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Subglacial till: Formation, sedimentary characteristics and classification

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Abstract

We review the major subglacial till forming processes as presently understood by glacial researchers and define the parameters within which tills are produced and reconcile them with sedimentary end members. Processes of deformation, flow, sliding, lodgement and ploughing coexist at the base of temperate glacier ice and act to mobilize and transport sediment and deposit it as various end members, ranging from glacitectonically folded and faulted stratified material to texturally homogeneous diamicton. The dominance of any one subglacial process varies both spatially and temporally, giving rise to the possibility that a till or complex till sequence contains a superimposed signature of former transportation/deposition at the ice-bed interface. We recommend that, while glacial geologists and geomorphologists should be able to recognize the sedimentary imprints of various subglacial processes, genetic fingerprinting of subglacial tills should be less process-specific and till classification must reflect the range of products encompassed by the subglacial till production continuum. Glacial geologists can presently unequivocally identify: a) *glacitectonite* (rock or sediment that has been deformed by subglacial shearing/deformation but retains some of the structural characteristics of the parent material); b) *subglacial traction till* (sediment deposited by a glacier sole either sliding over and/or deforming its bed, the sediment having been released directly from the ice by pressure melting and/or liberated from the substrate and then disaggregated and completely or largely homogenised by shearing); and support the theoretical case for c) *melt-out till* (sediment released by the melting of stagnant or slowly moving debris-rich glacier ice, and directly deposited without subsequent transport or deformation). Because observations on contemporary glaciers reveal that their beds are most likely to be mosaics of deformation and sliding and warm based and cold based conditions, the patterns of which change temporally and spatially, it is extremely unlikely that subglacial till end members in the geological record will be anything but hybrids produced by the range of processes operative in the subglacial traction zone.
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Keywords: till; subglacial processes; subglacial deformation; glacitectonite; subglacial traction till

1. Introduction

In the early 1980's it became apparent to glacial geologists and geomorphologists that the beds of many glaciers were not passive, rigid substrata but were actually part of a coupled ice-bed system in which

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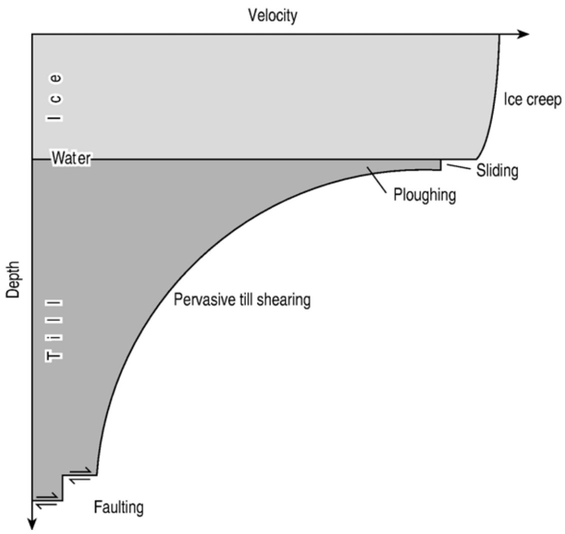


Fig. 1. Various modes of movement at the glacier ice-bed interface (after Boulton, 1996a,b).

unlithified subglacial materials deformed in response to applied glacier stress and thereby contributed to glacier motion (Fig. 1). This "paradigm shift in glaciology" (Boulton, 1986; Murray, 1997) has since fuelled lively debate on: (a) the temporal and spatial behaviour of the deforming bed; and (b) the recognition of such sediments in the geological record and their differentiation from tills deposited by lodgement and melt-out. Problems have arisen where incompatibility between study sites has been used to question the universality of particular till forming theories. However, it is likely that the very diversity of subglacial sediment properties provides us with the most valuable insight into glacier bed processes. For example, Murray (1997) makes a not insignificant point that the search for an effective stress-dependent rheology for subglacial till requires experiment on a homogeneous, fine-grained till and this in itself possesses an inherent bias towards tills of specific properties and, therefore, a non-representative selection of subglacial environments. The spatial and temporal variability of processes of till production, transport and deposition are well illustrated by the summary diagram of Alley et al. (1997) depicting the schematic location of particular subglacial processes (Fig. 2). The migration of zones through time may result in the superimposition of different processes and forms and the possible stacking of different subglacial sediment types at any one locality.

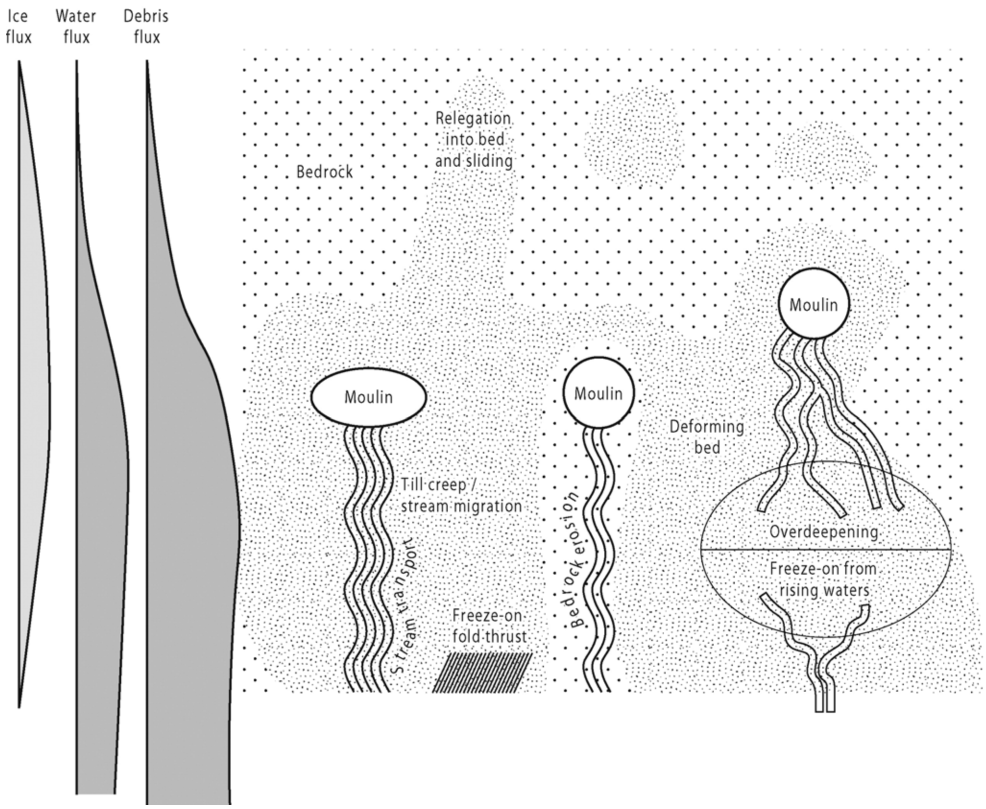


Fig. 2. Schematic plan view of a glacier bed showing important subglacial sediment transport mechanisms (after Alley et al., 1997).

This paper reviews the major subglacial till forming processes as we presently understand them and defines the parameters within which certain till properties are produced. The sedimentological characteristics of each till end member are then highlighted based upon the general consensus of glacial geologists and geomorphologists. Both process and form are then assimilated into our model of the subglacial till forming environment, and we conclude by providing criteria for the identification of particular till types that exist within a spatial and temporal subglacial sediment continuum. Our prime objective is to provide explanation for the widespread occurrences of thick multiple till sequences that often contain extensive beds of predominantly massive to laminated diamicton, interpreted by different researchers as the products of lodgement, melt-out or deformation.

2. Geotechnical properties and behaviour of subglacial diamictons

Before we review the various subglacial processes and assess the sedimentary and structural signatures observed in subglacial tills, we provide below in tabulated format (Table 1) an overview of the geotechnical properties of diamictons and the nomenclature employed by engineers when assessing the behaviour of such materials.

3. Subglacial processes

The following sections review the main processes involved in the production of subglacial tills based upon observations and data available in the existing literature. The characteristics of the major till types are then reviewed. This review highlights some aspects of compatibility that can be used in the development of a spatial and temporal subglacial sediment continuum.

3.1. Subglacial sliding and lodgement

Although glacier motion by subglacial sliding is a well documented process (see Benn and Evans, 1998, Section 4.5 for a review), the sliding of glacier ice over soft beds, and its implications for erosional and depositional processes, is somewhat more contentious. Soft bed sliding has been proposed by some researchers in order to explain the characteristics of certain till sequences (e.g. Brown et al., 1987; Clark and Hansel, 1989; Piotrowski and Tulaczyk, 1999). Specifically,

Table 1
Geotechnical properties and behaviour of glacial diamictons

Phase	Solid state	Semi-solid state	Plastic state	Liquid state	Suspension
Water	Low water content	Increase water content →			Very high water content
Limits	Dry	Shrinkage limit	Plastic limit	Liquid limit	
Shrinkage	Increase in volume →				
Shear strength	Decreasing shear strength →			Negligible to nil	
Till horizon	B	A/B	A		
Dilation	Non dilatant (solid)	Increase in dilation →			
Deformation	Solid state deformation	Solid state/soft sediment deformation	Mobile zone 'flow displacement'	Decoupling/basal sliding	
Structures	Ductile/brittle faults, folds	Ductile folding, shear zones, clast rotation, boudinage, disharmonic folding, convolutions, flame structures	Clast rotation, initiation of sediment mixing/ homogenisation and overprinting of pre-existing structures, no solid state deformation, on set of localised liquefaction at higher water contents	Liquefaction, homogenisation and overprinting of all pre-existing structures, clast rotation, no solid state deformation, injection features into adjacent sediments	

decoupling of the glacier from its bed due to increased basal water pressures prevents the transmission of stress to the sedimentary substrate. Fischer and Clarke (1997) demonstrated a stick-slip sliding behaviour at the ice-bed interface where higher water pressures produced such decoupling of ice from the underlying till (Fig. 3). At one location at the base of Ice Stream B, Engelhardt and Kamb (1998) demonstrated that glacier flow was by sliding over a clay-rich till. The clay-rich nature of the till retards water migration allowing the build up of high pore water pressures leading to glacier decoupling. This illustrates the potential lithological control on not only the subglacial hydrological system but also the mechanism for glacier motion across its bed. In contrast to clay-rich subglacial sediments, sandy tills would be relatively free draining, and consequently for decoupling to occur, pore water pressures would have to be much greater than for clay-rich tills (water input ≫ out flow due to drainage). In a theoretical overview of the deformation process, Boulton (1996a) proposed that clay-rich tills do not couple to the ice base as well as coarse-grained tills and will only deform to a shallow depth. This implies that the relative importance of sliding versus deformation will vary according to the granulometry of the glacier bed. Hindmarsh (1996) proposes that the till itself may slide over the bed, giving rise to polished bedrock surfaces. Fuller and Murray (2000) report sliding over soft sediments at the base of an Icelandic surging glacier. This was associated with shallow deformation of stratified sediments down to a depth of only <0.16 m. Fuller and Murray suggest that the strength of coupling of the ice-bed interface is weakened at low effective pressures. Tulaczyk (1999), like Boulton (1996a), suggests that this ice-bed coupling is weaker in fine-grained tills. He suggests, using a Coulomb plastic rheology, that fine-grained tills facilitate sliding and clast ploughing, due to lower hydraulic diffusivity and small numbers of clasts. These characteristics restrict strain distribution and produce a shear zone of only 0.01 m thick. In contrast, coarse-grained tills enable strong ice-till coupling and deformation down to 0.1 m.

Spatial variability in the intensity of sliding has been proposed by Piotrowski and Kraus (1997) in order to explain the characteristics of tills in northwest Germany (see also Piotrowski et al., 1997). They provide a model in which the glacier bed forms a mosaic comprising sliding bed conditions and deforming patches or spots (Fig. 4; see also van der Meer et al., 2003). Further details on the widespread preservation of evidence for subglacial sliding and the rarity of pervasive subglacial deformation features are provided by Piotrowski et al. (1999, 2001, 2002) and Hoffmann and Piotrowski (2001). These researchers also identify widespread evidence for the preservation of sedimentary structures that they propose can be explained only by melt-out of englacial debris concentrations (see section on melt-out below). Thorsteinsson and Raymond (2000) model the relative roles of sliding and deformation beneath an ice stream and suggest that sliding must be the dominant mechanism of basal motion, as opposed to till shearing unless there is either adhesion of till to the ice sole (cf. Hindmarsh, 1998a,b), short scale roughness develops at the ice-till interface or internal slip boundaries exist in the till.

Lodgement is defined as the plastering of glacial debris from the base of a sliding glacier on to a rigid or

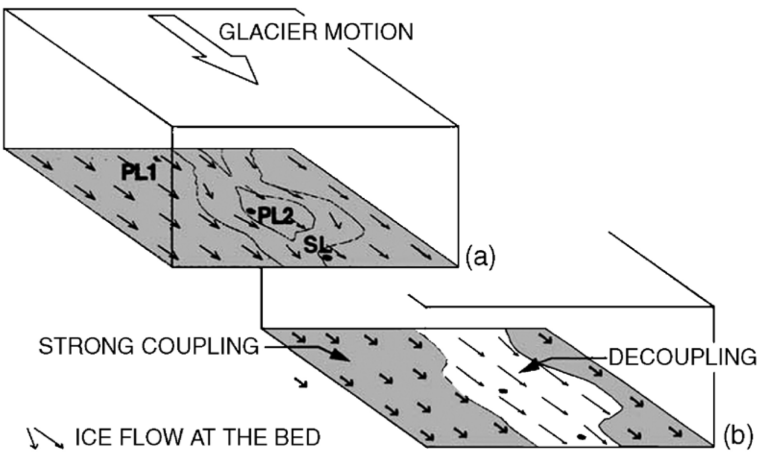


Fig. 3. Conceptual diagram (from Fischer and Clarke, 2001) to demonstrate the concept of variable rates of basal sliding due to changing ice-bed coupling. Ice flow direction and magnitude are depicted by arrows during periods of: a) low subglacial water pressures; and b) high subglacial water pressures in the connected region of the bed (outlined). The locations of ploughmeters (PL1 and 2) and sliding sensor (SL) upon which this reconstruction is based are marked.

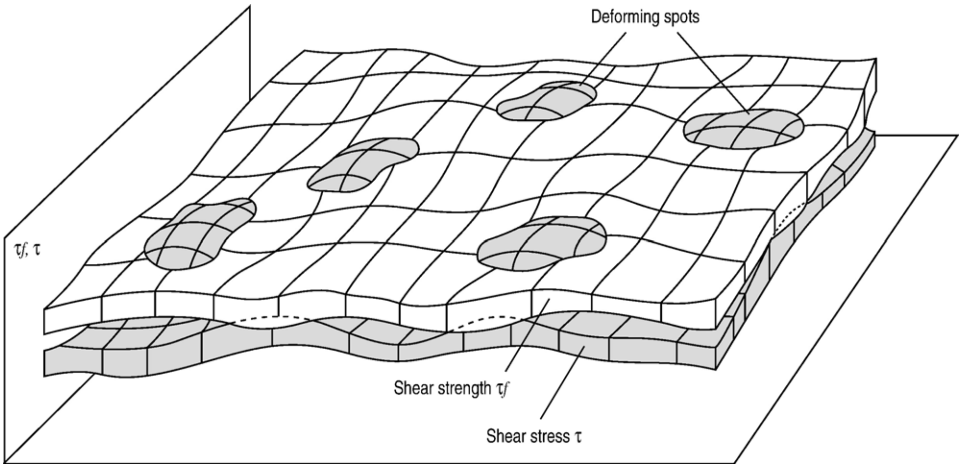


Fig. 4. Conceptual model of the subglacial deforming/sliding bed mosaic proposed by Piotrowski and Kraus (1997). The model compares subglacial shear stress (τ) with sediment shear strength (τ_f). The shear stress is lower than the sediment shear strength wherever high basal water pressures cause ice-bed decoupling. Elsewhere the bed develops deforming spots.

semi-rigid bed by pressure melting and/or other mechanical processes (Dreimanis, 1989). This includes the lodgement of debris-rich basal ice masses as well as individual clasts (Fig. 5). Some researchers have proposed that pre-existing till masses of various origins can be lodged and therefore should be regarded as lodgement till (e.g. “deformed lodgement till”, Dowdeswell and Sharp, 1986), thereby explaining the large number of occurrences of thick, fine-grained tills. This implies that the differentiation of the end members of the various subglacial processes is severely hampered by overprinted sedimentary and structural signatures. Indeed, lodgement of clasts on to a soft bed involves the ploughing of the deformable substrate so that it forms a prow (Boulton, 1982; Clark and Hansel, 1989; Jørgensen and Piotrowski, 2003). This prow arrests the forward momentum of the clast and gives rise to a final deposit that contains lodgement and deformation signatures (see Section 3.5). Because of this preferential lodgement of large clasts, a case will be made later in this paper for the use of the term lodgement in reference to large clasts only. Several researchers have proposed a range of contemporaneous processes at the bed of temperate glaciers in order to explain the accumulation of thick tills. For example, Boulton et al. (1974), Boulton and Hindmarsh (1987), Benn (1994a), Krüger (1994), and Evans and Twigg (2002) have advocated simultaneous lodging, ploughing and shear deformation at the glacier bed, whereby large particles lodge first and smaller particles remain in traction until strain rates fall.

3.2. Subglacial melt-out and subglacial meltwater deposits

The subglacial melt-out process is a notoriously difficult one to verify, because it was proposed and has been elucidated largely by theoretical postulates based upon interpretations of ancient tills (e.g. Shaw, 1979;

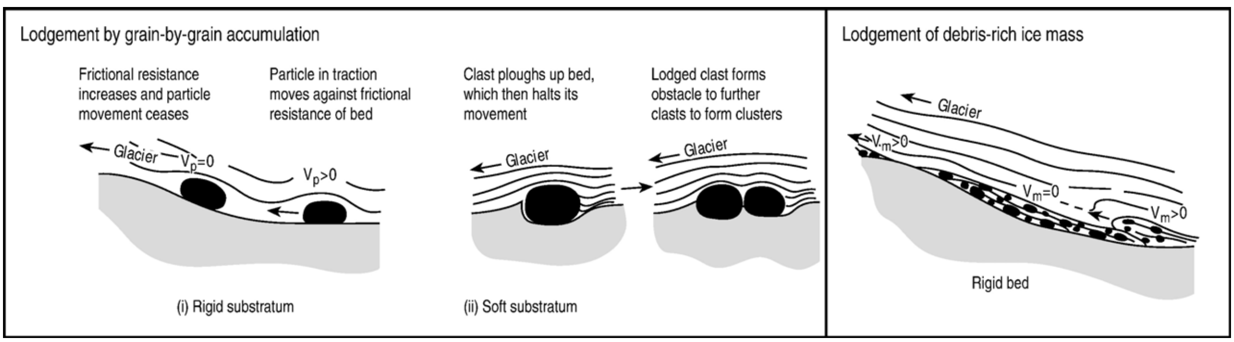


Fig. 5. Schematic depictions of the lodgement process (after Boulton, 1982). Note that deformation is inextricably linked to lodgement on a soft substratum.

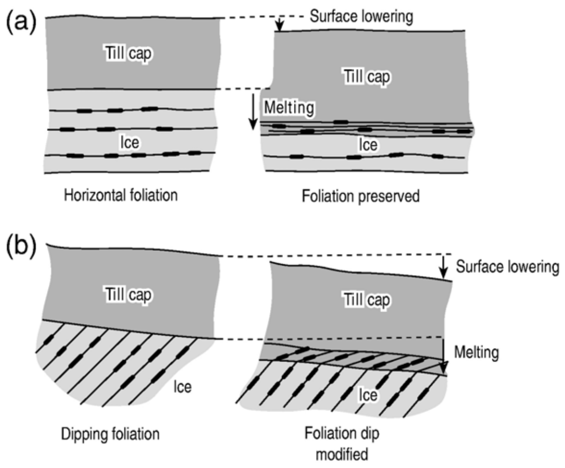


Fig. 6. The theoretical concepts of preservation and modification of melt-out till in horizontally bedded (a) and dipping (b) debris-rich ice folia (after Boulton, 1971; Sugden and John, 1976).

Haldorsen and Shaw, 1982; Shaw, 1982, 1983; Piotrowski, 1994; Munro-Stasiuk, 2000; Fig. 6). The characteristics of these tills can often be interpreted as the products of other processes such as deformation. However, some support has been provided from observations at modern glacier snouts where basal tills have apparently been released from overlying debris-rich ice (Boulton, 1971; Lawson, 1979a,b; Shaw, 1982; Fig. 7). Strictly defined, subglacial melt-out is the slow and largely passive release of sediment from debris-rich stagnant basal glacier ice. Where debris concentrations are high the thaw consolidation ratio is low and theoretically, therefore, delicate englacial structures may be preserved, especially where drainage is efficient. Because the ideal conditions for melt-out till preservation are probably rare, modification of former englacial foliation and structure is almost ubiquitous (Paul and Eyles, 1990), although Carlson (2004) has demonstrated

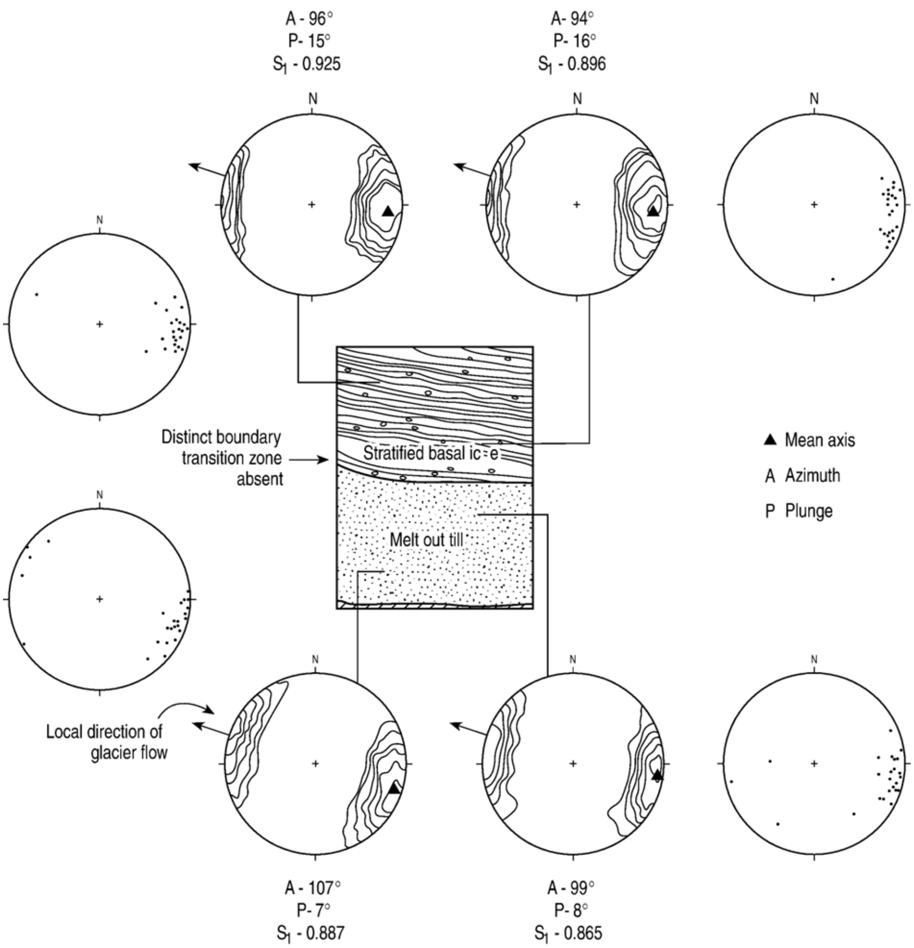


Fig. 7. Clast macrofabric data from subglacial till (interpreted as melt-out till) and overlying debris-rich (stratified) ice (from Lawson, 1979b).

that till with low hydraulic conductivity can accommodate the transport of 1.3 m^3 water a^{-1} m^{-2}, up to three orders of magnitude more than is produced at the base of a glacier, without initiating dewatering. The degree of modification is dictated by the initial debris concentration and the nature of the drainage conditions at the site of deposition. Poor drainage and high ice contents will tend to produce high porewater pressures in the accumulating melt-out sequence thereby initiating failure, remobilization and dewatering (Paul and Eyles, 1990; Carlson, 2004; Fig. 8). The drainage of meltwater from proposed sites of subglacial melt-out is cited as an important process in the deposition of significant parts of melt-out till sequences, specifically inter-till stratified lenses and beds (e.g. Shaw, 1982; Munro-Stasiuk, 2000).

