jansson, P., 2005. Fractures as main pathways of water flow in temperate glaciers. Nature 433, 618–621.
Fountain, A.G., Walder, J.S., 1998. Water flow through temperate glaciers. Reviews of Geophyics 36, 299(97RG03579).
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.
Gay, N.C., 1968. The motion of rigid particles embedded in a viscous fluid during pure shear deformation of the fluid. Tectonophysics 5, 81–88.
Ghosh, S.K., Ramberg, H., 1976. Reorientation of inclusions by combination of pure shear and simple shear. Tectonophysics 34, 1–70.
Glen, J.W., Donner, J.J., West, R.G., 1957. On the mechanism by which stones in till become oriented. American Journal of Science 255, 194–205.
Gjessing, J., 1965. On 'plastic scouring' and 'subglacial erosion'. Norsk Geografisk Tidsskrift 20, 1–37.
Glasser, N.F., Hambrey, M.J., Crawford, K.R., Bennett, M.R., Huddart, D., 1998. The structural glaciology of Kongsvegen, Svalbard, and its role in landform genesis. Journal of Glaciology 44(146), 136–148.
Hambrey, M.J., Bennett, M.R., Dowdeswell, J.A., Glasser, N.F., Huddart, D., 1999. Debris entrainment and transfer in polythermal valley glaciers. Journal of Glaciology 45(149), 69–86.
Hambrey, M.J., Dowdeswell, J.A., 1997. Structural evolution of a surgetype poly thermal glacier: Hessbreen, Svalbard. Annals of Glacialogy 24, 375–381.
Hambrey, M.J., Dowdeswell, J.A., Murray, T., Porter, P.R., 1996. Thrusting and debris entrainment in a surging glacier: Bakaninbreen, Svalbard. Annals of Glaciology 22, 241–248.
Hambrey, M.J., Huddart, D., Bennett, M.R., Glasser, N.F., 1997. Genesis of 'hummocky moraines' by thrusting in glacier ice: evidence from Svalbard and Britain. Journal of the Geological Society 154, 623–632. http://dx.doi.org/10.1144/gsjgs.154.4.0623.
Harper, J.T., Humphrey, N.F., 1995. Borehole video analysis of a temperate glacier' englacial and subglacial structure: implications for glacier flow models. Geology 23, 901–904.
Harrison, P.W., 1957. New technique for three-dimensional fabric analysis of till and englacial debris containing particles from 3 to 40 mm in size. Journal of Geology 65, 98–105.
Harrison, W.D., Truffer, M., Echelmeyer, K.A., Pomraning, D.A., Abnett, K.A., Ruhkick, R.H., 2004. Probing the till beneath Black Rapids Glacier, Alaska, USA. Journal of Glaciology 50(171), 608–614.
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., 1994. Till fabric associated with deformable beds. Earth Surface Processes and Landforms 19, 15–32.
Hart, J.K., 1995a. An investigation of the deforming layer/debris-rich ice continuum, illustrated from three Alaskan glaciers. Journal of Glaciology 41, 619–633.
Hart, J.K., 1995b. Glacial erosion, deposition and deformation associated with a deformable bed. Progress in Physical Geography 19, 173–191.
Hart, J.K., 1996. Subglacial deformation associated with a rigid bed environment, Aberdaron, North Wales. Journal of Glacial Geology and Geomorphology 1, 1–18.
Hart, J.K., 2006a. Deforming layer erosion over rigid bed rock at Athabasca Glacier, Canada. Earth Surface processes and Landforms 31, 65–80.
Hart, J.K., 2006b. An investigation of subglacial processes at the microscale from Briksdalsbreen, Norway. Sedimentology 53, 125–146.
Hart, J.K., Boulton, G.S., 1991a. The interrelationship between glaciotectonic deformation and glaciodeposition. Quaternary Science Reviews 10, 335–350.
Hart, J.K., Boulton, G.S., 1991b. The glacial geology of north east Norfolk. In: Rose, J., Gibbard, P.L., Elhers, J. (Eds.), The Glacial Deposits of Britain. Balkema, Rotterdam, pp. 233–244.
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., Khatwa, A., Sammonds, P., 2004. The effect of grain texture on the occurrence of microstructural properties in subglacial till. Quaternary Science Reviews 23, 2501–2512.