Some stratified sediment bodies found in association with basal tills are not interpreted as melt-out deposits per se, but instead are related to subglacial drainage during phases of active glacier flow. Such interpretations are guided by theoretical reconstructions of subglacial hyrdological conditions (see review in Benn and Evans, 1996; Fig. 9) but have been identified in deforming till using seismic data from beneath the Rutford Ice Stream by King et al. (2004). For example, Walder and Fowler (1994) suggest that drainage beneath a soft-bedded glacier occurs in a series of braided canals (Ng, 2000) at the ice-till interface when discharges are too large to be evacuated through the bed (compare 1 and 6 in Fig. 9). This leads to ice-bed separation, thereby temporarily inducing sliding and shutting down till deformation/lodgement. Drainage of meltwater through a till, particularly one that is deforming, can occur either by Darcian porewater flow or by pipe flow (2 and 3 on Fig. 9), the latter probably producing features like the mini-eskers of Alley (1991). Hindmarsh's (1996) concept of till sliding over bedrock may explain the occurrence of thin stratified beds at till bases (e.g. Piotrowski et al., 2001).

Many subglacial tills contain (sub) vertical dykes or injection structures composed of non-till sediment. On the foreland of Slettjökull, Iceland such features have been interpreted by van der Meer et al. (1999) as the products of subglacial meltwater discharges and related specifically to water escape. Clastic dykes are traditionally interpreted as the product of hydrofracturing due to the escape of pressurized groundwater (Mandl and Harkness, 1987; Boulton and Caban, 1995), during which tensional cracks are infilled by the sediment fluidized by the escaping water (Lowe, 1975; Nichols et al., 1994; Rijsdijk et al., 1999; Piotrowski, in press; Fig. 10). van der Meer et al. (1999) suggest that a marginal belt of permafrost forced increased discharges of subglacial meltwater into sub-till outwash, thereby producing downglacier dipping water escape structures. A second phase of fracture filling was initiated as the overlying till dried out after the termination of the meltwater drainage event. These later fracture fills

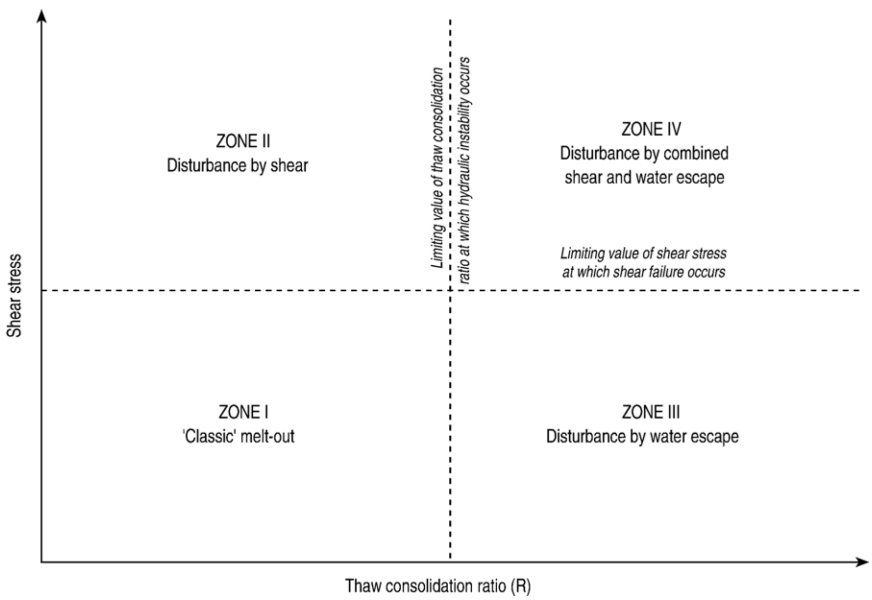


Fig. 8. Conceptual diagram showing the nature of disturbance of melt-out sequences due to thaw consolidation and shear stress (from Paul and Eyles, 1990).

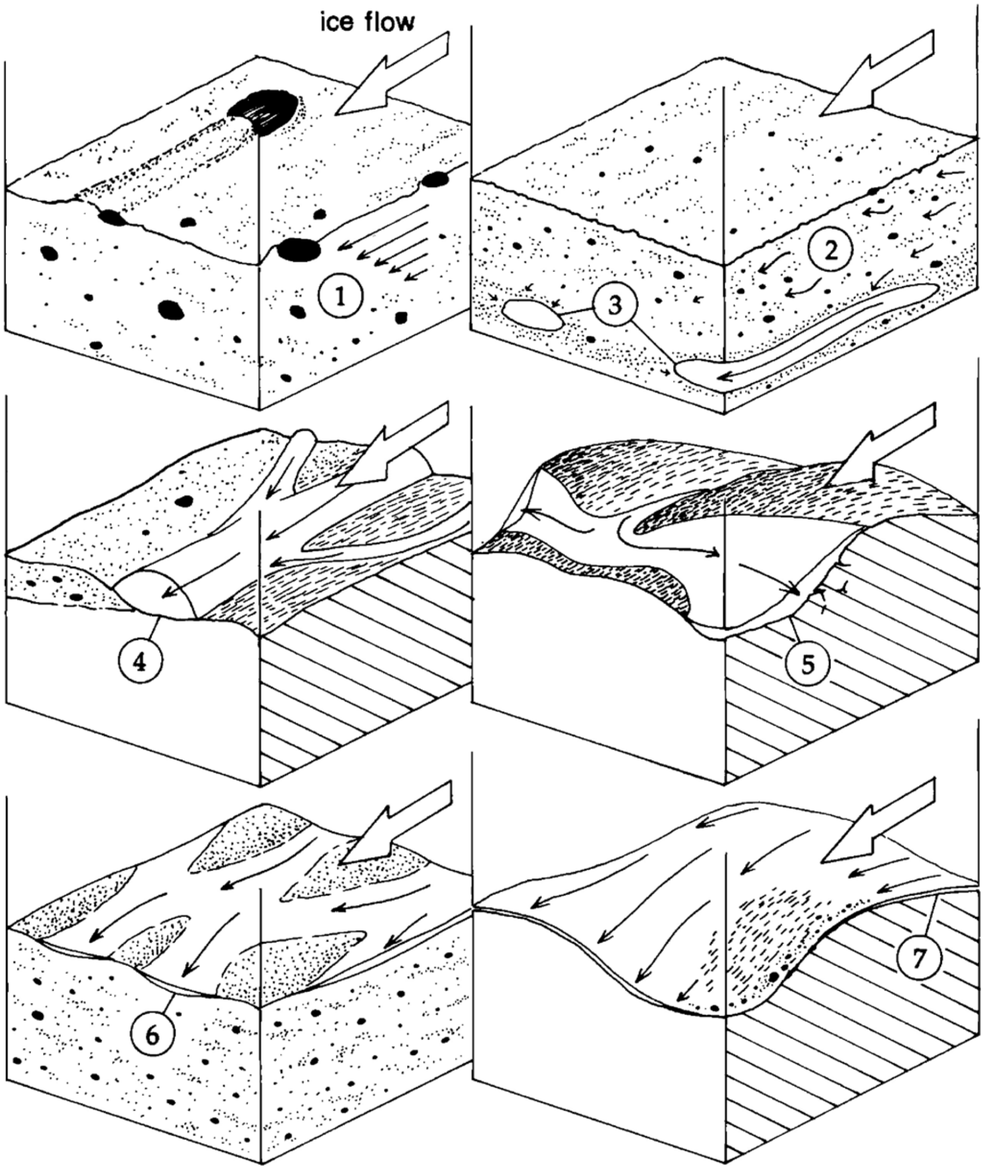


Fig. 9. Various subglacial drainage pathways for rigid and deformable glacier beds (from Benn and Evans, 1996): 1) bulk movement with deforming bed; 2) Darcian porewater flow; 3) pipe flow; 4) dendritic channel network; 5) linked cavity system; 6) braided canal network; 7) water film at ice-bed interface.

developed upwards in the till as water and liquified sand was driven upwards from the underlying outwash. The structures were then partially distorted by subglacial deformation in the upper layer of till. Although the occurrence of permafrost is not necessary to the development of subglacial fracture fills, the possibility of a frozen bed at the glacier margin for significant periods of time clearly has implications for subglacial processes such as those envisaged by van der Meer et al. (1999) at Slettjökull.

3.3. Subglacial deformation

The subglacial deformation of sediments and soft rocks is considered to account for a substantial amount of the forward motion of many glaciers (Alley et al., 1986; Boulton and Hindmarsh, 1987; Clarke, 1987; Alley et al., 1987a,b; Alley, 1989a,b; Humphrey et al., 1993). The stresses responsible for this deformation are imposed by the overlying ice. However, water content, composition and thickness of the sediments along with

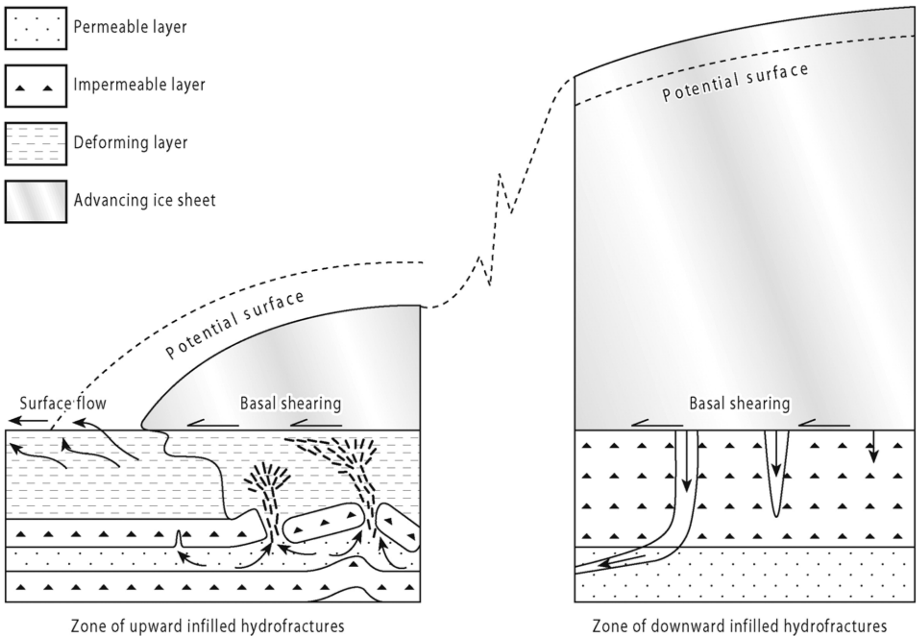


Fig. 10. Schematic reconstruction of subglacial hydrofracturing (from Rijsdijk et al., 1999). The sedimentary impact near the margin varies from upward-filled fractures to burst out plumes. Beneath thicker ice hydrofracturing results in downward-filled fractures.

temperature conditions within the subglacial environment will also exert a control on the style and intensity of deformation. In modern glacial systems it is extremely difficult to directly observe the processes and conditions encountered within the subglacial environment. Studies made at the glacier snout, or by using boreholes through the ice, at best, only provide a tantalising glimpse of this environment. At the glacier snout the ice has already retreated and proglacial processes have begun to modify the deposits. Boreholes can only provide point source data and having penetrated through the ice have already modified the conditions under the glacier in their immediate vicinity; for example a release of pore water pressure.

Two modes of deformation have been identified in modern glaciers and till sedimentology. The first mode involves an upwards increase in shear strain rates towards the glacier sole. The second is characterized by a downwards increase in shear strain rates towards a decollement layer. However, this may be an apparent upward increase in shear strain and what is actually being observed is simply an increase in displacement. The amount of strain may be uniform throughout the sedimentary pile. But the increase in pore water content and/or change in sediment composition may lead to dilation and lowering of cohesive/shear strength of the diamicton. This will lead to the 'weakening' of the sediment resulting in an increase in the magnitude of its response to any applied stress (even at low strains), i.e. lowering the shear strength upward through the sediment pile leads to an increase in displacement. Boulton et al. (2001) suggest that the second mode may reflect varying water pressures in sub-till aquifers and can result in folding at the interface between deforming till and underlying sediments, thereby, explaining the rafting and attenuation of intraclasts and ultimately the production of laminated tills.

3.3.1. *Evidence of subglacial deformation: process observation and sedimentology*

Evidence for subglacial deformation is available in a variety of forms, each of which is summarized in Tables 2–4. The concept of deforming beds beneath former glaciers was proposed by Boulton et al. (1974) and Boulton and Jones (1979) based upon a two-tiered till sequence at the margin of Breiðamerkurjökull, Iceland (Fig. 11). This concept was subsequently developed in palaeoglaciological reconstructions (e.g. Boulton and Jones, 1979) and supported by experiments on till beneath the margin of Breiðamerkurjökull (Boulton, 1979; Boulton and Hindmarsh, 1987; Boulton and Dobbie, 1998) and high resolution seismic surveys beneath Ice Stream B, Antarctica (Blankenship et al., 1986, 1987). Initial impressions by Boulton and Jones (1979) that the Breiðamerkurjökull till had a perfect plastic, Coulomb rheology were revised by Boulton and Hindmarsh (1987), who considered that the patterns of strain were more typical of a non-linearly viscous or

Table 2
Evidence cited for deforming beds (contemporary glaciers)

Source	Location and nature of evidence	Nature of deformation
Boulton (1979), Boulton and Hindmarsh (1987)	Sub-marginal tunnel at Breiðamerkurjökull, Iceland — strain markers in two-tiered till with dilated upper A horizon (porosity 0.4) and compact, sheared lower B horizon (porosity 0.2)	Pervasive in A horizon (up to 0.45 m thick) and brittle shear in B horizon= non-linear strain distribution
Clarke et al. (1984), Blake (1992), Blake et al. (1992)	Boreholes in Trapridge Glacier, Yukon — double bend in flexible rod inserted into bed materials (effective pressure 78–292 kPa)	Pervasive(?) in top 0.3 m (subglacial sediment is 0.1–1.0 m thick)
Blankenship et al. (1986, 1987), Alley et al. (1986, 1987a), Engelhardt et al. (1990), Rooney et al. (1987), Atre and Bentley (1993, 1994)	Base of Ice Stream B — saturated and highly dilated sediment (porosity 0.4 and effective pressure 50 kPa)	Actively deforming but may not be pervasive? (5–6 m thick and continuous for 8.3 km across glacier and identified at a number of sites separated by 300 km)
Echelmeyer and Wang (1987)	Sub-marginal tunnel in Urumqi Glacier No.1, China	Deformation of 36 cm thick layer of frozen sediment = 60% of glacier motion
Engelhardt et al. (1990)	Ice Stream B — high porosity till	Till deforms down to ≥2 m
MacAyeal (1992), Alley (1993), Anandakrishnan and Alley (1994), MacAyeal et al. (1995)	Antarctic ice streams	Sticky spots = bedrock high, till discontinuity and/or till inhomogeneity
Humphrey et al. (1993)	Borehole through Columbia Glacier, Alaska — drill stem stuck in deforming till and bent	Viscous deformation in upper 0.65 m of till
Atre and Bentley (1993, 1994)	Ice Stream B	Dilatant bed. Deformation may not be pervasive.
Fischer and Clarke (1994)	Ploughmeter at the base of Trapridge Glacier.	Deformation varies with grain size/rheology (sliding also occurs)
Iverson et al. (1994, 1995)	Borehole through subglacial sediments at Storglaciären, Sweden — tilt cells show till deformation	Viscous deformation in upper 0.33 m of till
Engelhardt and Kamb (1998)	Ice Stream B — teathered stake	Shear dilation/shallow deformation and/or basal sliding. Large strain rate variability = failure of a non-linear, plastic material
Scherer et al. (1998), Tulaczyk et al. (1998, 2001)	Till cores from Ice Stream B — microfossils and lack of crushing and abrasion indicate mixing of pre-existing sediment and its deformation in its upper layers	Shallow plastic deformation by ice keel ploughing
Tulaczyk et al. (2000a,b)	Ice Stream B	Plastic deformation — failure plane migrating vertically on diurnal cycle
Truffer et al. (1999, 2000)	Black Rapids Glacier	Failure along a decollement at >2 m in a 7.5 m thick till
Fuller and Murray (2000)	Continuous clay layers between tills in drumlin, Hagafellsjokull Vestari, Iceland	Shallow deformation (<16 cm) = sliding and deformation by ploughing clasts
Boulton et al. (2001)	Breiðamerkurjökull — drag spools and strain markers used over 12 day period in boreholes (porewater pressure measured in one borehole)	Stick-slip motion related to water pressure fluctuations — alternate sliding and deformation in descending dilating shear zone
Porter and Murray (2001)	Bakaninbreen — tilt cells installed in the subglacial till	Deformation to at least 0.2 m depth in addition to glacier sliding. Till is not behaving as a Coulomb plastic.
Vaughan et al. (2003), Atre and Bentley (1993)	Antarctic ice streams — patterns in acoustic impedance of subglacial sediment correlated with deforming and lodged states	Spatial mosaic of bed processes related to material properties or sediment deformation history. Ice streams in stagnant phase underlain by lodged sediment.

Bingham material. Because the Breiðamerkurjökull study has become a benchmark in the evaluation of till rheology, it is important to note some limitations of the data (Murray, 1997). First, the experiment site was ice marginal where shear stresses are higher than average and sediment is better drained (see also views of Price (1970) and van der Veen (1999) on the squeezing of sediment at the glacier margin). Second, the displacement profiles measured from the till record total strain rather than mean strain.

Table 3
Evidence cited for deforming beds (laboratory experiments)

Source	Experiment and nature of evidence	Nature of deformation
Engelhardt et al. (1990)	Triaxial test on clay-rich till from Ice Stream B	Perfect plastic rheology
Kamb (1991)	Shear experiment on Ice Stream B till (<2 mm fraction) — single plane failure	Plastic deformation
Iverson et al. (1997, 1998)	Ring shear tests on modern Stoglaciaren and Pleistocene tills and linear viscous putty — strain localization in the tills	Perfect plastic rheology — failure along aligned clay particles
Tulaczyk (1999)	Ring shear tests and theoretical analysis	With Coulomb plastic rheology, fine-grained tills facilitate sliding and clast ploughing = shear zone of 0.01 m thick. Coarse-grained tills = ice-till coupling and deformation down to 0.1 m.
Hooyer and Iverson (2000)	Ring shear tests on beads in putty and ancient tills	Diffusive mixing at boundaries of shearing granular layers. Constant clast rotation in putty but tendency to align *a*-axis permanently in direction of shear in till.
Iverson and Iverson (2001)	Modelling of ring shear tests and previous field data from Breiðamerkurjökull	Distributed shear via multiple failure planes (convex upward displacement profiles) = Coulomb plastic response
Watts and Carr (2002)	Deformation tank using various materials	Brittle deformation along distinct shear planes (convex upward/S shape displacement curve) = plastic response
Hiemstra and Rijsdijk (2003)	Shear test on potters clay	Microscale shear planes and grain rotations due to Coulomb plastic failure
Thomason and Iverson (2006)	Ring-shear tests on water-saturated basal tills	Coulomb plastic response: microscale shear planes and sand grain fabric developing

Experiments carried out in excavations below the glacier are risky (see Boulton and Hindmarsh, 1987) and, as a result, difficult to reproduce. The problems involved in establishing subglacial conditions encountered in the geological record are multiplied, as the ice sheets and glaciers have long since receded, often leaving a complex assemblage of deposits. Consequently, our current understanding of the conditions encountered in the subglacial environment rely heavily upon theoretical models. Some significant uncertainties still exist, as outlined by Boulton et al. (2001). They include the spatial and temporal patterns of subglacial deformation, the variability of subglacial sediment rheology and the inter-relationships of sediment deformation and subglacial hydrology.

Borehole experiments on the surging Trapridge Glacier revealed that bed deformation was a complex process driven by changes in shear stress via variability in ice-bed coupling and possible changes in deforming layer thickness (Blake, 1992; Blake et al., 1992). Fluctuating subglacial water pressure at the base of Trapridge Glacier has been linked with “time varying sticky spots” by Fischer et al. (1999). Experiments at Storglaciären (Iverson et al., 1994, 1995) also revealed complexity in the deformation process and highlighted that strain rates in the subglacial sediment were poorly correlated with porewater pressure, although later experiments identified elastic responses by the bed material to water pressure fluctuations (Iverson, 1999; Iverson et al., 1999). The till beneath Storglaciären is thought to act as a lubricant for glacier flow and sliding and ploughing dominate as modes of basal motion. Some subglacial experiments have revealed that, instead of increasing coupling at the ice-bed interface, ploughing clasts actually weaken sediment by elevating porewater pressures in sediment prows, thereby instigating decoupling (Iverson et al., 1994; Iverson, 1999; Fischer et al., 2001).