Hart, J.K., Martinez, K., Ong, R., Riddoch, A., Rose, K., Padhy, P., 2006. An autonomous multi-sensor subglacial probe: design and preliminary results from Briksdalsbreen, Norway. Journal of Glaciology 52(178), 389–397.
Hart, J.K., Rose, K.C., Martinez, K., 2011b. Subglacial till behaviour derived from in situ wireless multi-sensor subglacial probes: rheology, hydro-mechanical interactions and till formation. Quaternary Science Reviews 30, 234–247.
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.
Hart, J.K., Rose, K.C., Waller, R.I., Vaughan-Hirsch, D., Martinez, K., 2011a. Assessing the catastrophic break up of Briksdalsbreen, Norway, associated with rapid climate change. Journal of the Geological Society, London 168, 1–16. http://dx.doi.org/10.1144/0016-76492010-024.
Hättestrand, C., Johansen, N., 2005. Supraglacial moraines in Scharffenbergbotnen, Heimefrontfjella, Dronning Maud Land, Antarctica – significance for reconstructing former blue ice areas Antarctic. Science 17(2), 225–236.
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.
Hicock, S.R., Goff, J.R., Lian, O.B., Little, E.C., 1996. On the interpretation of subglacial till fabric. Journal of Sedimentary Research 66, 928–934.
Hiemstra, J., Evans, D.J.A., Ó Cofaigh, C., 2007. The role of glaciotectonic rafting and comminution in the production of subglacial tills: examples from SW Ireland and Antarctica. Boreas 36, 386–399.
Hindmarsh, R., 1997. Deforming beds: viscous and plastic scales of deformation. Quaternary Science Reviews 16, 1039–1056.
Hock, R., Hooke, R.L., 1993. Evolution of the internal drainage system in the lower part of the ablation area of Storglaciären, Sweden. Geological Society of America Bulletin 105, 537–546.
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.
Hooyer, T.S., Iverson, N.R., 2000. Clast-fabric development in a shearing granular material: implications for subglacial till and fault gouge. Geological Society of America Bulletin 112, 683–692.

Hoppe, G., 1952. Hummocky moraine regions with special reference to the interior of Norbotten. Geografiska Annaler 34, 1–26.
Humlum, O., 1978. A large till wedge in Denmark: implications for the subglacial thermal regime. Bulletin of the Geological Society of Denmark 27, 63–71.
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., Rothlisberger, H., Floton, 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, 28–248.
Ildefonse, B., Mancktelow, N.S., 1993. Deformation around rigid particles – the influence of slip at the particle matrix interface. Tectonophysics 221(3–4), 345–359.
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.
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., Hooyer, T.S., Thomason, J.F., Graesch, M., Shumway, J.R., 2008. The experimental basis for interpreting particle and magnetic fabrics of sheared till. Earth Surface Processes and Landforms 33, 627–645.
Jeffery, G.B., 1922. The motion of ellipsoidal particles immersed in a viscous fluid. Proceedings of the Royal Society of London, Series A 102, 161–179.
Kamb, B., 1991. Rheological nonlinearity and flow instability in the deforming-bed mechanism of ice stream motion. Journal of Geophysical Research 96, 16585–16595.
Kamb, B., LaChapelle, E., 1964. Direct observation of the mechanism of glacier sliding over bedrock. Journal of Glaciology 5(38), 159–172.
Kilfeather, A.A., van der Meer, J.J.M., 2008. Pore size, shape and connectivity in tills and their relationship to deformation processes. Quaternary Science Reviews 27, 250–266.
King, E.C., Hindmarsh, R.C.A., Stokes, C.R., 2009. Formation of mega-scale glacial lineations observed beneath a West Antarctic ice stream. Nature Geoscience 2, 585–596.
Kjaer, K.H., Kruger, J., 1998. Does clast size influence fabric strength? Journal of Sedimentary Research 68, 746–749.
Kjær, K.H., Larsen, E., van der Meer, J., et al., 2006. Subglacial decoupling at the sediment/bedrock interface: a new mechanism for rapid flowing ice. Quaternary Science Reviews 25, 2704–2712.