Essentially, an increase in pore water pressure eventually leads to decoupling of the ice from its bed, resulting in a dramatic fall in the shear stress translated to the underlying sediments. As pore water pressures increase, the magnitude of shear stress being applied to the underlying sediment initially remains the same but dilation of the sediment results in a fall in cohesive strength, leading to deformation. However, as the degree of dilation increases and the sediment eventually enters a liquid/fluid state and the shear stress falls — it is impossible to translate shear stress into the underlying sediment through the highly dilated/fluidised sediment. Any applied stress is then taken up by ‘flow displacement’ within a highly mobile zone (see Section 5).

Once subglacial deformation had been accepted by glaciologists as a glacier flow mechanism, questions arose regarding the ability of extensive deforming layers to support the calculated basal shear stresses of large ice masses. This was particularly problematic in the case of Ice Stream B whose deforming layer could not support

Table 4
Evidence cited for deforming beds (ancient tills)

Source	Location and nature of evidence	Nature of deformation
Boulton et al. (1974), Benn (1995)	Breiðamerkurjökull foreland, Iceland — two-tiered till (upper tier is dilated with porosity of 0.4 and lower tier is denser with porosity of 0.2 and numerous small shears)	Pervasive in upper tier but brittle shear in lower tier (compared with subglacial experiments of Boulton (1979) and Boulton and Hindmarsh (1987)
Berthelsen (1979), Hart and Roberts (1994), Evans et al. (1995), Hart (1995), Benn and Evans (1996)	Deformed inclusions (boudins, streaks/wisps, folded lenses/pods) = passive markers	Less homogenized at till base due to lower cumulative strains + gradational contact with underlying glacitectonite
Krüger (1984), Benn and Evans (1996, 1998)	Double stoss and lee clasts, polished clast facets (see also lodgement indicators in Table 6)	Clast collisions and/or striation development at shear plane in deforming layer
Menzies (1990a,b)	Ontario, Canada — sand intraclasts in diamicton melange	Quarrying of substrate by deforming layer followed by brecciation of till
Hicock (1992), Hicock and Fuller (1995)	Ontario and British Columbia, Canada — till sequences overlying deformed sediments and containing deformed intraclasts. Tills exhibit a range of characteristics=	Hybrid tills = lodgement-deformation continuum (with ploughing clasts)
	a) girdle fabrics, variable striae directions on tops and bottoms of clasts, inconsistent clast lee end orientation	Ductile deformation = squeeze flow
	b) bi-modal to girdle fabrics, increased fissility and shallow shears with slickensides	Brittle–ductile deformation due to dewatering
	c) unimodal fabrics and lodgement indicators (see Table 6)	Lodgement
Clark (1991)	Clast pavements in tills	Sinking of clasts to base of deforming layer.
Boulton (1996a)		"Excavational deformation" at base of deforming layer preferentially removes finer material from underlying tills
Clark and Walder (1994), Evans et al. (1995)	Eastern England — stratified intra-till lenses in massive to laminated tills (internally disturbed and margins attenuated and smeared into till)	Subglacial canal fills documenting periods of bed stability — later ingested in deforming layer
Hart (1994), Benn (1995), Benn and Evans (1996)	Till fabrics	Constant clast rotation in thick viscous deforming till = weak clast fabrics. Clast rotation restricted by stiff till matrix in brittle deformation tills = moderate to strong clast fabrics.
Evans et al. (1998, 1999)		Fabric strength related to till maturity (travel distance, till thickness and cumulative strain).
van der Wateren (1995)	Strong mixing in upper part of till = homogenization (S_h zone)	High strain
	Middle part of till = boudins, detached folds, transposed foliation (S_b zone)	Decreased strain
	Lower part of till = rooted structures, attenuated folds, shear lenses, till wedges (S_r zone)	Low strain
	Undeformed sediments	Stable substrate
Benn and Evans (1996), Phillips et al. (2002)	Drymen, Scotland — vertical continuum of glacitectonite and deformation till (type A and B — similar to Breiðamerkurjökull till)	Vertical continuum from low strain ductile to brittle–ductile deformation in the glacitectonite and then from brittle shear to ductile deformation in overlying till (includes rheological jumps)
Boulton et al. (1996)	Sefstrombreen, Svalbard — 20 m thick glacimarine muds sheared over 2 km during a surge	Ductile deformation
Piotrowski and Kraus (1997)	Tills of NW Germany — isolated large scale folds in sub-till sediment. Slightly deformed till intraclasts.	Patchy low strain deformation = deforming spots in otherwise sliding ice-till interface. Low homogenization = non-pervasive deformation.
Evans (2000a)	Skalafellsjokull, Iceland — type A and B deformation tills overlying glacitectonized outwash	Ductile and brittle deformation along multiple failure zones in outwash. Brittle shear and ductile deformation in overlying till (includes rheological jumps)
Boulton et al. (2001)	Sharp, undeformed basal contact of deformation till.	Protection of substrate by deforming layer.
Roberts and Hart (2005)	East Anglia, England — stratified diamictons comprise glacitectonic laminae and primary sedimentary laminae deformed to low strains.	Vertically differentiated zones of brittle and ductile failure produced by variations in intergranular pervasive shear.

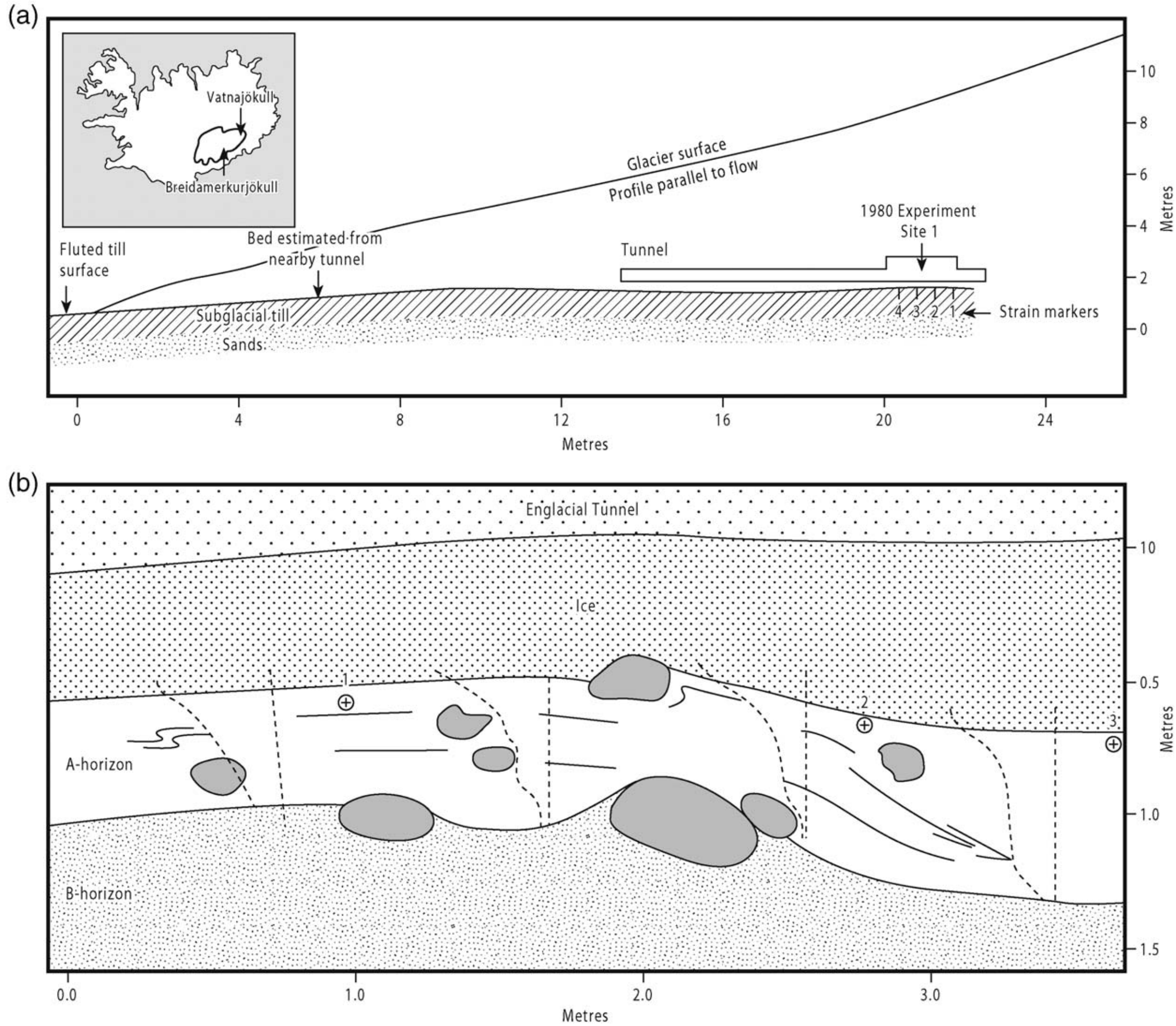


Fig. 11. Location map and schematic diagram (from Murray, 1997, after Boulton and Hindmarsh, 1987) of the experimental tunnel below Breiðamerkurjökull, Iceland (a) and summary diagram depicting the results of the deformation experiment conducted beneath the tunnel through the insertion of strain markers in the till (b). The dashed lines represent the positions of the strain markers at the beginning of the experiment and after 136 h. Pore pressure transducers are numbered 1–3 and sand wisps in the till A horizon are marked by thin lines. Large clasts are shaded.

the basal shear stress of the flowing ice and, therefore, must have been flowing relatively slowly due to side drag at the ice stream walls (Jackson and Kamb, 1997; Raymond et al., 2001) or to "sticky spots" on the bed (MacAyeal, 1992; Alley, 1993; Anandakrishnan and Alley, 1994; MacAyeal et al., 1995). The latter highlights the fact that there is a large spatial variability in basal friction below ice streams due to till discontinuity, bed roughness and till inhomogeneity. In fact there is every reason to believe that glacier beds generally may comprise mosaics of sliding, deformation, lodgement and ploughing (e.g. Alley et al., 1997; Piotrowski and Kraus, 1997; Piotrowski et al., 2004; see Section 3.5) and that subglacial tills are typically heterogeneous in their behaviour. This concept has been elucidated by van der Meer et al. (2003) with reference to the migration of hard, mobile and quasi-mobile zones (H, M and Q beds; Menzies, 1989) of active glacier beds. Seismic investigations undertaken by Vaughan et al. (2003) beneath Antarctic ice streams reveal variations in acoustic impedance of subglacial sediment, interpreted as the product of deforming versus nondeforming states and thereby verifying that ice stream flow is at least partially driven by deformation of the bed. Interestingly, some ice stream beds contain juxtaposed deforming and nondeforming sediment, lending support to models of subglacial till mosaics in the ancient sedimentary record (e.g., Piotrowski et al., 2004; Fig. 12). Vaughan et al.

(2003) also highlight the association of nondeforming sediments with ice streams that have recently shut down. Ice stream shut down may be signalled by the basal freeze-on of subglacial sediment (Bougamont et al., 2003), as recorded by Christoffersen and Tulaczyk (2003) at interstream ridges and modeled by Iverson (2000). Temporal and spatial variability in the amount of basal melting versus freezing appears to be well correlated with ice stream activity (Joughin et al., 2003; Vogel et al., 2003) and shorter-term motion variations (stick-slip motion) have been linked to tidal influences on basal till properties (Bindschadler et al., 2003).

This is significant when assessing tills in the geological record, because at any one locality multiple phases of deformation and erosion/sliding may be represented in a till or till sequence. Moreover, the strain recorded in the sedimentary imprint at such a site will be a product of cumulative strain over a period of time. An alternative way of viewing glacier movement is that forward motion is the exception rather than the rule (i.e. due to the weight of ice, friction forces etc., a glacier will tend to remain static). The various processes outlined above are the mechanism(s) by which this “static state” is overcome. But due to the transitory nature of the controlling factors on these processes (e.g. high pore water pressure, dilation, thermal properties of the bed), continuous forward motion of the glacier will not be maintained. One problem which still remains, however, is that in a significant number of cases the subglacial diamictons that are interpreted as ‘deformation tills’ show no macroscale evidence of deformation (e.g. folds, faults, shear zones) and are essentially massive in appearance (negligible or no visible sign of deformation has even been used as an indicator of high strain rates, e.g. Hart et al., 1996). If a deformation model was the primary method of forward motion of a glacier then evidence of this process should be preserved, and this is now routinely identified at the microscale (van der Meer, 1993, 1997; Menzies, 2000; van der Meer et al., 2003; Roberts and Hart, 2005).

The position of deformation in sampled subglacial sediment layers also appears to vary. Whereas, the Boulton (1979) and Boulton and Hindmarsh (1987) experiments document a vertical deformation profile typical of a non-linearly viscous material, other researchers have observed failure at deeper levels in the till. For example, Truffer et al. (2000) report almost all the basal motion of the Black Rapids Glacier in Alaska occurs at depths of greater than 2 m in the underlying till. Shear zones below most contemporary glaciers, however, appear to be 0.3 to 0.5 m thick. The rheology of the material is significant in this respect in that a viscous till will possess a relatively thick shear

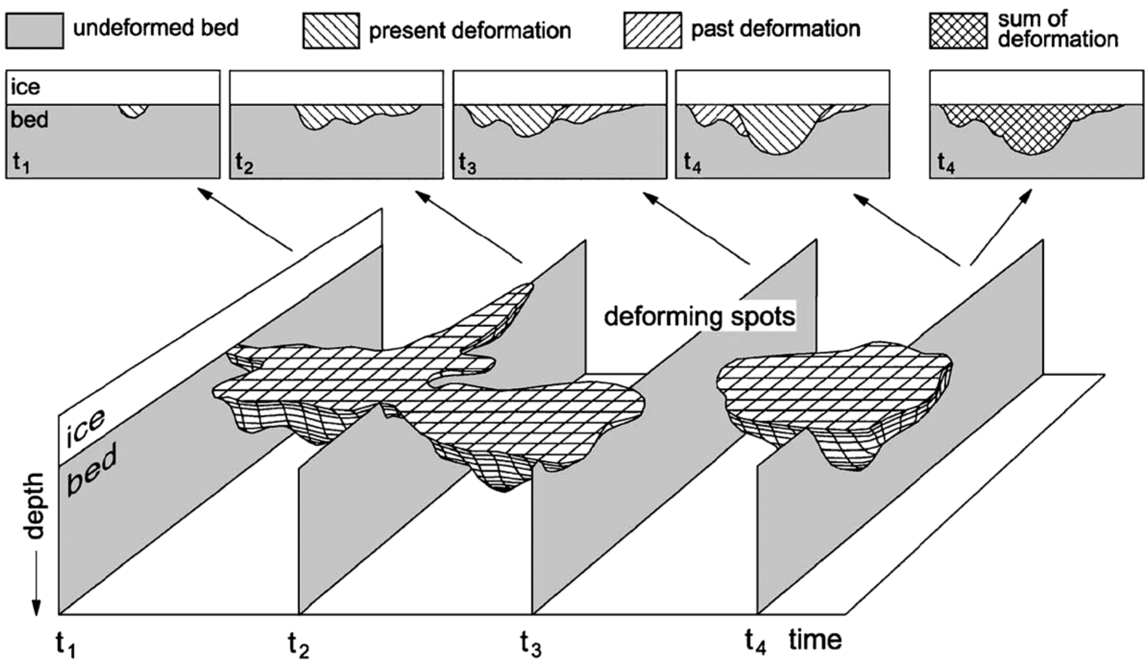


Fig. 12. Schematic reconstruction of the concept of the stable/deforming subglacial bed mosaic concept of Piotrowski et al. (2004). The position of the deforming spots on the bed changes spatially and temporally, producing overprinted deformation signatures in the subglacial material.

zone compared to a Coulomb plastic till. Most experiments on sediments from modern glacier beds appear to support a Coulomb plastic rheology, although at larger scales than those of individual dislocations in the till a case can be made for viscous-type response (cf. Hindmarsh, 1997, 1998a,b). Consequently, it is possible that the behaviour of an active/mobile/dilated diamicton could be more realistically modelled using a Bingham non-linear model (M. Paul pers. comm. 2002). Boulton et al. (2001) suggest that variable responses by a till may be driven by temporal variations in water pressure/effective pressure and consequent vertical variations in the locus of plastic failure (see also Iverson et al., 1998). The result would be cumulative, distributed net strain in response to localized failure events, constituting Hindmarsh's (1997) viscous behaviour at the large scale.

The primary sedimentary structures, bedding and grain sizes in pre-existing sediment piles that are overridden by glacier ice will clearly influence the nature and location of substrate deformation. This is best illustrated at former glacier margins where complex, thick sequences of stratified glacigenic sediments have been modified by moderate to high strains. For example, Roberts and Hart (2005) provide sedimentary and stratigraphic evidence for the variable shear responses of laminae due to granulometry and porewater pressures. The greater porosity of coarser laminae promotes higher porewater pressures and therefore intergranular pervasive shear and dilation. Conversely, the lower porosity of finer laminae promotes lower porewater pressures and increased effective pressure, thereby initiating brittle shear. Roberts and Hart (2005) differentiate two types of laminae in the deforming sediment pile in East Anglia: "Type 1" laminae produced by intergranular shear and "Type 2" laminae produced by the deformation of pre-existing sedimentary bedding. The progressive attenuation of such laminae due to subglacial deformation to high cumulative strains has been cited as the main process in the production of laminated to massive deformation tills (Hart et al., 1990; Benn and Evans, 1996).

Despite findings such as these, based on studies of ancient tills, many of the arguments presented above on subglacial deformation apparently assume that the 'active' sediment layer (the layer in which displacement occurs) below a glacier is compositionally homogeneous. However, in reality small-scale variations in the modal proportion of clasts and/or clay/silt matrix of a diamicton will lead to significant variations in its rheological properties and, hence, its response to any applied stress. The result will be the partitioning of deformation or displacement into discrete zones that may occur at any level within the active part of the glacier bed. Furthermore, the location of these zones will vary with time as the imposition of a deformation fabric (or any related structures) within the high strain zone will lead to a change in the rheological properties of the sediment. As the high strain zones migrate through the deforming bed then they will reactivate, deform and/or overprint previously developed structures and/or fabrics (leading to refolded folds, crenulations, etc.). Reports of motion at various levels in tills (e.g. Truffer et al., 2000; Tulaczyk et al., 2000a,b) could conceivably be examples of deformation partitioning. Tulaczyk et al. (2000a,b) report that the failure surface in till below Ice Stream B migrates vertically on a diurnal cycle in response to changing water pressure and supply. Strain blocking by clasts in coarse-grained deforming tills is considered by Boulton and Dobbie (1998) to be critical to local failure events and the reduction of non-linearity; hence the removal of coarse clasts from clay-rich tills prior to laboratory shear tests increases the tendency for plastic behaviour. Moreover, interlocked clusters of clasts in a deforming till, which can effectively block deformation, may be unlocked by grain fracture (Boulton et al., 1974; Hiemstra and van der Meer, 1997), thereby imparting a localized stick-slip motion. However, although examples do occur where clasts have failed/fractured, it is more likely that with increased strain deformation will be preferentially partitioned into the weaker matrix of a diamicton and, therefore, will by-pass large boulders or clusters of clasts. Cataclasis/fracturing of larger clasts within a diamicton is thought to reflect either (a) failure of an inherent weakness within the clast, or (b) very localised high strain due to point contacts between grains (possibly coupled with (a)).

Although data from monitored glacier beds indicate that deformation is restricted to less than 1 m, a wide variety of case studies in Pleistocene tills and associated sediments clearly display deformation to far greater depths (Table 4; see Sections 4.4 and 4.6). Deep vertical displacement structures are common in proglacially thrust and deformed sediments, for example in thrust block moraines/composite ridges and hill-hole pairs, and may have become subglacial only after their initial proglacial thrusting (e.g. cupola hills; Aber et al., 1989; Benn and Evans, 1998). In each of the examples cited in Table 4 there is no reason to believe that any of the large glacitectonic structures were not produced initially at the glacier margin. Indeed some examples are definitively proglacial to sub-marginal in origin (e.g. Boulton et al., 1996; Benn and Evans, 1996; Evans and Twigg, 2002; Phillips et al., 2002). Such spectacular and obvious deformation features are indicative of small strains and may provide structural evidence of sediment emplacement near the glacier margin. More intense strain is reflected in less obvious structures such as tectonically laminated and homogenized tills that develop as the deforming bed system evolves (Boulton, 1987; Hart et al., 1990; Hart, 1995; van der Wateren, 1995; Benn and Evans, 1996; see Section 4). However, it must be stressed that the absence of deformation structures within an apparently homogeneous subglacial diamicton should not be used on its own as an indicator of intense deformation. Unless a progression from undeformed, through intensely deformed and into homogenised sediments can be demonstrated, the homogenisation of a diamicton due to intense deformation can not be proven. Furthermore, homogenisation can not be used as an indicator of very high strains. An increase in pore water pressure leading to dilation and partial liquefaction of a sediment can result in homogenisation even at low strains. The composition of the sediment and pore water content, therefore, represent important controlling factors on the homogenisation of subglacial deposits during over-riding by ice.

The emplacement of subglacial diamicton is not necessarily instantaneous as Boulton et al. (2001) demonstrate, but rather, a cumulative process whereby till is deposited/accreted at the base of the 'deforming' horizon. The cessation of deposition and deformation would produce a single deformation till horizon but in many instances deformation tills probably accumulate by increments as material is deposited in tectonic slices or in individual sediment packages separated by thrusts or some form of fault/detachment (e.g. tectonic/depositional slices (Fig. 13), Boulton et al., 2001; Evans and Hiemstra, 2005). Later stage deformation features may also be superimposed on earlier structures, although such superimposition is more difficult to detect at higher strains or after more prolonged periods of strain. In the literature, however, the relative ages and relationships between successive generations of macroscopic and microscopic deformation structures are poorly constrained or, in some cases, not described at all. The inter-relationships between structures are of critical importance in understanding the depositional and deformational history of subglacial deposits. In particular, we need to distinguish between structures developed in response to active forward motion of the overlying glacier and those formed during a subsequent, potentially unrelated, deformation event.

3.3.2. Laboratory based till deformation experiments

Laboratory experiments have been undertaken on a variety of till types, although it is difficult to reproduce anything like true field conditions. Material extracted from the bed of Ice Stream B and subjected to shear experiments by Kamb (1991) failed along a single failure plane, suggesting a plastic rheology. This contrasts with field experiments at Storglaciären (Iverson et al., 1995) and Columbia Glacier (Humphrey et al., 1993) where subglacial materials were behaving as viscous mediums. Iverson and Iverson (2001) propose a Coulomb plastic model of subglacial deformation in which failure occurs along numerous slip planes (distributed shear), a mode of failure also recorded at the microscale during shear tests on potters clay by Hiemstra and Rijsdijk (2003). Most significantly, Iverson and Iverson (2001) reproduce of a convex-upward displacement curve, similar to that reported in the classic Breiðamerkurjökull studies, thereby implying that such curves do not necessarily indicate a viscous rheology. A similar convex-upward displacement curve has been reproduced by Watts and Carr (2002) in a deformation tank. This experiment also demonstrated that failure was along discrete failure

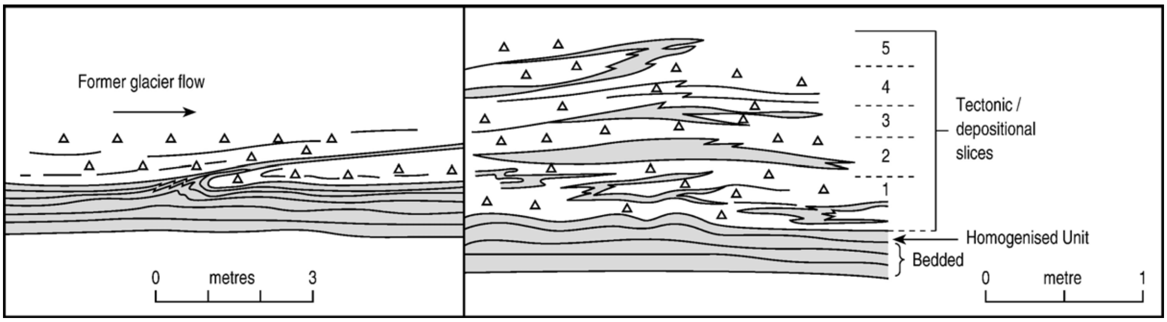


Fig. 13. Examples of sedimentary structures produced by cumulative shear and the inclusion of substrate material in till due to subglacial deformation (from Boulton et al., 2001): Left — inclusion of sand lamina through the attenuation of a drag fold at the till/substrate interface. Adjacent sand wisps represent other laminae produced by earlier folding events; Right — multiple fold structures evident as attenuated, folded and boudinaged sand laminae. Each structure is interpreted as a separate phase of deformation till accumulation, termed a tectonic/depositional slice.

planes and therefore representative of a plastic response. The consensus that has now evolved regarding the rheological behaviour of subglacial tills has been summarized by Fowler (2002, 2003), who concludes that tills behave plastically but undergo spatially distributed deformation, thereby producing a pattern of displacement that resembles a viscous material.

Using ring shear experiments Hooyer and Iverson (2000) propose that shearing granular layers like tills will mix across boundaries. Their mixing coefficient, D, decreases with strain and allows the calculation of an upper limit on bed shear strain based upon the distribution of index lithologies across till boundaries. These subtle boundaries often appear sharp or erosional in the field and have fuelled debate on the origin of the tills (e.g. Boulton et al., 2001; Piotrowski et al., 2001, 2002). The mixing that takes place at the boundary, however subtle, is the type of evidence cited by Kemmis (1981) and Clayton et al. (1989) as indicative of pervasive deformation (e.g. gradational contact). This is in contrast to Alley's (1991) contention that sharp boundaries are the product of a downward increase in effective pressure (total normal stress − porewater pressure). Specifically, at a critical depth till will be deforming too slowly to maintain its high porosity and will therefore compact and stop shearing, resulting in a sharp boundary between the upper deforming layer and the lower rigid layer. This is akin to Boulton's A and B horizons at Breiðamerkurjökull. Lithologically distinct layers above and below the boundary, whether truly sharp or diffusive, indicate that till provenance changes. In addition to changing the dominant clast lithology, this may also import a different matrix to that of the earlier till, thereby introducing a different rheology and deformation signature in the till sequence. Studies of ancient sediments such as that by Roberts and Hart (2005) indicate that erosion at decollement surfaces at the base of deforming layers takes place locally by sediment excavation, leading to the liberation of pods of underlying sediment and their attenuation and disintegration down flow, explained by Boulton et al. (2001) as the consequence of rheological contrasts between the deforming layer and the eroded pods (Fig. 13). However, Roberts and Hart (2005) provide evidence also for sediment mixing, as proposed by Hooyer and Iverson (2000) and Piotrowski and Hoffman (1999), at the microscale.

3.4. Subglacial ploughing

Whereas the ability of boulders to plough through and often lodge in soft subglacial sediment has long been recognized (e.g. Weertman, 1964; Beget, 1986; Brown et al., 1987; Clark and Hansel, 1989), the potential for grooves in the ice base to plough through soft substrates has only recently been proposed (Tulaczyk et al., 2001). It has been acknowledged that ploughing clasts embedded in the glacier sole can effectively distribute shear to greater depths in till than that achieved by debris-poor ice alone (Boulton, 1978; Tulaczyk, 1999). The production of a prow in front of a ploughing clast retards movement at the sediment–ice interface resulting in localised dewatering and increased consolidation of the sediment. As discussed above this initiates lodgement, thereby necessitating an appreciation on behalf of glacial sedimentologists that lodgement and deformation should not be considered as mutually exclusive. In this section we concentrate on the ploughing of soft substrates by the ice, although the till forming processes associated with ploughing clasts are relevant.

Tulaczyk et al. (2001) and Clark et al. (2003) proposed an ice ploughing model because previous models of subglacial deformation were increasingly unable to explain: a) the results of laboratory experiments on subglacial tills, in which a Coulomb-plastic rheology has been demonstrated; and b) field measurements in which basal sliding and/or shallow deformation is apparent (see Tables 2 and 3). Additionally, the intra-till inhomogeneities in porosity, composition and microfossil content detected in tills recovered from beneath Ice Stream B (Scherer et al., 1998; Tulaczyk et al., 1998) are thought to be inconsistent with pervasive deformation to depths any greater than 1.5 m. The ploughing model advocates disturbance and transportation of subglacial till up to a few metres thick by the keels in a sliding, bumpy glacier sole. Essentially, the till deforms around bumps in the ice sole as they are dragged through the substrate. At the base of the West Antarctic ice streams this model explains why streamlining of the substrate takes place even though the basal ice is debris-poor and the underlying till is fine-grained and clast-poor. Tulaczyk et al. (2001) propose an analogy with the fault gouge model of Eyles and Boyce (1998) in which the sliding ice base acts as the rigid upper fault plate (Fig. 14), a concept illustrated by Boulton (1970b) in the plastering of till beneath a Svalbard glacier. The asperities in the fault plate, whether clasts or bumps/keels in the ice sole, plough through the soft substrate, generating the deformable till (fault gouge layer) above the underlying, rigid strata (lower fault plate). Only large keels or bumps in the ice sole will generate new till, because they can protrude through the existing till layer into the underlying substrate. This should be effective at liberating soft

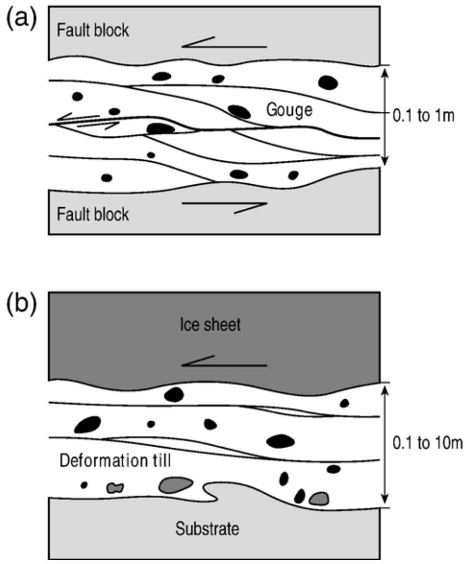


Fig. 14. Comparison of till undergoing shear between: a) fault blocks (fault gouge); and b) a glacier sole and a soft substratum (from Eyles and Boyce, 1998).

clasts from the substrate while at the same time producing erosional contacts between the base of the deforming layer and the underlying non-deformed sediments (Fig. 13). Smaller bumps act to transport the existing till. Because the ploughing model requires no sediment input from the glacier base, it is particularly appropriate as an explanation of substrate deformation and streamlining of pre-existing sediments (i.e. glacitectonite/deformation till production, see below), avoiding inherent problems of till continuity (Alley, 2000). It also explains many of the features observed in glacially streamlined terrains (e.g. Clark, 1993, 1994; Canals et al., 2000; Clark and Stokes, 2001; Wellner et al., 2001; Ó Cofaigh et al., 2002). Sedimentologically, the ploughing model helps to explain extensive till units of relatively uniform thickness in that there is a "stabilizing feedback". Specifically, as a till thickens fewer ice bumps can penetrate through it to the underlying substrate, thereby arresting and ultimately terminating the thickening rate. Alternatively, if a till thins, more ice bumps will protrude into and erode the substrate, thereby generating more till.

3.5. The lodgement-deformation continuum

Progressive changes in bed properties at one location are difficult to monitor in modern glaciers but can be inferred from till sequences. Although such inferences carry with them the inherent weaknesses of preferred interpretations of till structures, they do acknowledge the likely temporal and spatial variability of till forming processes at glacier beds. Spatial and temporal variability in ice-bed coupling due to changes in pressure distribution of the basal water system leads to variability in basal motion mechanics (Fischer et al., 1999; Fischer and Clarke, 2001). This gives rise to a patchwork of sticky spots and areas of stick-slip sliding, the extent of which vary in response to changes in the basal meltwater pressure (Fig. 12). Changes in bed properties/till forming processes are often proposed in the explanation of complex till sequences. For example, Lian and Hicock (2000) propose a change from lodgement to deformation to explain complex tills in the North American Cordillera. They suggest that the thickening of lodgement till brought about increased porewater pressures and this initiated ductile deformation. In places the deforming medium moved as a viscous slurry, thereby explaining the entrainment of lumps of soft bedrock and the preservation of fragile bioclasts (e.g. complete, articulated bivalves/ostracods, foraminifera etc.). Till dewatering and stiffening also led to the overprinting of ductile deformation patterns by structures indicative of brittle failure.

Changes in subglacial water pressure and associated stick-slip motions measured at the base of Breiðamerkurjökull have been explained by Boulton et al. (2001) as the result of a change from basal sliding to subglacial deformation (Fig. 15). The concomitant downward migration of a dilatant shear zone is a similar process to that reported by various researchers who have observed failure at various levels in subglacial materials (see Section 3.3). Based upon the discussion presented in the sections above, it is clear that a combination of till transport and deposition processes is most likely in subglacial environments. Boulton et al. (2001) observations of changes from sliding to deformation at specific locations on the glacier bed (Fig. 16) can be reconciled with the spatial variability in sliding intensity proposed by Piotrowski and Kraus (1997) and Piotrowski et al. (2004) subglacial mosaic comprising sliding bed conditions and deforming patches or spots (Fig. 12). Additionally, during periods of sliding, ploughing of the substrate by ice keels and/or clasts may take place. Sedimentary evidence for ploughing and its role in the lodgement of clasts has been widely reported (see Section 3.1). This demonstrates that there is clear linkage between substrate deformation and the lodgement process. We later provide a model for subglacial till production that encompasses the various processes recognized in modern glacier systems and acknowledges the temporal and spatial variability in those processes at the glacier bed.

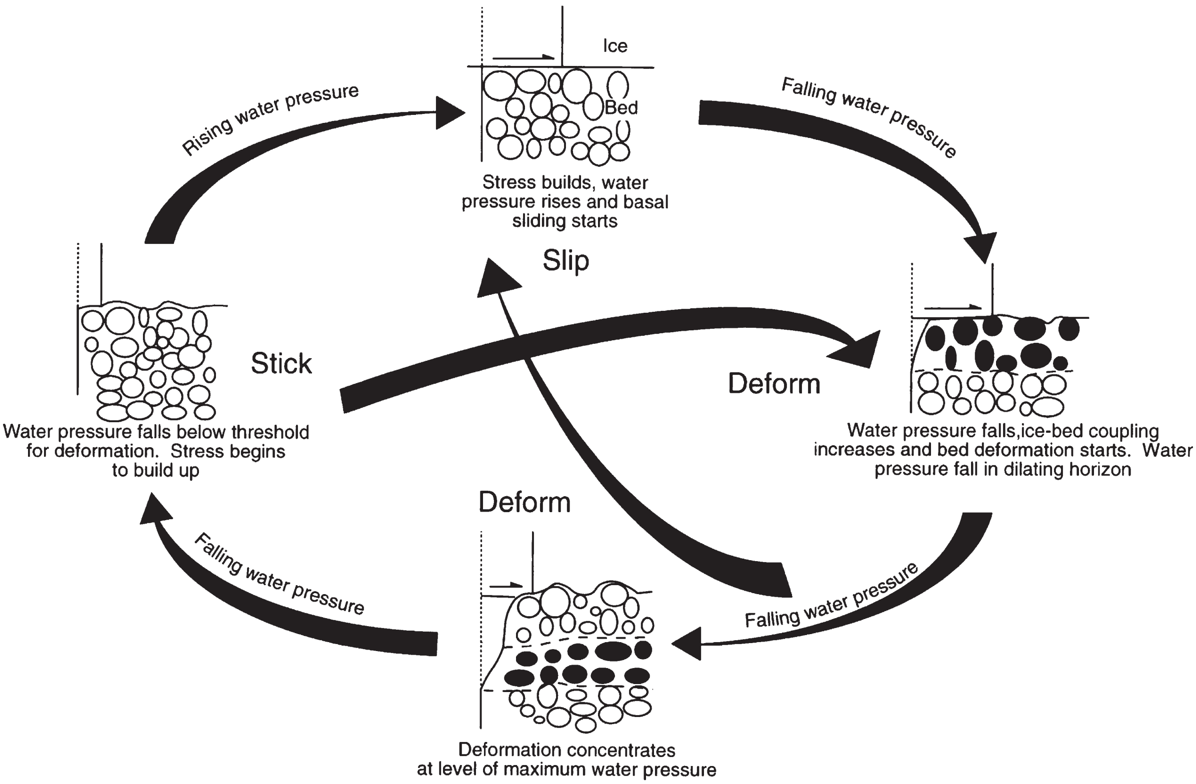


Fig. 15. Flow diagram showing the importance of subglacial water pressure to the temporal variability in deformation versus sliding (from Bennett, 2003, after Boulton et al., 2001).

3.6. Lee-side cavity filling

The infilling of lee-side cavities on the irregular beds of glaciers with rigid substrates involves a range of processes that interact with all of the above sediment emplacement mechanisms. The processes involved in the initial filling of a lee-side cavity have been elucidated by Peterson (1970), Vivian (1975), Boulton and Paul (1976), and Boulton (1982) based upon observations in subglacial environments and are illustrated in Fig. 17. These include slurrying, expulsion and fall, decollement and debris-rich ice "curl" detachment and fluvial inwashing. The sedimentary characteristics of this cavity fill deposit are discussed below, but it is important to note here that the sedimentary and structural signatures of other till forming processes can

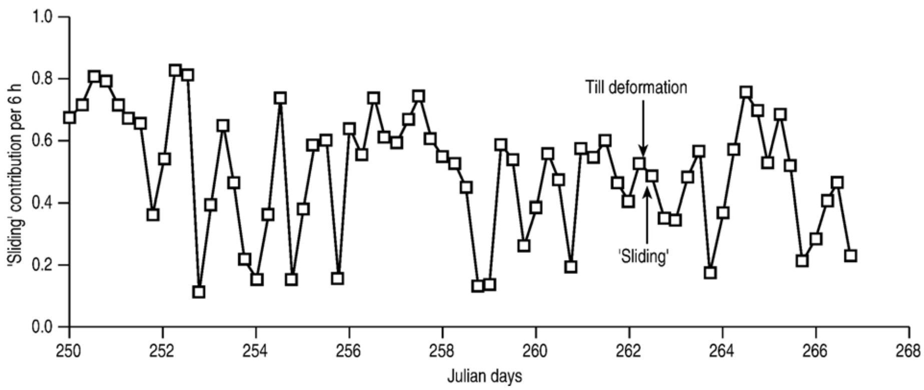


Fig. 16. Results from the Breiðamerkurjökull subglacial experiment showing the proportion of glacier movement due to till deformation versus basal sliding (from Boulton and Dobbie, 1998).

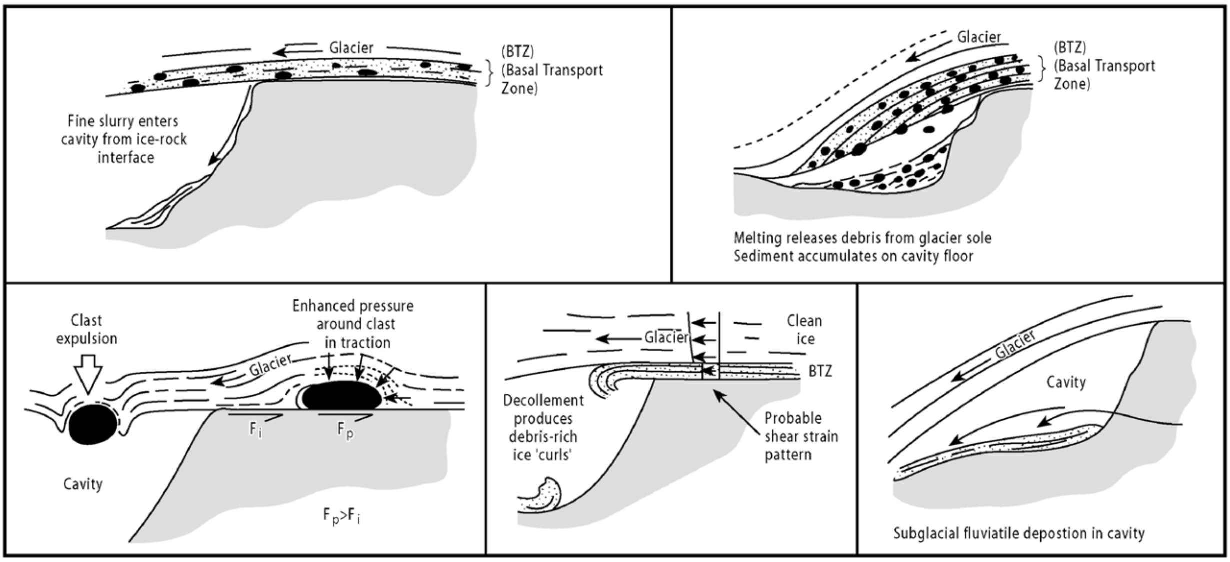


Fig. 17. Schematic diagrams representing observations of sediment accumulation in subglacial cavities (from Boulton, 1982).

be superimposed onto lee-side cavity fills when glacier ice recouples with its bed. Indeed, Boulton (1971) regarded cavity filling as essential to the smoothing of the irregularities in the bed of a glacier depositing till by the lodgement process.

4. Subglacial till types — the geological record

We now review the geological characteristics used in the differentiation of the till types and associated subglacial stratified sediments that are traditionally regarded as the products of the processes discussed above. The various forms of evidence used in the interpretation of lodgement tills, melt-out tills and sliding bed deposits are summarized in Tables 5–7. Evidence used in the interpretation of deformation till and glacitectonite is summarized in Table 4.

4.1. Lodgement till

Originally named by Chamberlin (1895), lodgement till is defined as:

Table 5
Evidence used in the interpretation of lodgement tills

Source	Nature of evidence	Process
Westgate (1968), Boulton (1976, 1982), Boulton and Paul (1976), Ehlers and Stephan (1979), Shaw (1982, 1987), Sharp (1982), Clark and Hansel (1989)	Linear grooves in sub-till sediment and prows in front of clasts. Clast pavements.	Ploughing of clasts through soft substrate and their lodgement behind sediment prow (release by melt from sliding ice).
Boulton (1971, 1978), Krüger (1979, 1984), Sharp (1982), Clark and Hansel (1989), Benn (1994a), Benn and Evans (1996)	Stoss and lee clasts (lee side facing down glacier) and double stoss and lee clasts, strong *a*-axis fabrics and a–b plane imbrication	Constrained shear at ice-till interface and drag imposed by ice and (deforming/shearing?) matrix. Ploughing leads to imbrication.
Hicock (1991), Hicock and Dreimanis (1992b), Hicock and Fuller (1995)	Parallel striae on top and base of clasts, strong long axis fabrics, consistent clast lee end orientations, shears and fractures with slickensides, flat topped and striated clast pavements (+ all of above showing consistent flow direction) — only exhibited in parts of some tills	Variability in nature of evidence within and between tills = dewatering and stiffening of deformation till followed by lodgement and brittle fracture.
Piotrowski (1994)	Erosional contact with underlying, contorted sand. Sand intensely sheared in upper few cms. Till base intensely sheared with sand stringers.	"Syndepositionally" sheared till = intense shear in basal zone.
Piotrowski et al. (2001)	Flat topped, striated clasts at till-substrate interface (substrate deformed in lee of clasts)	Ploughing and lodgement of clast after melt-out from ice sole

Table 6
Evidence used in the interpretation of melt-out tills

Source	Nature of evidence	Process
Boulton (1970a,b, 1971), Lawson (1979a)	Similar fabrics to englacial debris but with reduced dips and reduced maxima.	Passive melt-out with lowered up-glacier dips due to ice removal and some re-orientation due to inter-clast contacts.
	Massive, fine-grained till with shear planes and structural foliation, whole shells and glacier ice lenses.	Passive release of englacial debris in stagnant basal ice, observed at late stage of melt-out. Shearing imparted by overriding active ice.
Lawson (1979a,b, 1981a,b)	Three end members: 1) structureless, pebbly sandy silt 2) discontinuous laminae, stratified lenses and pods in massive pebbly silt 3) bands or layers of contrasting sediment.	Release of grains from debris-poor ice and melting of ice debris of similar texture both produce structureless till. Ice-poor debris lenses are intact but distorted. Ice-poor layers of mixed grain sizes produce blurred contacts.
Shaw (1979, 1982, 1983), Lawson (1981a)	"Stratified" appearance as a result of sorted intrabeds and draped layers over large clasts.	Volume loss during melting along ice folia.
	Infilled scours beneath clasts and between melt-out till and soft substrate.	Subglacial meltwater film erodes into substrate and around clast protruding from basal debris-rich ice.
	Infilled scours beneath clasts and in intra-till lens.	Meltwater flow in englacial cavity in debris-rich ice or between debris-rich ice and underlying melt-out till.
	Diapirs of till protruding into overlying stratified sediments.	Mass displacement in till due to thaw-consolidation.
	Sub-till sediment clasts (faulted and slightly deformed but with angular borders) in till.	Quarried in frozen state and melted out from debris-rich ice.
Piotrowski and Tulaczyk (1999), Munro-Stasiuk (2000)	Sub-horizontal layers of intra-till stratified sediments (bedded tills)	Subglacial cavity fills (stratified sediments) recording periods of elevated basal water pressure
Ruszczynska-Szenajch (1987), Menzies (1990a,b), Piotrowski and Kraus (1997), Hoffmann and Piotrowski (2001), Piotrowski et al. (2001, 2002)	Sediment blocks and rafts in till (sharp contacts and weak or no internal disturbance).	No pervasive deformation. Englacial transport and later melt-out.
Piotrowski et al. (2001, 2002)	Sharp (erosional) contacts between till and substrate. Substrate undisturbed.	No diffusive mixing between till and substrate. Ice was sliding and/or ploughing.