Koerner, R.M., Fisher, D.A., Parnandi, M., 1981. Bore-hole video and photographic cameras. Annals of Glaciology 2, 34–38.
Krüger, J., 1984. Clasts with stoss-lee form in lodgement tills: a discussion. Journal of Glaciology 30, 241–243.
Krüger, J., 1993. Moraine-ridge formation along a stationary ice front in Iceland. Boreas 22, 101–109.
Larsen, N.K., Piotrowski, J.A., 2003. Fabric pattern in a basal till succession and its significance for reconstructing subglacial processes. Journal of Sedimentary Research 73, 725–734.
Lukas, S., 2005. A test of the englacial thrusting hypothesis of 'hummocky' moraine formation: case studies from the northwest Highlands, Scotland. Boreas 34, 287–307.
MacAyeal, D.R., Bindschadler, R.A., Scambos, T.A., 1995. Basal friction of Ice Stream E, West Antarctica. Journal of Glaciology 5(41), 661–690.
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., Sharp, M.J., Wohlleben, T., Willis, I., 2002. Influence of subglacial drainage system evolution on glacier surface motion: Haut Glacier d'Arolla, Switzerland. Journal of Geophysical Research 107(B8), no. 2175.
March, A., 1932. Mathematische theorie der regelung nach der korngestalt bei affiner deformation. Zeitschrift für Kristallographie 81, 285–297.
Marques, F.O., Schmid, D.W., Andersen, T.B., 2007. Applications of inclusion behaviour models to a major shear zone system: The Nordfjord-Sogn Detachment Zone in Western Norway. Journal of Structural Geology 29, 1622–1631.
Mark, D.M., 1973. Analysis of axial orientation data, including till fabrics. Geological Society of America Bulletin 84, 1369–1374.
van der Meer, J.J.M., 1993. Microscopic evidence of subglacial deformation. Quaternary Science Reviews 12, 553–587.
van der Meer, J.J.M.x, 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.
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. Geological Society Special Publication, London, vol. 176, pp. 245–258.
Mickelson, D.M., Clayton, L., Fullerton, D.S., Borns, H.E., 1983. The late Wisconsin glacial record of the Laurentide Ice Sheet in the United States. In: Wright, Jr. H.E., Porter, S.C. (Eds.), Late Quaternary Environments of the United Statess, Vol. 1. The Late Pleistocene. University of Minnesota Press, Minneapolis, Minn, pp. 3–37.
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., 1997. Assessing the paradigm shift: deformable glacier beds. Quaternary Science Reviews 16, 995–1016.
Murray, T., Gooch, D., Stuart, G.W., 1997. Structures within the surge-front at Bakaninbreen, Svalbard using ground penetrating radar. Annals of Glaciology 24, 122–129.
Murray, T., Porter, P.R., 2001. Basal conditions beneath a soft-bedded polythermal surge-type glacier: Bakaninbreen, Svalbard. Quaternary International 86, 103–116.
Murton, J.B., Waller, R.I., Hart, J.K., Whiteman, C.A., Pollard, W.H., Clark, I.D., 2004. Stratigraphy and glaciotectonic structures of permafrost deformed beneath the northwest margin of the Laurentide ice sheet, Tuktoyaktuk Coastlands, Canada. Journal of Glaciology 50(170), 399–412.
Nelson, A.E., Willis, I.C., Ó Cofaigh, 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.
Ó Cofaigh, C., Evans, D.J.A., Hiemstra, J.F., 2010. Formation of a stratified subglacial 'till' assemblage by ice-marginal thrusting and glacier overriding. Boreas. ISSN 0300-9483.http://dx.doi.org/10.1111/j.1502-3885.2010.00177.x ISSN 0300-9483.
Ó Cofaigh, C., Evans, J., Dowdeswell, J.A., Larter, R.D., 2007. Till characteristics, genesis and transport beneath Antarctic paleo-ice streams. Journal of Geophysical Research 112, F03006. http://dx.doi.org/10.1029/2006JF000606.
Pattyn, F., De Smedt, B., De Brabander, S., Van Huele, W., Agatova, A., Mistrukov, A., Decleir, H., 2003. Ice dynamics and basal properties of Sofiyskiy Glacier Altai, (Russia) based on DGPS and radio-echo sounding surveys. Annals of Glaciology 37, 286–292.