Sediment deposited by plastering of glacial debris from a sliding glacier sole due to the combined effects of pressure melting and frictional drag.

Such tills are characterized by high bulk density and penetration resistance and are either massive in appearance at outcrop or contain numerous sub-horizontal joints (highly fissile structure; Fig. 18). The joints may be polished or slickensided and striated, indicating that they may be shear planes (Boulton, 1970b; Benn, 1994a), but very small displacements can lead to polishing and so a fracture displaying these features is not necessarily a major fault or thrust. Additionally, joint development by dewatering has been proposed by Muller (1983). Alternatively, horizontal and subvertical joint patterns observed in some tills may have developed as a result of stress release during unloading, analogous to joints formed in igneous

Table 7
Evidence used in the interpretation of sliding bed deposits

Source	Nature of evidence	Process
Eyles et al. (1982), Clark and Walder (1994), Evans et al. (1995), Boyce and Eyles (2000)	Stratified interbeds (canal fills) in multiple till sequences	Till deposition interrupted by subglacial meltwater drainage — possible sliding of the bed not stated but could be implied
Brown et al. (1987)	Layered tills and evidence of high subglacial water pressures.	Ice-bed separation
Hindmarsh (1996)	Polished bedrock	Till sliding
Piotrowski and Kraus (1997), Piotrowski and Tulaczyk (1999)	Sub-horizontal fissures in till, often with slickensides and syndepositional sorted sediments. Layered tills comprising stratified sediment stringers and till. Thin, horizontal intra-till sand layers associated with flat clasts. No stratified layers are deformed.	Waterlaid sediments deposited at ice-bed interface during glacier decoupling.

Fig. 18. Highly fissile, compacted diamicton with bullet-shaped and facetted clasts, typical of subglacial lodgement till.

intrusions during un-roofing. The grain size characteristics and clast forms within lodgement tills reflect the processes of grain crushing and abrasion, especially where clasts have been brought into contact while lodged on a rigid bed and moving in the subglacial traction zone. Once lodged at the bed clasts continue to be abraded and plucked much like miniature roches moutonnees and, therefore, lodgement tills contain abundant stoss-and-lee clasts (Boulton, 1978; Krüger, 1979; Sharp, 1982; Krüger, 1984, 1994). However, stoss-and-lee forms may be produced also within deforming layers (Benn and Evans, 1996) and are therefore not solely diagnostic of the lodgement process (Fig. 19). Lodgement may produce clast clusters or pavements where lodged clasts cause the retardation of further debris protruding from the glacier sole (Boulton, 1975, 1982), although such pavements are also regarded by some as deformation products. Boulton (1982) identifies a further lodgement mode whereby debris-rich basal ice masses are lodged on a hard bed (Fig. 5). Although the debris is finally released by melt-out its structural elements and fabric are both conditioned by the lodgement process; the inherent problems in differentiating lodgement and melt-out tills are immediately obvious.

Lodgement may also take place on a soft or deformable bed and indeed may be significant in the production of deformation tills whereby large clasts embedded in the glacier sole plough through the substrate until their forward momentum is arrested. This process is inherent within the lodgement-deformation continuum outlined above. Indeed the close association between lodged clasts and deforming matrices in the subglacial environment has led many to question the use of the term "deformation till" to define a till type. This is because it implies an exclusive deformation origin and, moreover, deformation may have contributed to the production of all types of till (e.g. Ruszczynska-Szenajch, 2001). The inclusion of

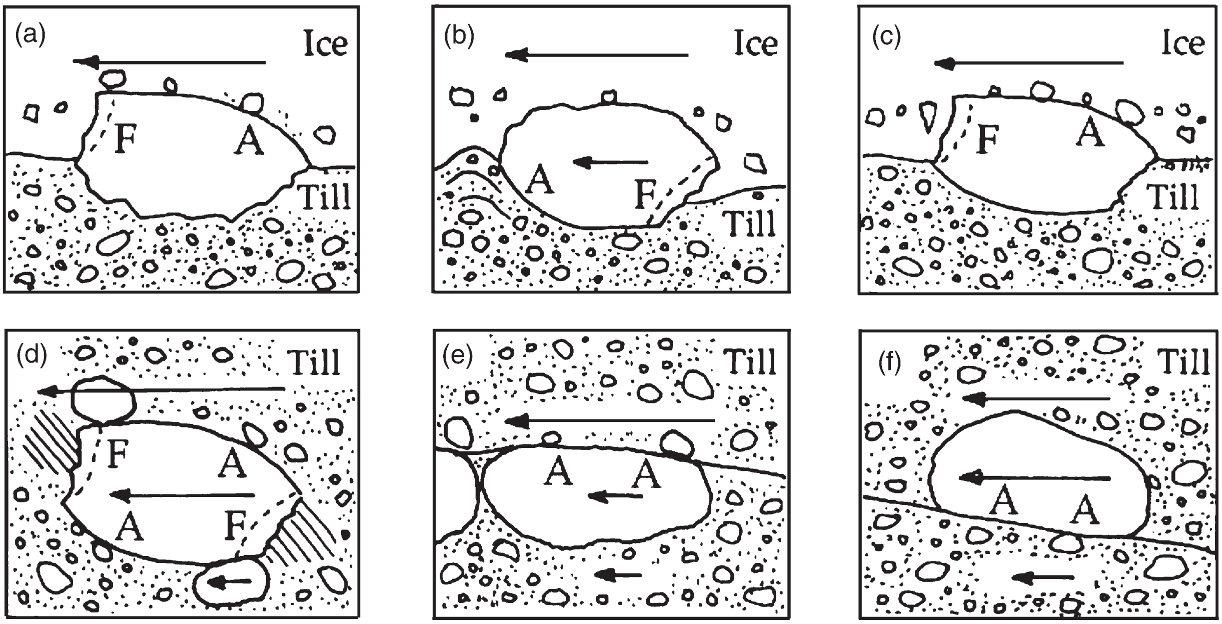


Fig. 19. Examples of clast wear patterns in subglacial tills showing locations of abrasion (A) and fracture (F) and relative velocities as variable arrow lengths (from Benn and Evans, 1998): a) stoss and lee shaped lodged clast; b) and c) double stoss and lee form due to two stage process of ploughing and lodgement; d) double stoss and lee form due to transport in deforming layer (low pressure zones are shaded); e) and f) flat and polished facets eroded on upper and lower clast surfaces at a shear plane in a deforming layer.

deformed sediment rafts in tills interpreted to be a product of lodgement (e.g. Ruszczynska-Szenajch, 1983, 1987; Piotrowski, 1994) suggests that the predominant mode of production is most likely to have been deformation (see Section 3.3). Studies of modern lodgement tills have highlighted the combination of lodged particles, ploughing particles and shearing/deforming sediment (e.g. Benn, 1994a; Krüger, 1994), the relative importance of lodgement and deformation in some instances varying with clast size (e.g. Benn, 1994a, 1995; Benn and Evans, 1996). A fundamental question arises from these observations: exactly what proportion of a subglacial diamicton must be lodged before it can be classified as a lodgement till rather than a deformation till? It is apparent also that the lodgement process per se is probably not capable of producing thick till sequences. Moreover, it is clearly inappropriate to classify sediment as a lodgement till when the majority of its mass has been emplaced by deformation (e.g. Ruszczynska-Szenajch, 2001).

Although some features are strongly suggestive of the ploughing and lodgement process, the emplacement of thick sequences of till above such features is often difficult to explain. For example, linear grooves in sub-till sediment (Fig. 20) have been explained as the products of clasts being dragged along by a sliding ice base (e.g. Westgate, 1968; Shaw, 1982; Clark and Hansel, 1989). The deposition of the till that infills the grooves has been associated with the melt-out of debris-rich basal ice by Shaw (1982, 1987; see below). Alternatively, grooved substrates are not regarded as incompatible with deforming beds by some other researchers, because large clasts can protrude through the deforming layer into the substrate and the base of the deforming layer may also erode downwards into a substrate (excavational deformation of Hart et al., 1990; Hart and Boulton, 1991).

Fig. 20. Grooves cut in laminated silts and clays by overlying till base, Lethbridge, Alberta, Canada.

Because ploughing of the substrate by keels or bumps in the ice base has only recently been proposed as a subglacial till emplacement process, sedimentary evidence of its former occurrence has not been extensively recognized. However, Piotrowski et al. (2001) suggest that some characteristics of tills previously credited to subglacial deformation could be re-interpreted as the products of ice keel ploughing of melt-out deposits. For example, a soft-sediment clast in a pervasively deforming layer should develop two attenuated tails, one at the top stretching down-glacier and one at the bottom stretching up glacier, due to the velocity differences with depth (Hart and Boulton, 1991). Piotrowski and Kraus (1997) and Piotrowski et al. (2001) identify soft clasts in north German tills that exhibit only an upper tail extending down glacier, interpreting them as evidence for clast stability and ploughing of its surface by the glacier base (Fig. 21). In essence, the upper tail represents a shear plane or erosional surface and could be interpreted alternatively as the base of a deforming layer or a large clast in the deforming layer that had migrated downwards into a pre-existing diamicton. The preservation of soft clasts that are later deformed, ploughed or eroded by active ice clearly document the emplacement of their enclosing sediment bodies by more passive mechanisms, implying that till sequences potentially contain overprinted signatures of more than one subglacial process.

4.2. Subglacial melt-out till

The concept that stratified sediments and diamictons could be deposited beneath glaciers and ice sheets was first proposed by Goodchild (1875) and elucidated, somewhat controversially (cf. Bennett and Doyle, 1994; Evans, in press), by Carruthers (1939, 1947–48, 1953) in his “undermelt” theory. Although the undermelt theory had some serious flaws, the work of Carruthers nonetheless inspired many glacial sedimentologists to later consider a subglacial melt-out origin for many heterogeneous diamictons. Recent developments in the understanding of supercooling in subglacial overdeepenings (Alley et al., 1998; Lawson et al., 1998; Alley et al., 1999; Evenson et al., 1999; Roberts et al., 2002) have provided fresh impetus for the concept of till production by subglacial melt-out by recognizing that thick sequences of basal debris-rich ice are widespread phenomena in glacier systems and therefore the potential for melt-out till preservation may be much higher than previously thought (Larson et al., 2006). However, studies that appear to clearly demonstrate till genesis by subglacial melt-out are rare (e.g. Lawson,

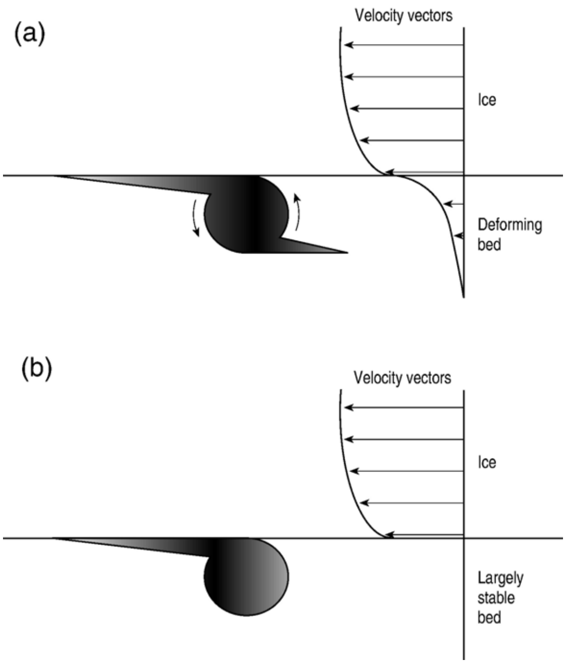


Fig. 21. Conceptual diagram (from Piotrowski and Kraus, 1997) depicting the development of erosion tails from a soft-sediment clast in: a) a deforming bed where the vertical distribution of velocity causes the clast to rotate and dispersion tails develop on its up ice lower side and down ice upper side; b) stable bed subject to ice sliding where the dispersion tail is at the sliding interface only.

1979a,b, 1981a,b; Ham and Mickelson, 1994; Larson et al., 2006) and have not been substantiated by laboratory experiments. Consequently, the characteristics of melt-out tills are largely based upon inferences from the geological record with reference to debris sequences in modern glacier snouts (e.g. Boulton, 1970a,b, 1971; Mickelson, 1973; Haldorsen and Shaw, 1982; Shaw, 1982; Ronnert and Mickelson, 1992; Larson et al., 2006). Melt-out till is defined as:

> Sediment released by the melting of stagnant or slowly moving debris-rich glacier ice, and directly deposited without subsequent transport or deformation (Benn and Evans, 1998).

Although subglacial melt-out tills are thought to inherit the foliation and structure of the parent ice, they are usually modified to some extent during the melt-out process. The degree of modification is dictated by the initial debris concentration and the nature of the local drainage conditions, as explained above. The purest or least disturbed type of "melt-out till" is produced in situations where ice is removed from an ice-debris sequence by sublimation, prompting the more correct term "sublimation till" (Shaw, 1977, 1988). Descriptions of supposed subglacial melt-out tills highlight internal features like discontinuous and contorted layers and lenses, textural and compositional banding with indistinct contacts and internal flow structures and undeformed, intra-till soft sediment or soft bedrock rafts (Lawson, 1979a,b; Shaw, 1979, 1982, 1983; see Table 7; Fig. 22). Lawson (1979a,b) presents clast fabric data from debris-rich ice and tills assumed to have been derived by melt-out (Fig. 7). The fabrics have clearly preserved the sense of former glacier flow direction and have been widely cited as representative of melt-out tills generally. However, Lawson's fabric samples are from one site and may not be representative of all melt-out tills. Moreover, a debris-rich ice sequence overlying a deforming bed would yield similar fabric characteristics and therefore the similarities in fabric between the ice and underlying sediment do not constitute unequivocal criterion for a melt-out process-form continuum.

Despite several case studies in which a melt-out origin for foliated or banded tills has been preferred (e.g. Clayton et al., 1989; Ronnert and Mickelson, 1992; Munro-Stasiuk, 1999, 2000), the characteristics of such tills have been alternatively interpreted as the products of deformation (e.g. Alley, 1991; Boulton, 1996b; Evans, 2000b; Evans et al., in press). A deformation origin involves the incomplete or partial incorporation of sediment derived from the underlying sedimentary sequence within a diamicton resulting in a stratified, bedded or laminated appearance (e.g. Hart and Roberts, 1994; Evans et al., 1995; Benn and Evans, 1996; Evans et al., 1998; see below). More fundamentally, the palaeoglaciological requirements for the production of many ancient "melt-out tills" often appear unrealistic. For example, Boulton (1996b) points out that in order to produce a melt-out till sequence in excess of 10 m (a commonly reported thickness) would require more than 100 m of debris-rich ice of average debris concentration. This thickness of debris-rich ice is far in excess of any present day basal ice sequences. Moreover, the thick "melt-out till" sequences are often reported from areas that contain no supraglacial hummocky moraines or ice marginal dump moraines, landforms that would have been constructed by glacier snouts containing large volumes of debris-rich ice (e.g. Evans, 2000b).

Recently, evidence used in support of a melt-out interpretation for tills has been in the form of evidence against pervasive subglacial deformation (see Table 7; e.g. Piotrowski et al., 2001, 2002). Specifically, this includes sedimentary structures in tills and associated sediments that are inconsistent with a deformation origin, for example undeformed intra-till soft-sediment clasts (Fig. 22c) and erosional contacts between tills and

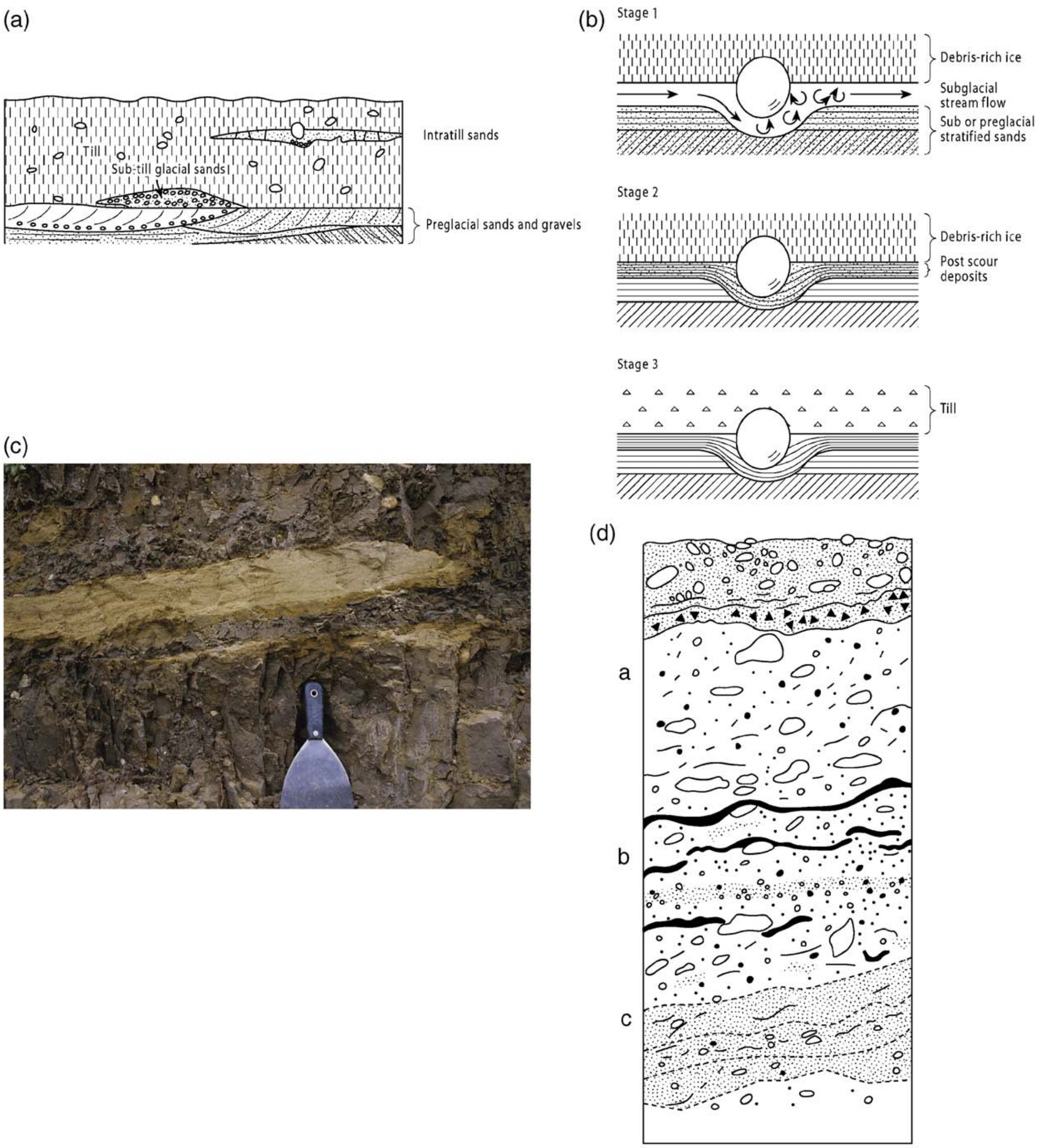


Fig. 22. Characteristic features of melt-out till as proposed by various studies: a) schematic diagram of stratified lenses in sub-till and intra-till positions (from Shaw, 1983); b) explanation of the development of scour fills beneath clasts held in basal ice during melt-out (from Shaw, 1983); c) soft sediment intra-till lens, Alberta, Canada; d) idealized vertical profile of typical features of proposed melt-out at the Matanuska Glacier, Alaska (from Lawson, 1981a) — "a") structureless pebbly, sandy silt; "b") discontinuous laminae, stratified lenses and pods of texturally distinct sediment in massive pebbly silt; "c") layers of texturally-, compositionally- or colour-contrasted sediment. Laminae or layers may drape over large clasts.

undeformed sub-till stratified sediments (Fig. 20). Such features argue against pervasive deformation of the deforming layer and the plucking/cannibalization typical of the transitional contacts between deforming layers and their soft substrates. However, this does not dismiss the concept of deformation in thin (mm scale) shear zones or as multiple failure planes (Coloumb plastic behaviour) within the till. Moreover, the detachment of sediment blocks and glacitectonic rafts (Stalker, 1976; Aber et al., 1989) and their emplacement in englacial positions still require adequate explanation with respect to debris entrainment processes (e.g. Moran et al., 1980). For example, although some rafts are known to have been transported up to 300 km (Aber et al., 1989), raft transport distances are often unclear and it is uncertain whether or not they formed part of a marginal debris-rich basal ice sequence and, as such, were entrained by marginal thrusting and apron entrainment in association with a cold-based outer zone of a glacier snout (e.g. Shaw, 1977; Evans, 1989). Additionally, not all rafts are undeformed and clearly demonstrate partial aggregation into the surrounding till (e.g. Evans and Campbell, 1992; Evans, 2000b).

Although numerous authors have proposed a melt-out origin for at least parts of some ancient till sequences, they often infer that their melt-out deposit provided the raw material for later deformation till production (e.g. Boulton, 1970b; Åmark, 1986; Evans and Campbell, 1992; Evans, 1994; Evans and Campbell, 1995). The implications of such inferences are that till sequences contain a complex suite of signatures of former subglacial processes that may be difficult, if not impossible, to disentangle and that deformation tills and glacitectonites will emanate from locations where debris-rich basal ice sequences have previously melted out. An important corollary of the latter point is that deformation till continuity can be especially satisfied in former ice-marginal locations where bulk freeze-on of debris resulted in thick debris-rich basal ice facies. Additionally, deformation of the accumulated melt-out sequences will take place only if active, warm-based ice moves over the site at some later date, and this may take place during the same glacial event or during a later glaciation. As is discussed below, we also know that other pre-existing sediment masses, such as waterlain deposits, act as suitable deforming layers but are often easier to recognize in their deformed state. Similarly, some localized interpretations of tills suggest that the former glacier bed is a mosaic of lodgement and melt-out features, representing patchy preservation of till types perhaps due to the former uneven distribution of environmental conditions suitable to melt-out production and preservation. For example, Shaw (1982, 1983, 1987) argues for the preservation of meltwater scours beneath clasts (Fig. 22b) protruding into the same sub-till sediments that at nearby locations contain ploughing/lodgement products (linear grooves and lodged clasts). This demonstrates that meltwater films scoured the till-substrate interface during melt-out at some locations but not others.

4.3. Subglacial sliding bed deposits

Associated with the products of lodgement and melt-out but used as evidence of non-deforming subglacial materials (e.g. Piotrowski et al., 2001), are sub-till and intra-till stratified sediments thought to be indicative of sliding glacier bed conditions (Fig. 23). The non-deformed character of these lenses and stringers of waterlaid sediment (c.f. Boyce and Eyles, 2000) and their association with slickensided fissures typical of lodgement (see evidence of grooves etc. in Table 6), prompts Piotrowski and Kraus (1997) and Piotrowski and Tulaczyk (1999) to suggest deposition in a water film at the ice-bed interface (see Table 7). This implies also that the tills found in association with the stratified units must be deposited by passive melt-out. An alternative interpretation of these sub-till stratified units is that they record water films at the base of sliding tills (Hindmarsh, 1996).

Using evidence of juxtaposed undeformed, sub-till stratified sediments and deformed/mixed till–substrate contacts, Piotrowski et al. (2001, 2002) make a convincing argument in support of the sliding and deforming glacier bed mosaic of Piotrowski and Kraus (1997; see also Fischer et al., 1999; Fischer and Clarke, 2001 on temporally varying sticky spots). Support for such variable drainage conditions beneath a glacier comes from Alley's (1992) proposal of coexistent deforming layers and subglacial channels (see Section 5.4). In such cases it is conceivable that till characteristics may change over short distances depending upon the predominant process at the time the glacial depositional system shut down. Moreover, stratified sediments could be interbedded with tills squirted into channels from nearby deforming layers or may record periods of subglacial meltwater sheetflow between phases of accretion of deformation till. Such interbedded sequences could then be glacitectonized during later periods of ice-bed coupling (e.g. Eyles et al., 1982; Evans et al., 1995; Boyce and Eyles, 2000).

Although the above arguments advocate the juxtaposition of sliding and deforming beds, the characteristics of ancient glacier beds have been used to argue a predominantly sliding glacier base during previous glaciations. For example, Piotrowski (1997) and Piotrowski et al. (1996, 1997) cite glacier decoupling around tunnel valleys, low hydraulic transmissivity of the substrate and minimal preconsolidation of subglacial sediments as indicators of overpressurised water at the ice-bed interface and therefore widespread basal sliding (see also Iverson et al., 1995). In combination with sedimentary evidence against a pervasive deformation

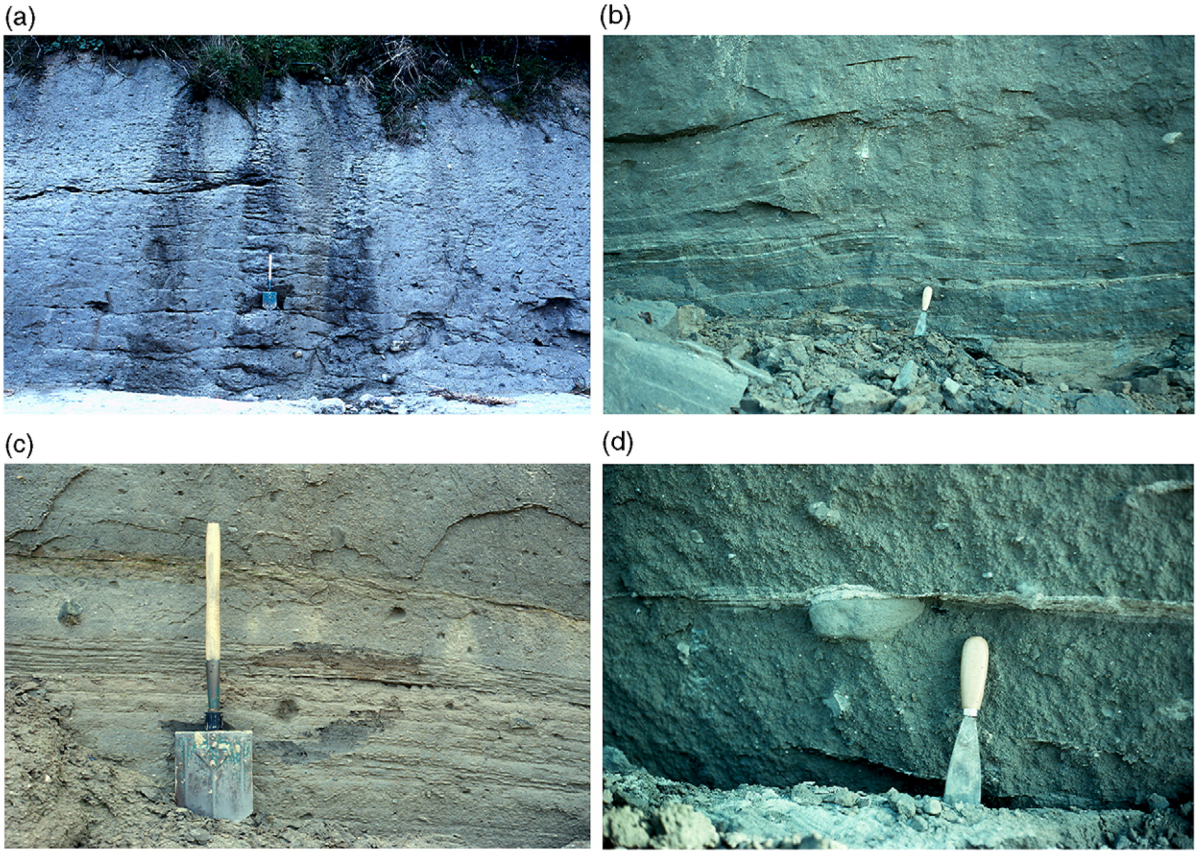


Fig. 23. Examples of proposed ice-bed separation features (from Piotrowski and Tulaczyk, 1999). All features lack significant deformation and sand layers are interpreted as the product of thin water films at the ice-bed interface: a) sub-horizontal, often slickensided fissures, in places filled with syndepositional sorted sediments; b) sub-horizontal fissures (upper part) and thin stringers of sorted sediments interbedded with till matrix (lower part); c) horizontally stratified till consisting of mm-thick sand layers intercalated with till matrix; d) single horizontal stringer of stratified sand in till matrix. Reproduced with kind permission of Jan Piotrowski.

origin for tills, these factors are used to promote spatially restricted bed deformation at the base of the Pleistocene ice sheets (e.g. Piotrowski et al., 2001, 2002).

4.4. Glacitectonite

Initially introduced by Banham (1977) and later reinforced by Pedersen (1988) the term glacitectonite refers to subglacially sheared rocks and sediments. Benn and Evans (1998) proposed the definition:

> Rock or sediment that has been deformed by subglacial shearing (deformation) but retains some of the structural characteristics of the parent material.

The appearance of glacitectonites reflects both the nature of the parent material as well as their strain history. They display evidence of either brittle or ductile deformation or a combination of the two processes. Inhomogeneous materials can display extremely complex deformation structures (Fig. 24), because the nature of their response will be dictated by the rheology of individual sedimentary beds (e.g. Hicock, 1992; Hicock and Fuller, 1995; Benn and Evans, 1996; Evans et al., 1998; Evans, 2000a; Ó Cofaigh and Evans, 2001a,b; Phillips et al., 2002). Glacitectonites are subdivided by Benn and Evans (1996) into Type A and Type B varieties. Type A glacitectonites show evidence of penetrative deformation due to brittle deformation or intense localized ductile deformation (Fig. 25). They may also form by pervasive deformation to high cumulative strains, thereby producing a tectonic foliation as primary structures are attenuated and rotated towards parallelism with the direction of shear (e.g. Hart and Boulton, 1991; Hart and Roberts, 1994; Hart, 1995) or transposed due to the imposition of a new foliation. The role of both lithology and pore water content/pressure should not be under estimated. The lowering of the shear strength of a sandy sediment by an increase in

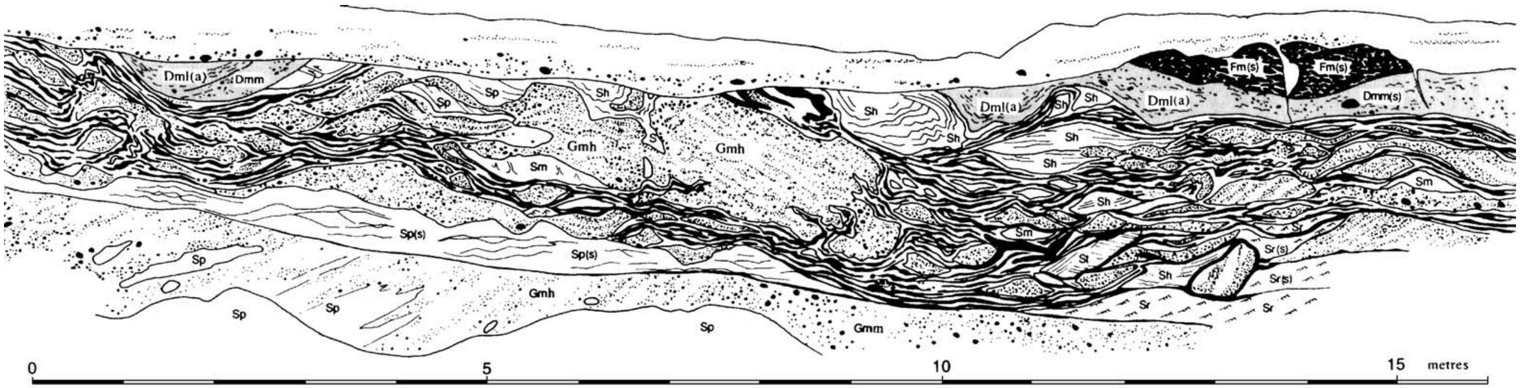


Fig. 24. Example of glacitectonite from a glacially overridden ice-contact delta, Loch Lomond, Scotland (from Benn and Evans, 1996). Erosional lower and upper contacts separate the glacitectonite from delta foreset beds and readvance till respectively. Attenuated muddy laminae form anastamosing shear zones around boudinaged rafts of stratified sand and gravel. Deformation has taken place largely by ductile failure in the finer grained beds of the sediment pile but internal disturbance of the better drained sand and gravel was dominated by small scale brittle failure.

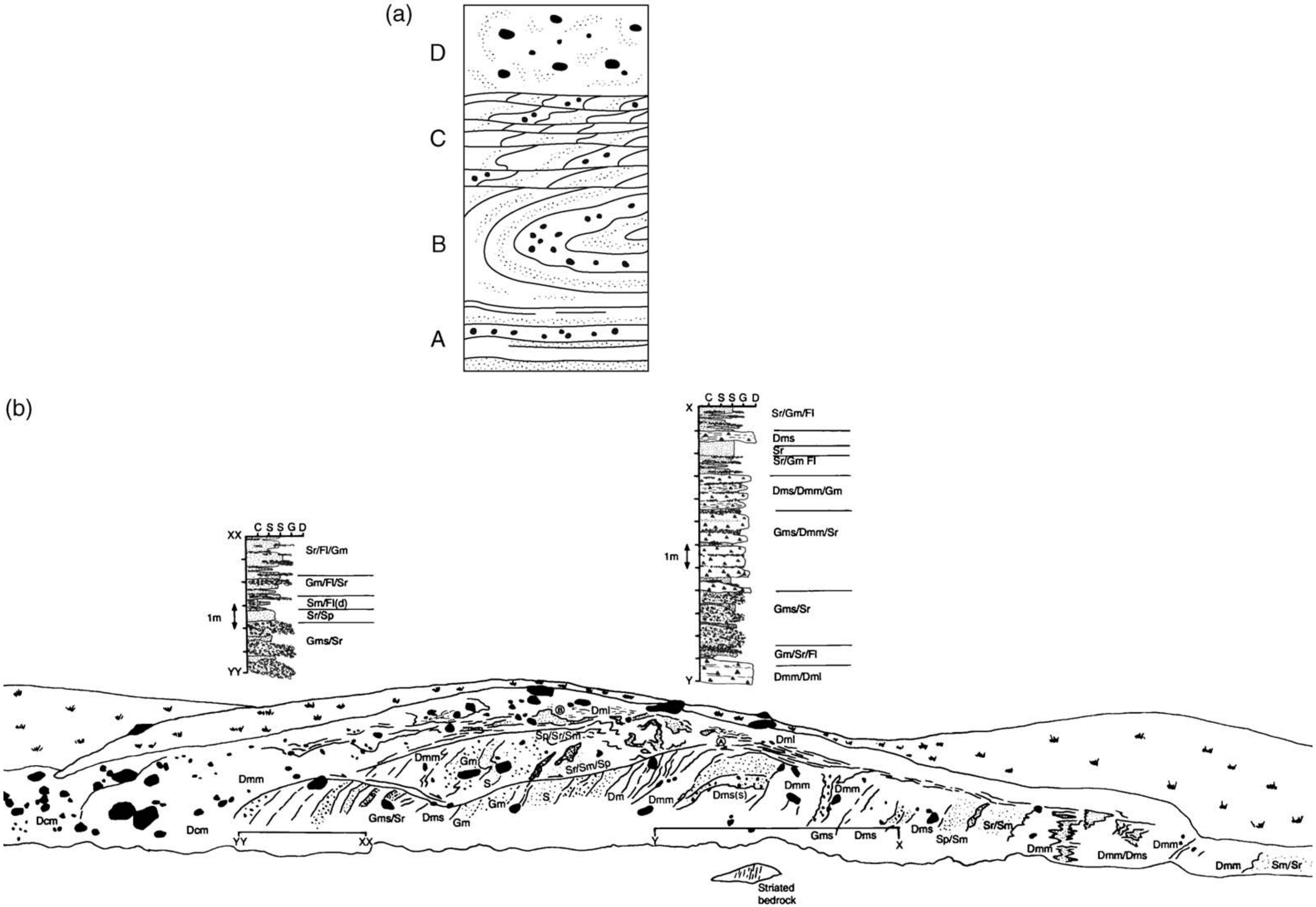


Fig. 25. Glacitectonite terminology and example: a) idealized vertical sequence/continuum of glacially deformed material (from Benn and Evans, 1996, after Banham, 1977). A — undeformed parent material (e.g. stratified sands and gravels); B — Type B glacitectonite with non-penetrative deformation (e.g. folded sands and gravels); C — Type A glacitectonite with penetrative deformation (e.g. complexly folded, faulted, sheared, attenuated and boudinaged sands and gravels); D — laminated or macroscopically massive till with sheared inclusions of sand and gravel (interpreted as a mixture of local glacitectonite and far-travelled glacially transported sediment); b) example of vertical continuum of glacitectonites and subglacial till, Loch Quoich, Scotland (from Evans et al., 1998). Folded glacilacustrine sediments (Type B glacitectonite) are exposed as vertically inclined beds at the base of the exposure (logs record the pre-folded vertical sequence). Type A glacitectonite at the centre of the exposure lies in fault contact with the underlying Type B glacitectonite and is capped by massive to laminated till.

pore water content/pressure will assist deformation and the overprinting of pre-existing structures even at low shear strains. This interpretation is supported by the fact that, as pointed out by van der Wateren et al. (2000), measured strains within subglacially deformed sediments are much lower than expected. Type B glacitectonites (Fig. 25) have undergone non-penetrative deformation. This involves pervasive ductile deformation to small total cumulative strains and so pre-deformational sedimentary structures are still recognizable in the material.

4.5. Comminution till

Elson (1988, p. 85) defines comminution till as:

> Very dense till that appears to have been formed by abrasion of bedrock and the crushing of detritus dragged along underneath the ice, accompanied by a mixing process that results in the incorporation of rock powder produced by abrasion at the till-rock interface into the overlying glacial load (Elson, 1988).

The crushing and pulverizing of bedrock results in the reduction of pore spaces and an increase in inter-particle contacts (Elson, 1988), with a grain size similar to that produced by industrial crushing and grinding (Benn and Evans, 1998). This clearly requires softer bedrock types and the comminution process must be initiated by the initial displacement of bedrock slabs or thrust slices prior to crushing and dis-aggregation, as described by Hiemstra et al. (in press). Although there is widespread evidence that grain crushing, fracturing and attrition occur in the subglacial environment (e.g. Boulton et al., 1974; Haldorsen, 1981; Hooke and Iverson, 1995), direct observation of such processes has mostly been restricted to microscopic studies (e.g. Hiemstra and van der Meer, 1997; Yi Chaolu, 1997). Moreover, there are very few studies that describe comminution tills (e.g. Croot and Sims, 1996; Domack et al., 2001), possibly as a direct consequence of either their rarity and/or the overlap in the definitions of comminution till and glacitectonite. Other terms which are effectively synonymous with comminution till as it is defined above are glaciotectonic breccia (Croot and Sims, 1996) and shear till (Stephan, 1988).

Crucial to the production of comminution till is the liberation of bedrock fragments from the substrate and numerous studies have highlighted the occurrence of bedrock rafts in tills often linked to large-scale glacitectonic structures (e.g. Stalker, 1973; 1976; Sauer, 1978; Ruszczynska-Szenajch, 1987). The soft nature of the bedrock facilitates in situ brecciation, thrusting, shearing and plucking, and also the formation of attenuated or boudinaged till intraclasts. Once liberated, rafts are crushed and thereby contribute to the matrix of subglacial tills (Fig. 26). Previous research has often referred to comminution till as a type of glacitectonite or glacitectonic breccia (e.g. Croot and Sims, 1996) and Hiemstra et al. (in press) propose subsuming the comminution variant fully into the glacitectonite classification because the term glacitectonite covers sediments formed from subglacial reworking of bedrock, both in-situ or as displaced blocks and slabs.

4.6. Deformation till

First introduced by Elson (1961) and generally related to sediment that has undergone strain of sufficient magnitude to change the grain structure, a deformation till is broadly defined as:

> A rock or sediment that has been disaggregated and completely or largely homogenised by shearing in a subglacial deforming layer (Benn and Evans, 1998).

Subglacial tills are commonly massive and lack any obvious macroscopic and/or microscopic evidence of deformation (Fig. 27). However, in the literature these deposits may still be interpreted as deformation tills (or endiamict glacitectonite Banham, 1977; Benn and Evans, 1998) and used as evidence for widespread subglacial deformation. In many studies, the massive appearance of subglacial tills is regarded as evidence for high cumulative strains (e.g. Boulton, 1987; Hart et al., 1990; Benn and Evans, 1996; Evans, 2000b; Boulton et al., 2001). However, as pointed out by van der Wateren et al. (2000), observed finite strains within subglacial sediments are typically much lower than expected. In the case of the Laurentide Ice Sheet, this has led to the development of two opposing views: (1) that the massive tills provide evidence of widespread subglacial deformation (Boulton and Jones, 1979; Alley, 1991); and (2) that they are simply a product of melt-out (Clayton et al., 1989; Ronnert and Mickelson, 1992).

The varying states of preservation of primary sedimentary structures in subglacial tills have been at the centre of many debates concerning their genesis but, rather than preclude a deformation origin, such structures may constitute evidence for depositional/deformational continuums. The concept of a melt-out/deformation continuum has been elucidated by Larsen et al. (2004), who explain similarly strong macrofabrics throughout a thick till sequence in Denmark as the

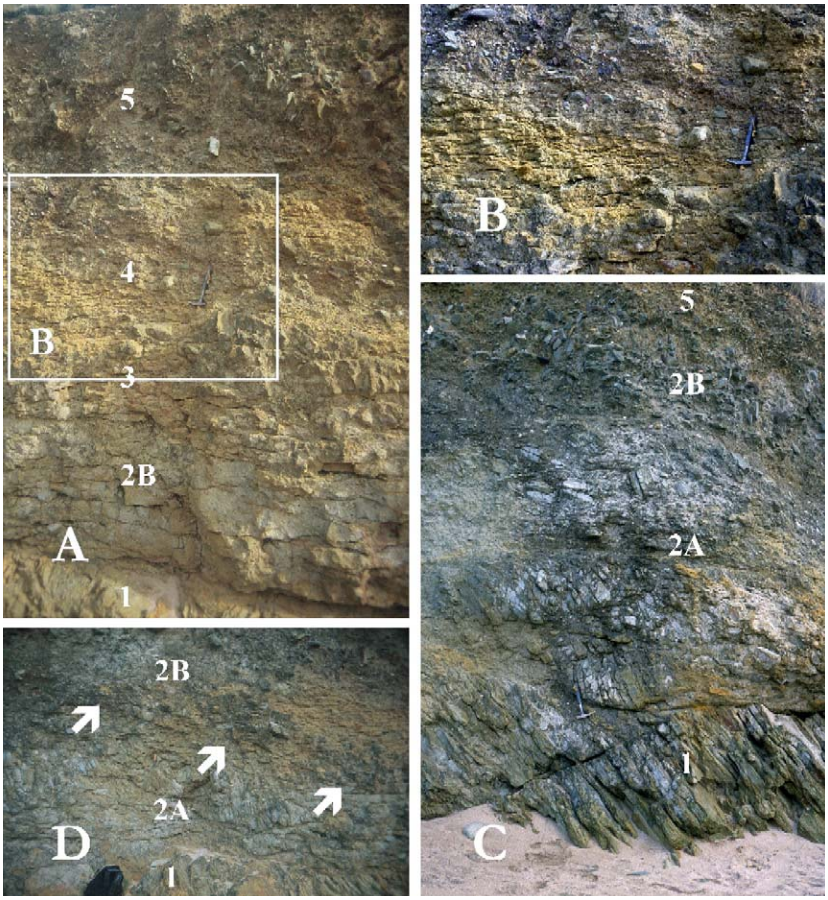


Fig. 26. Glacitectonically thrust and stacked slices of siltstone bedrock grading vertically to subglacial till, representing comminution till production, Clogher Bay, Ireland (from Hiemstra et al., in press): A) the sequence of units 1, 2B, 3, 4 and 5; B) photograph showing the fissile character of unit 4; C) photograph showing sequence of units 1, 2A, 2B and 5; D) photograph showing the sequence of units 1, 2A and 2B in detail. White arrows indicate the contact between sub-unit 2A and 2B. Unit 1 is intact (i.e. undeformed, but jointed) bedded siltstone bedrock. Unit 2 is a bed of deformed siltstone, the deformation signature consisting of straight, parallel and anastomosing fractures interpreted as shear planes. Unit 3 is more heavily deformed, brecciated siltstone in which primary bedrock structures are largely unidentifiable. Unit 4 is a zone of heavily sheared siltstone mixed with diamictic sediment. Unit 5 is a massive, predominantly matrix-supported diamicton (*D*mm) with dispersed clast-supported zones (*D*cm). Vertical changes in the internal characteristics of the stacked slices represent a gradual upward transition from bedrock to subglacially sheared material thereby recording thrusting, stacking, shearing and pulverizing of soft bedrock and its incorporation into the base of a subglacial till layer. This is evident in the destruction of bedrock structures and occurrence of bedrock rafts in unit 2, the complete brecciation of the bedrock in unit 3 and the intermixing of diamicton with erratic clasts and sheared bedrock in unit 4. The introduction of bedrock rafts at the boundary of units 4 and 5 indicates that bedrock continued to be plucked from the bed and plastered on to the stacked slices during the early stages of diamicton deposition. Unit 5 is interpreted as a subglacial till that records the gradual dominance of far-travelled materials over the locally thrust-stacked bedrock.

product of the vertical accretion of subglacial sediment released from the ice base by melting and then deformed in its uppermost layers, thereby preserving soft sediment intraclasts. A similar origin has been proposed for complex till sequences on the Canadian prairies by Evans (1994).