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. http://dx.doi.org/10.1016/j.quascirev.2008.01.012.
Piotrowski, J.A., 1992. Till facies and depositional environments of the upper sedimentary complex from the Stohl Cliff, Schleswig-Holstein, North Germany. Zeitschrift für Geomorphologie 84, 37–54.
Raymond, C.F., Benedict, R.J., Harrison, W.D., Echelmeyer, K.A., Sturm, M., 1995. Hydrological discharges and motion of Fels and Black Rapids Glaciers, Alaska, U.S.A.: implications for the structure of their drainage systems. Journal of Glaciology 41, 290–304.
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.A., 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(1–2), 123–140.
Roberson, S., Hubbard, B., 2010. Application of borehole optical televiewing to investigating the 3-D structure of glaciers: implications for the formation of longitudinal debris ridges, midre Lovenbreen, Svalbard. Journal of Glaciology 56(195), 143–156.
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., Martinez, K., 2009. Seasonal changes in basal conditions at Briksdalsbreen, Norway: the winter–spring transition. Boreas 38, 579–590.
Ruszczyńska-Szenajch, H., 1987. The origin of glacial rafts: detachment, transport, deposition. Boreas 16, 101–112.
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 Reviews 27, 267–283.
Schmid, D.W., Podladchikov, Y.Y., 2004. Are isolated stable rigid clasts in shear zones equivalent to voids? Tectonophysics 384, 233–242.

Seaberg, S.Z., Seaberg, J.Z., Hooke, R.L., Wiberg, D.W., 1988. Character of the englacial and subglacial drainage system in the lower part of the ablation area of Storglaciaren, Sweden, as revealed by dye-trace studies. Journal of Glaciology 34(117), 217–227.
Sharp, M.J., 1982. Modification of clasts in lodgement tills by glacial erosion. Journal of Glaciology 28, 475–481.
Small, R.J., Clark, M.J., Cawse, T.J.P., 1979. The formation of medial moraines on Alpine glaciers. Journal of Glaciology 22(86), 43–52.
Smith, A.M., 1997. Basal conditions on Rutford Ice Stream, West Antarctica, from seismic observations. Journal of Geophysical Research 102, 543–552. http://dx.doi.org/10.1029/96JB02933.
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., 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.
Stroeven, A.P., van der Meer, J.J.M., Stroeven, P., Dalhuisen, D.H., Hiemstra, J.F., Stroeven, M., 2002. Improved microfabric determination using stereological analysis: orientation direction of sand particles in Mount Feather Sirius Group tillite Antarctica. In: Gamble, J.A., Skinner, D.N.B., Henrys, S.A. (Eds.), Antarctica at the Close of the Millennium. Royal Society of New Zealand Bulletin, Wellington, vol. 35, pp. 327–334.
Stroeven, P., Stroeven, A.P., Dalhuisen, D.H., 2001. Image analysis of 'natural' concrete samples by automated and manual processes. Cement and Concrete Composites 23, 227–236.
Thomason, J.F., Iverson, N.R., 2006. Microfabric and microshear evolution in deformed till. Quaternary Science Reviews 25, 1027–1038.
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.
Tsai, V.C., Ekstrom, G., 2007. Analysis of glacial earthquakes. Journal of Geophysical Research 112, F03014. http://dx.doi.org/10.1029/2006JF000596.
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 Jounal of Earth Science 41, 1123–1139.
Walder, J.S., Fowler, A., 1994. Channelized subglacial drainage over a deforming bed. Journal of Glaciology 40, 3–15.
Waller, R.I., Hart, J.K., Knight, P.G., 2000. The influence of tectonic deformation on facies variability in stratified debris-rich basal ice. Quaternary Science Review 19, 775–786.
Walter, F., Deichmann, N., Funk, M., 2009. Basal icequakes during changing subglacial water pressures beneath Gornergletscher, Switzerland. Journal of Glaciology 54(186), 511–521.
Wiens, D.A., Anandakrishnan, S., Winberry, J.P., King, M.A., 2008. Simultaneous teleseismic and geodetic observations of the stick-slip motion of an Antarctic ice stream. Nature 453(7196), 770–774. http://dx.doi.org/10.1038/nature06990.

Biographical Sketch

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