Deformation, by definition, is a change in shape and orientation of an object or volume of rock (or any other material) from an initial to a final state (Passchier and Trouw, 1996). In general, these changes are recorded by the presence of structures such as folds, faults and/or foliations. In the absence of such structures subglacial tills can not unequivocally be interpreted as having been deformed. If a progression from layered, heterogeneous sediment into a deformed homogeneous till can be demonstrated, the term deformation till can be applied (Fig. 25). However, if such a deformation path can not be recognised, the simplest interpretation is that the homogeneous and massive nature of a subglacial till is a primary sedimentary/depositional feature. Consequently, unless evidence can be found in support of such tills having been produced as a result of homogenisation

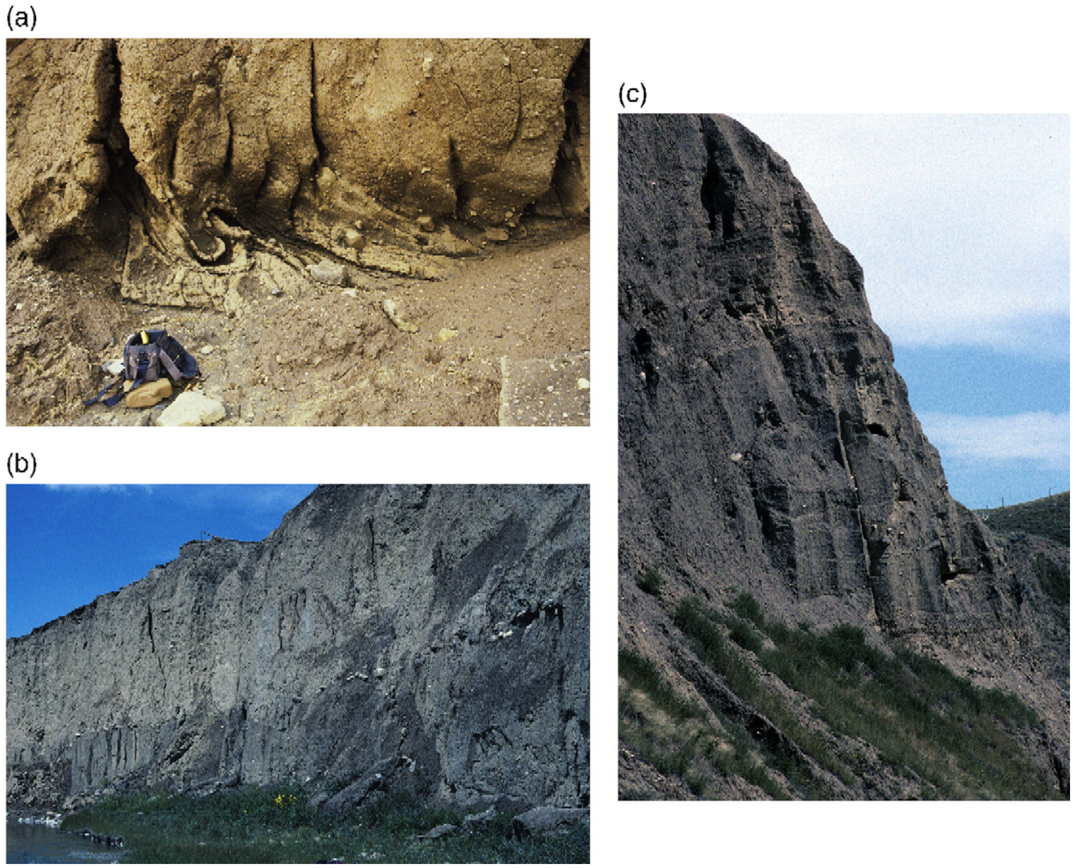


Fig. 27. Examples of diamictic sediments interpreted as deformation till: a) Skipsea Till at Filey, England, clearly showing fold structures due to preferential weathering of sand-rich intra-till wisps. In the absence of such weathering the till appears macroscopically massive; b) multiple till sequence near Milk River, Alberta, Canada, displaying all of the characteristics cited by Alley (1991) as indicative of subglacial deformation; c) intensely folded multiple tills at the Cameron Ranch section in southern Alberta. Each till unit displays textural banding, thereby allowing the identification of strain signature.

during deformation, the term deformation till, with its accompanying genetic connotations, is probably best avoided. At a more fundamental level of sedimentological interpretation, it must be recognized that many of the diagnostic criteria outlined in Table 4 can be produced by iceberg keel ploughing in glacioaqueous environments (e.g. Woodworth-Lynas, 1990; Eyles et al., 2005), highlighting the essential nature of holistic assessments of site specific sedimentology and stratigraphic architecture that avoid over-reliance on deformation structures alone.

The base of deformation tills is often marked by a sharp, erosional boundary with underlying sediments. This boundary may also be marked by slickensided surfaces, suggesting that it is a shear plane. The rheology contrast between the till and the underlying sediment will play an important role in determining whether detachment occurs along this lithological contact. Boulton et al. (2001) propose that such characteristics, as described at the base of tills in northern Germany by Ehlers and Stephan (1979), are indicative of erosion at the base of a deformation till, although Ehlers and Stephan (1979) initially proposed erosion by clasts in the ice base. In contrast, Hooyer and Iverson (2000) suggest that the shear zone between two sediments should be characterized by mixing at the interface. Other types of structure associated with the base of deforming layer tills include incorporated or plucked intraclasts/smudges of underlying sediments and highly attenuated, folded and boudinaged laminae of underlying sediment ingested or cannibalized by the deforming layer (e.g. Boulton, 1987; Hicock and Dreimanis, 1989, 1992a,b; Evans, 2000a). These laminae may be vertically stacked in the till and thereby represent tectonic slices produced during sequential phases of deformation till accumulation (Boulton et al., 2001; Fig. 13). However, the occurrence of such intra-till rafts is not indicative of till deformation per se, their emplacement being a product of subglacial erosion. It has been proposed that large numbers of folding and attenuation events may stretch out glacitectonic laminae to such an extent that the resultant highly strained and homogenized till may appear massive until viewed under the microscope (Boulton, 1987; van der Meer, 1993; Benn and Evans, 1996; Menzies, 2000; Hiemstra and Rijsdijk, 2003; Fig. 28).

In reality, imposing "large numbers of folding or attenuation events" on to a body of rock or sediment is extremely difficult. In the geological record it is typical to see only two or three deformation events. Once a body of rock possesses a well developed fabric this will reactivate or be transposed/overprinted during any subsequent event. Additionally, the clarity of deformation signatures is restricted by strain hardening and consolidation. Once the sediment becomes over consolidated the amount of strain required to deform it increases dramatically and the "memory" of previous deformation events is impossible to erase unless the sediment becomes re-dilated. Deformation will be preferentially partitioned into any adjacent weaker sediment or even the over-riding ice. In thin section the micromorphological evidence of deformation within

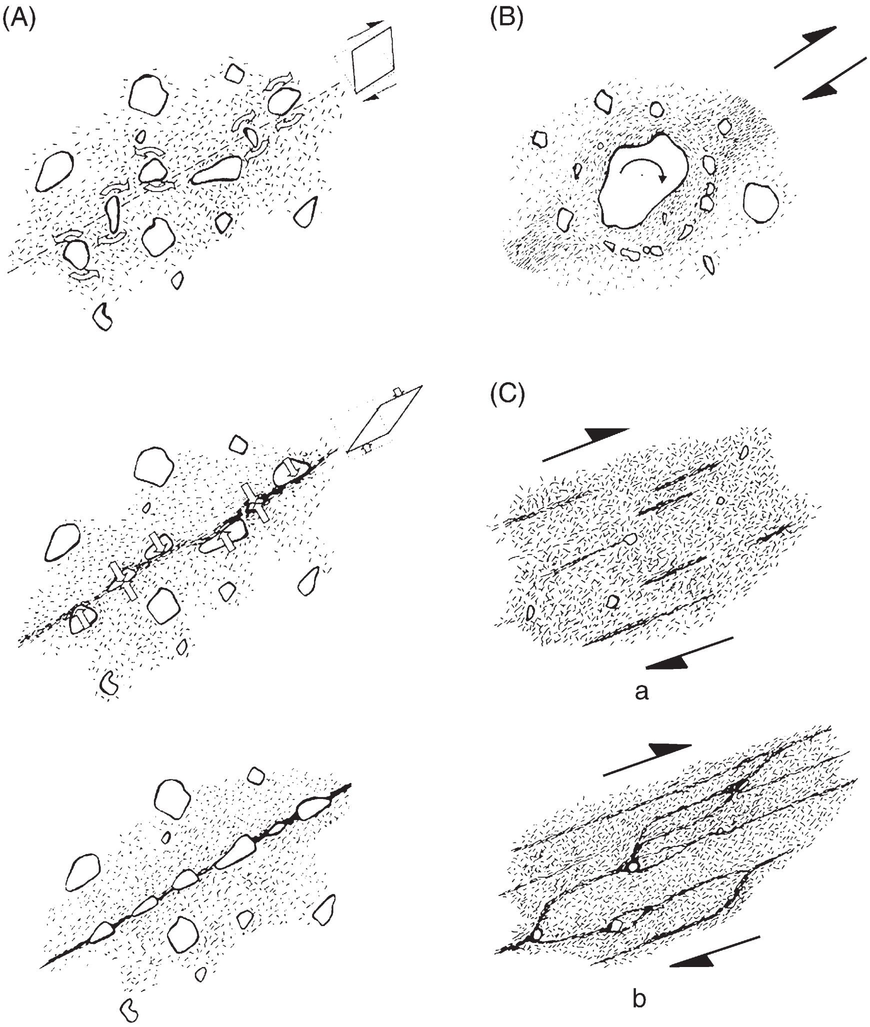


Fig. 28. Micromorphological evidence of artificially induced strain (from Hiemstra and Rijsdijk, 2003): A) schematic illustration of the development (sequentially from top to bottom) of grain lineaments and unidirectional plasmic fabrics. Dashed line in upper sketch represents the position of a developing shear plane. Elongate grains near the shear plane rotate until they are aligned plane-parallel. They also move towards the shear plane due to contraction of the sediment (see strain boxes); B) sketch to illustrate the relationship between unidirectional plasmic fabrics, skelsepic plasmic fabrics and turbate structures; C) schematic diagram to show the development of branching-and-merging characteristics in unistrial plasmic fabrics — short, discontinuous unistrials in "a" grow to form continuous features in "b" and where unistrials meet they split or bifurcate.

subglacial tills, interpreted as deformation till, may also be limited or absent. Many of the features equated with subglacial deformation, such as galaxy or similar rotational structures, have also been described from mass flow deposits. Furthermore the mode of origin of these structures is still a matter of debate.

The large-scale architecture of deformation tills has been theoretically reconstructed by Boulton (1996a,b) based upon the premise that there is a strong coupling between a glacier and its deforming bed. This coupling ensures that erosion or net loss of subglacial sediment occurs in the accumulation area where ice is undergoing acceleration. Conversely, the deformation of subglacial sediments will slow and eventually cease in the ablation zone where ice is decelerating. This produces a pattern of till deposition characterized by till thickening towards the sub-marginal zone of the glacier (Fig. 29). Similarly, retreat phase tills may be superimposed on advance phase tills during glacier recession, the thickness and complexity of till sequences at individual sites being dictated by the recession distance (Boulton 1996a; Fig. 30). Additionally, Boulton and Dobbie (1998) point out that the relative thickness of deformation tills will reflect their rheological properties. Specifically, Coulomb plastic behaviour will initiate low rates of erosion and deposition and therefore produce thin tills. The converse is true for viscous tills. We must also remember that a major control on till thickness is the amount of sediment being supplied and the hardness of the source rocks. Boulton (1996a) proposes that during the advance phase, the deposition/thickening of the deforming layer till involves the vertical migration of the interface between the A and B horizon (Fig. 31). The occurrence of an erosional phase at any one site is marked by the descent in the A–B horizon interface, giving rise to the concentration of clasts at the interface, essentially a clast pavement. Alternatively, the concentration of large clasts at a particular level within a till unit could simply be due to the removal of the matrix of the diamicton by liquefaction; reworking or winnowing of a till surface by the combined effects of subglacial meltwater (canal) flushing and glacier sliding can also isolate larger clasts at the tops of individual till sheets (e.g. Boyce and Eyles, 2000). The pebble and boulder sized clasts would be deposited at the base of the A horizon i.e. on top of the over-consolidated B horizon. Boulton (1996a) proposes that this is a function of a reduced lift force in the low density deforming horizon. If the same site is then subject to retreat phase till deposition then the interface moves upwards and leaves the clast pavement isolated in the till. Consequently, an oscillating glacier margin that has repeatedly readvanced to approximately the same position during a single glacial cycle will produce a thick marginal sequence of subglacial deformation tills often displaying clast pavements. An erosional basin will exist on the up ice sides of such till stacks. These large scale architectural elements are recognized in

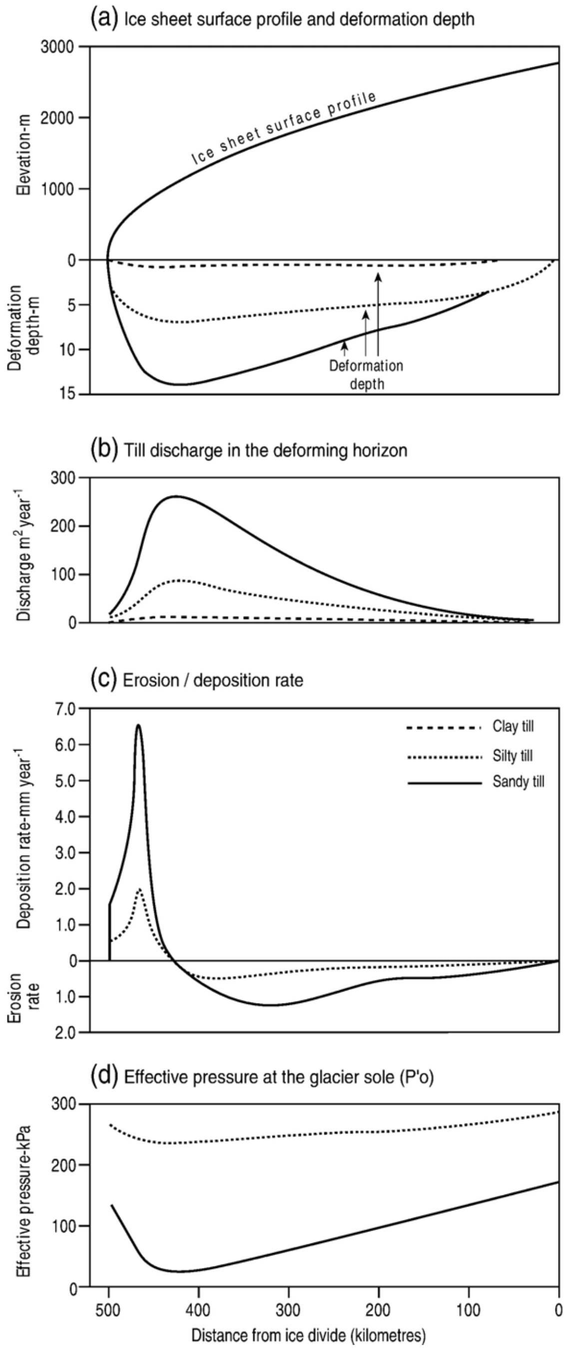


Fig. 29. Theoretical conditions at the base of a steady state glacier underlain by a deformable bed (from Boulton, 1996a).

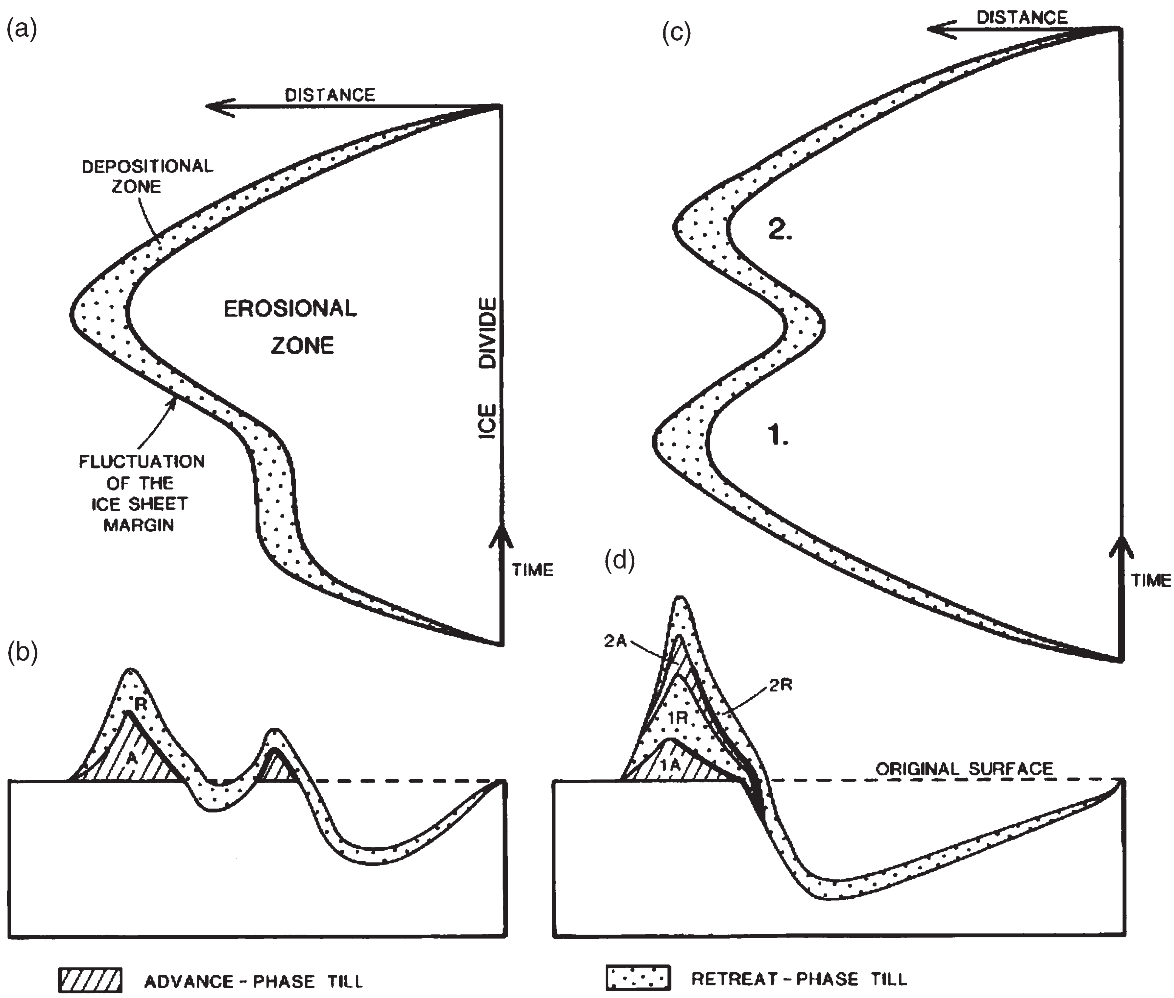


Fig. 30. Schematic time–distance diagram showing the theory of till deposition due to different styles of ice advance and recession (from Boulton, 1996a): a, b) ice margin with prolonged period of stillstand during advance, leading to the incomplete erosion of a substantial advance phase till; c, d) re-advance of an ice margin after initial recession leads to stacking of till units separated by erosion surfaces (thick black lines).

North American and European case studies by Boulton (1996b), Johnson and Hansel (1999), and Evans (2000b).

The marginal thickening model proposed by Boulton (1996b) has been modified in an application to the glacial geology of the southeast coast of Ireland by Evans and Ó Cofaigh (2003). They propose that ice marginal till/glacitectonite thickening is facilitated by the folding and stacking of pre-existing sediment masses, thereby dispensing with the need to imply that the glacier undergoes large numbers of readvances in order to deliver "waves" of till to the ice margin. This, however, does not explain the thickening of massive subglacial tills at glacier margins and it is likely that such till sequences are produced by largely stationary temperate glacier snouts whose high activity indexes and erosional capacities effectively transport large volumes of subglacial sediment from an up ice erosional zone to an outer depositional zone of a few hundred metres width (Boulton, 1987). The mode of subglacial transport, as discussed above, is difficult to ascertain but based upon our present understanding of subglacial processes is likely to be a function of sliding, ploughing and deformation, each process being capable of net down ice displacement of basal sediment. Because the transport ceases in the sub-marginal zone of such glaciers and englacial debris is released by melt-out, the subglacial debris layer thickens. This thickening, together with the increase in meltwater produced during the melt season elevates porewater pressures, often producing a viscous slurry, and initiates ductile deformation (e.g. Lian and Hicock,

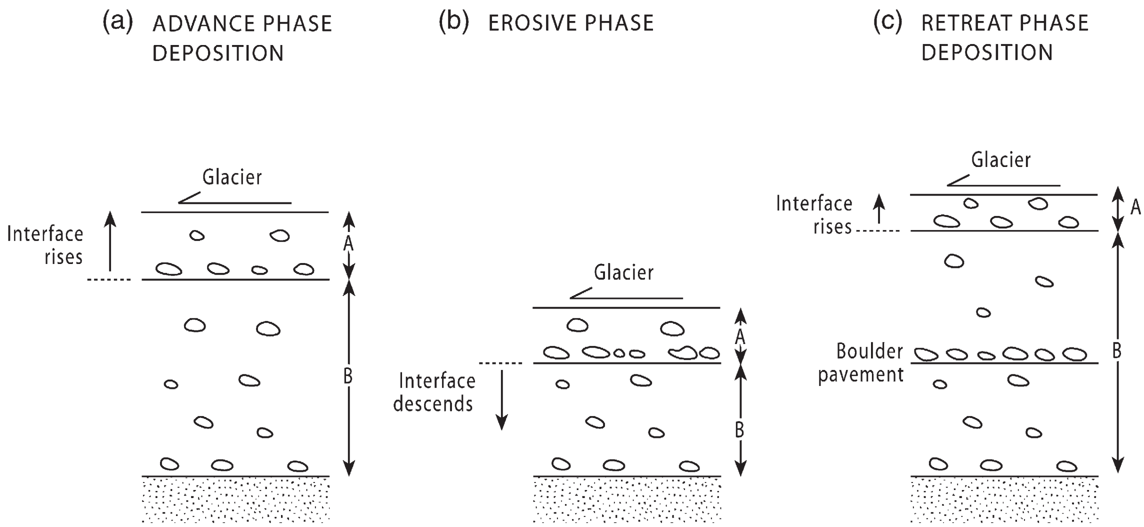


Fig. 31. Theoretical model of clast pavement production in subglacial till (from Boulton, 1996a). During the advance phase (a), the interface between the till A and B horizons rises and no clasts become concentrated. As the glacier erodes its bed (b), the interface descends and thereby concentrates clasts due to the reduced lifting force of the A horizon. During recession, the till again thickens near the glacier margin, causing the clast pavement to be isolated at the former location of the A/B interface.

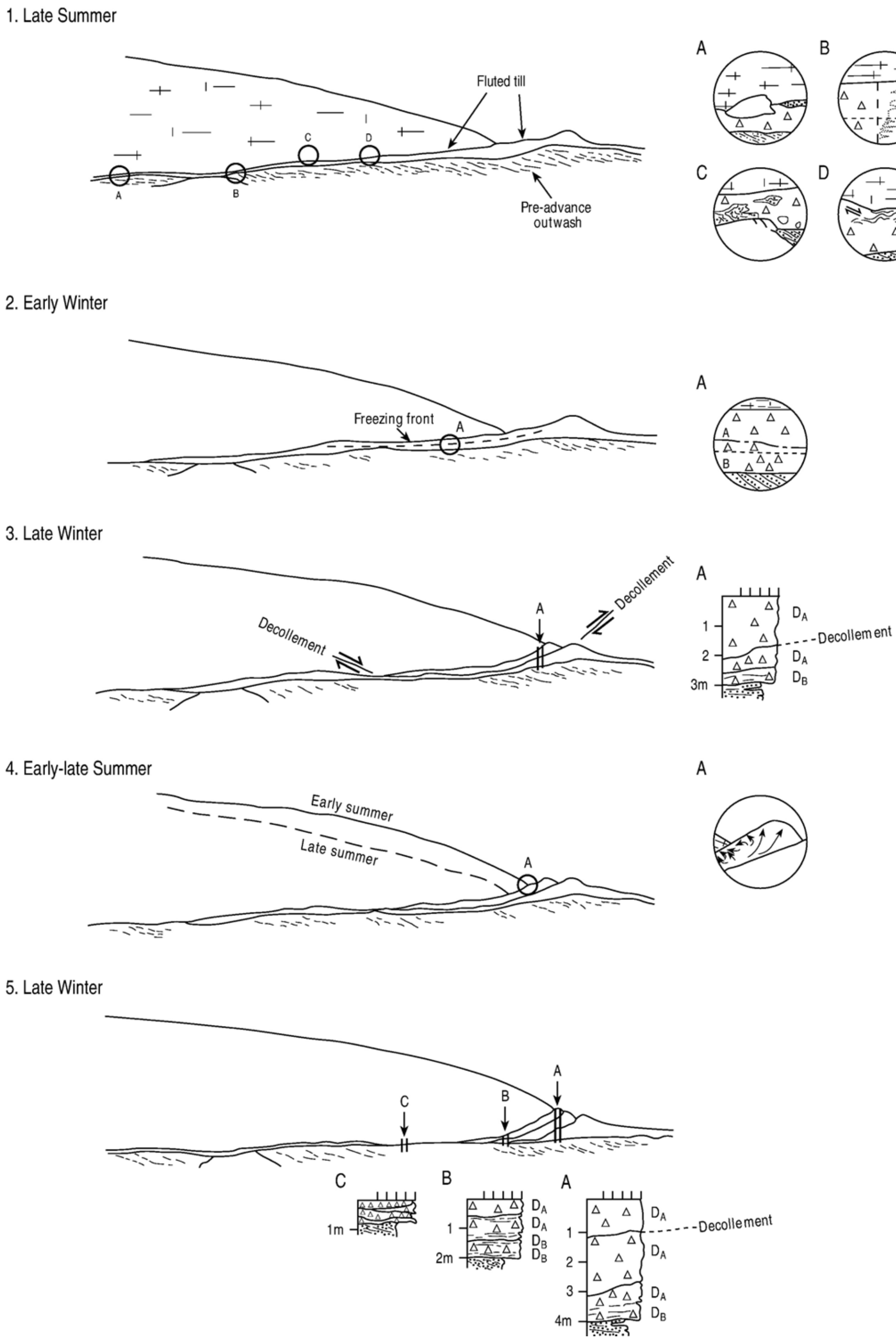
2000). This is manifest in ice-marginal squeezing at the margins of Icelandic glaciers like Breiðamerkurjökull (Price, 1970; Evans and Twigg, 2002). During the winter the tills are likely to freeze on to the thin glacier snout and be transported short distances before melt-out in the summer (Fig. 32). Each till slice or stack produced in such ice marginal settings is therefore likely to be a seasonal feature and will construct a large end moraine if the glacier remains stationary (Krüger, 1996; Evans and Twigg, 2002; Evans and Hiemstra, 2005). Moreover, deformation is only partly responsible for the emplacement of the till slices. A change in subglacial till transport mode may take place also further up ice where deforming sediments are frozen by regelation through the bed and effectively become basal debris-rich ice for at least part of their evolutionary cycle (Iverson, 1993; Iverson and Semmens, 1995; Iverson and Souchez, 1996; Iverson, 2000).

4.7. Lee-side cavity-fill deposits

The infilling of lee-side cavities at the beds of glaciers with rigid substrates produces sediments with a wide range of sedimentary characteristics. The processes of mass flowage, fall, melt-out and fluvial reworking are all active in such cavities (Fig. 17) and therefore the resultant cavity fills form down ice thinning, wedge-shaped masses of massive to crudely stratified diamictons with steeply dipping lenses of water-sorted sediments. Clasts are striated and possess a strong down-valley dipping fabric (Levson and Rutter, 1986, 1989a,b), although other characteristics of ploughing and lodgement are absent. Hillefors (1973) referred to such sediments as "lee-side tills", although much of the material has been emplaced by non-glacial processes. As cavities may close over the period that a cavity fill is deposited, the sediment is subject to reworking and/or overprinting by the subglacial processes of ploughing, lodgement,

Fig. 32. Schematic model of till slab emplacement over several seasonal cycles (after Evans and Hiemstra, 2005). The codes D_A and D_B refer to the A and B horizons of the deforming till layer and follow the classification of Benn and Evans (1996): 1) situation in late summer at typical Icelandic glacier snout where subglacial processes include lodgement and sliding (A), bedrock and sediment plucking (B), subglacial deformation (C) and ice keel ploughing (D) in a temporally and spatially evolving process mosaic; 2) during early winter, the thin part of the glacier snout freezes on to part of the subglacial till. The till slab that freezes on to the ice sole is likely to be from the more porous A horizon (A); 3) the later winter readvance initiates failure along a decollement plane within the A horizon or at the junction with the more compact B horizon, resulting in the carriage of A horizon till onto the proximal side of the previous years push moraine; 4) in the early summer, the melt-out of the till slab (A) initiates porewater migration, water escape and sediment flow (small arrows) and sediment extrusion due to glaciostatic and glaciodynamic stresses; 5) the late summer situation is again followed by winter freeze-on and marginal stacking of subglacial till produced by the reworking of existing subglacial sediments and fresh materials advected to sub-marginal locations from up-ice. Repeated reworking of the thin end of sub-marginal till wedges produces overprinted strain signatures and clast pavements.

glacitectonic disruption and deformation. This implies that the apparent stratification in some glacitectonites and deformation tills may be imparted by the re-mobilization of cavity-fills during the deformation process. Levson and Rutter (1986, 1989a,b) record the truncation of lee-side cavity fills by subglacial tills that they interpret as lodgement and melt-out in origin. As lee-side cavity fills require a rigid, uneven bed, they are best preserved on the down ice sides of roches moutonnees, forming crag and tail landforms (Benn and Evans, 1998).



5. A model of till development in the subglacial environment

5.1. Rationale

It is clear from the above description that problems arise when theoretical models are applied to subglacial deposits in the geological record. If a deforming bed was the major process responsible for forward motion of a glacier, as suggested by Boulton and Hindmarsh (1987) amongst others, then evidence for deformation within subglacial tills should be widely apparent. However, in reality macroscopically massive subglacial tills are common and may even overlie undeformed sediments. Consequently, the concept of a deforming bed being present everywhere below soft-bedded glaciers is more difficult to sustain. Any model of the subglacial environment allowing displacement of the glacier over the underlying sedimentary sequence needs to take field observations into account. Based upon all of the discussion presented so far in this paper can we identify some form of consensus about subglacial till production?

It is widely acknowledged that subglacial materials are derived from melt-out from the ice base, quarrying and abrasion of hard rock surfaces and the excavation/liberation of rafts or soft clasts from weak or unlithified substrates through the processes of comminution (including quarrying, crushing and pulverizing) and ploughing. To this may be added the process of substrate folding followed by pinching, boudinage and attenuation of folded strata in deforming layers. Sediment is also reworked cyclically in water films and canals at the ice-sediment interface or within the till. Subglacial deformation is no longer controversial but is regarded as a process that co-exists or switches with sliding, freeze-on and melt-out on a spatial and temporal continuum. Although existing models of subglacial till vary in detail and some clear contradiction is evident, they all agree that subglacial materials will only undergo deformation when the yield stress/critical shear stress or critical shear strength of the sediment has been exceeded. This can be achieved by either increasing the magnitude of the shear stress applied by the ice or, alternatively, weakening the sediment. Deformation takes place largely in the upper few metres of a subglacial material and this can be partitioned according to the rheological properties of the substrate. In soft substrates, the effectiveness of the excavation processes and the sediment deformation history is reflected at any one site in the total strain signature, manifest in a range of subglacial sediment types from glacitectonites to laminated and macroscopically massive tills. The latter are often cited as the product of deformation to cumulatively high strains, but what do we know about the processes involved?

To answer this question it is appropriate to focus on the benchmark study at Breiðamerkurjökull, Iceland, where the upper 0.5 m of the subglacial till has a very low density, high porosity and high water content (Boulton and Hindmarsh, 1987; Benn, 1995). These characteristics are believed to be typical of many subglacial environments, with most deformation having occurred whilst the sediments were saturated with water (Boulton and Hindmarsh, 1987; Boulton, 1996a). A high water content is believed to result in a possible weakening of electrostatic bonds and an increase in the distance between the component clastic grains and the volume of the sediment. This has the effect of leading to a decrease in both the cohesion and frictional strength of the sediment. In contrast, with a low water content, pore water tension may actually add to the frictional strength, in effect making the sediment more competent and resistant to deformation. The weakening of the sediment due to high pore water content may explain why observed finite shear strains are typically much lower than expected. The low density and high porosity of subglacial sediments is attributed to a volume increase or dilation of the sediment which occurs during shear (Smalley and Unwin, 1968; Alley, 1991). An increase in dilation will, in effect, allow the component grains of the sediment to move past each other more easily during shear (Murray and Dowdeswell, 1992). Alley (1991) concluded that a critical strain rate has to be maintained to sustain dilation, if the rate falls below this level the sediment will collapse leading to an increase in shear strength.

Based upon the above, all subglacial tills should theoretically show at least some evidence of deformation. However, the massive nature of many subglacial tills testifies that this is not the case. An important factor which appears to have been over looked in previous models is that water saturation can lead to the eventual liquefaction of the sediment, particularly where subglacial drainage is poor and/or impeded by the presence of low permeability layers (e.g. clay-rich beds). An important point to be made here is that a dilated or liquefied granular material will not take up solid state deformation (c.f. van der Wateren et al., 2000). The response of any dilated or liquefied material to an applied shear stress is to flow rather than deform. Folding, faulting or foliation development will only occur when a coherent deformable framework, here referred to as a till-matrix framework, begins to develop as the pore water content/pressure falls and the sediment goes from behaving as a plastic or liquefied material into a semi-solid and finally solid state. Dilation of the sediment, therefore, rather than reflecting strain rate, as proposed by Alley (1991), is more likely to occur at a critical value of pore water pressure (Fig. 33). As this point is reached expansion of the sediment occurs (volume increase) dramatically lowering the cohesive and frictional strength of the sediment. Expansion of the sediment precludes the formation of a till-matrix framework and reduces the ice overburden pressure allowing further expansion/dilation of the sediment. The overall effect would be like a 'hydrogeological jack' lifting the overlying ice and reducing friction between the glacier and its underlying bed. Pore water pressure must, however, be lower than the confining pressure of the overlying ice and cohesive strength of the underlying sediment, otherwise catastrophic failure of the ice (accompanied by escape of the liquefied sediment) and/or hydrofracturing of the subglacial sedimentary pile will occur.

The dilated sediment should represent a major zone of weakness within the subglacial environment and provide a focus for movement of the overlying glacier. Displacement within this 'active zone' may occur as a result of either laminar or, possibly, turbulent flow within the dilated till, the latter behaving like a viscous fluid rather than a solid (Fig. 34); this situation effectively produces a hyperconcentrated flow and raises questions about the use of the term "till" in such cases. The critical pore water pressure must be maintained for ice movement to continue. Small-and large-scale fluctuations (e.g. diurnal, annual) in pore water pressure/content of the sediments coupled with changes in the efficiency of subglacial drainage means that dilation cannot be maintained. Fluctuations in pore water content and pressure means that the thickness of the 'active zone' within the till should also vary, from zero up to a potential maximum thickness as defined by the total depth of the sedimentary pile. This variation in the thickness of the dilated layer may exert a control on the amount and rate of ice movement. During periods of low water pressure or increased subglacial drainage the increase in shear strength of the till should result in a deceleration and/or retardation of ice movement. The retardation of glacier

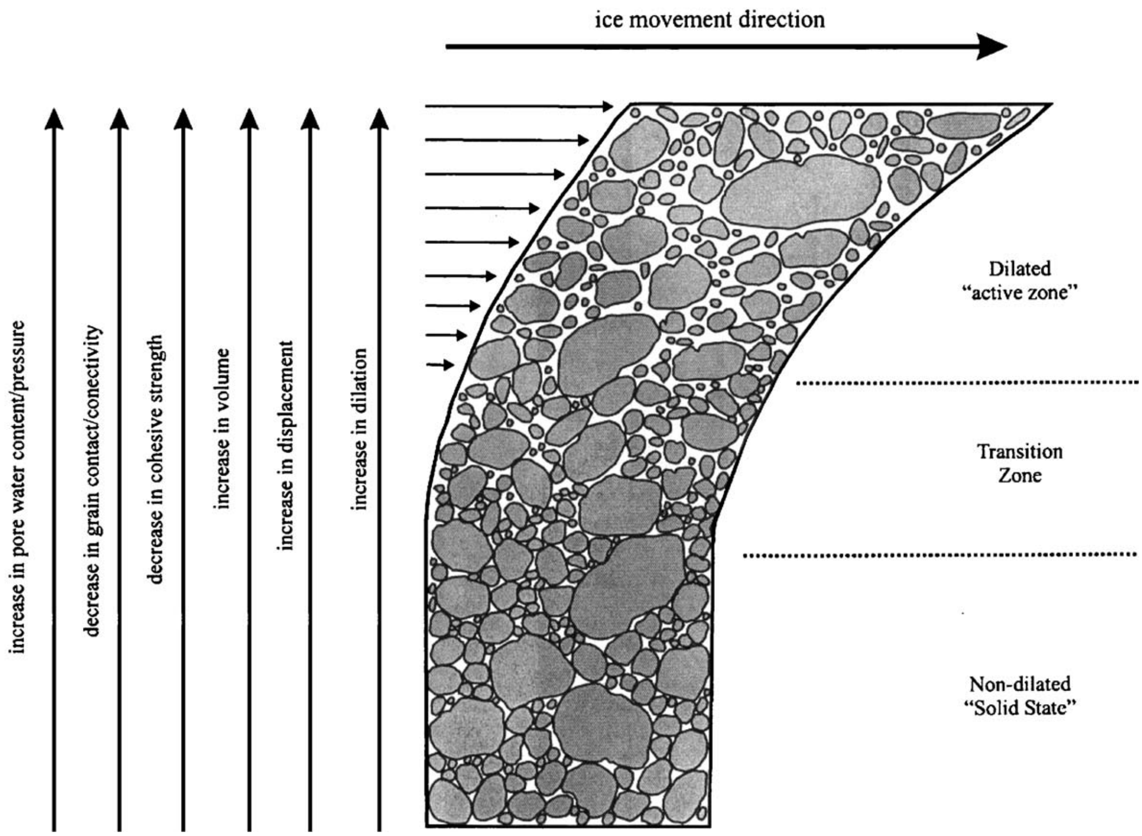


Fig. 33. Simplified diagram portraying the zonation of a relatively homogeneous subglacially deforming material and its relationship to dilation, displacement, sediment volume, cohesive strength, connectivity and porewater pressure.

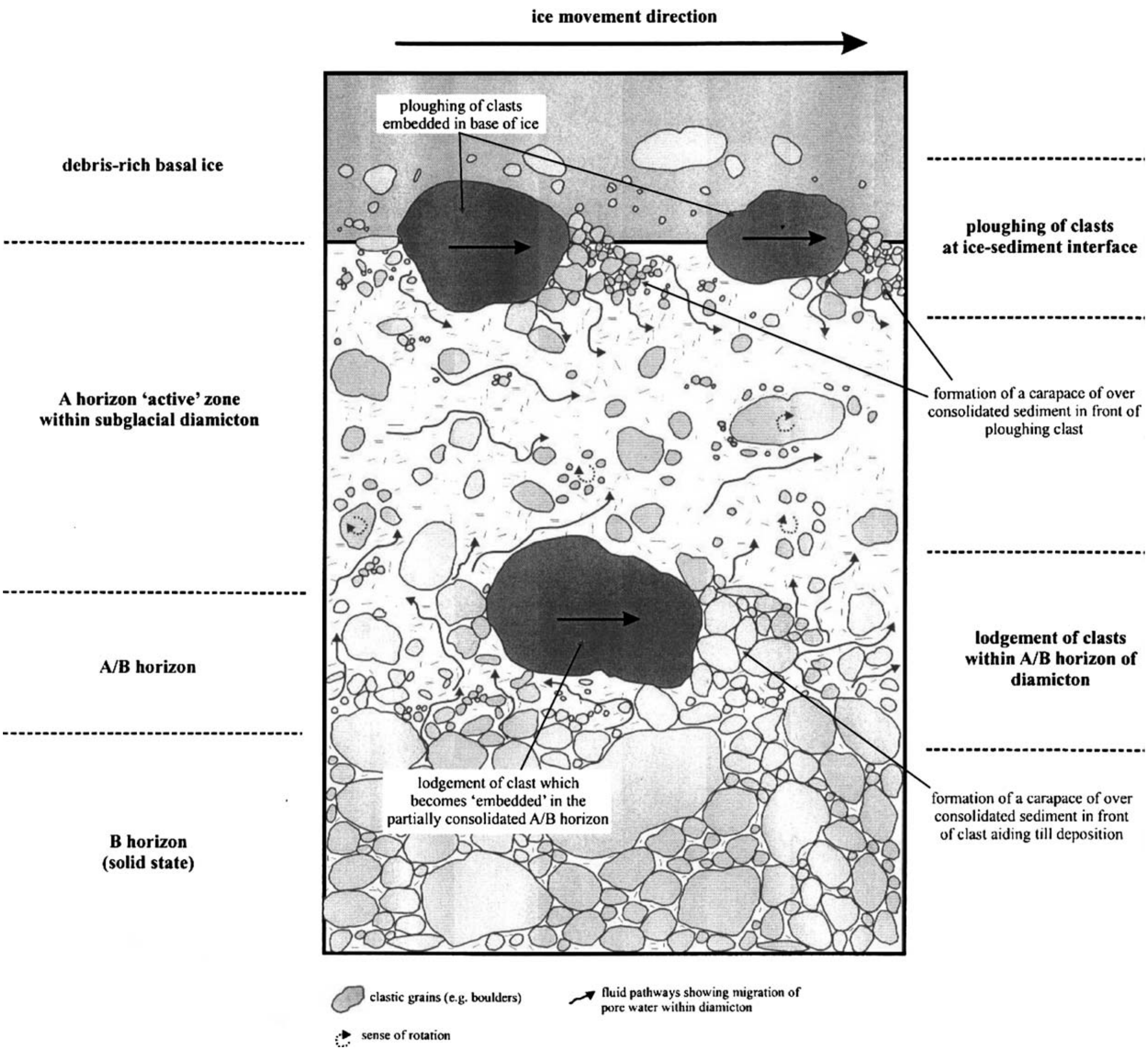


Fig. 34. Characteristics of the subglacial deforming layer beneath moving debris-rich basal ice. The dilated A horizon is regarded as an "active" zone where wide fluid pathways allow porewater to migrate within the diamicton and displacement occurs as a result of either laminar or turbulent flow. Note that ploughing and lodgement take place at the boundaries of this active zone. The A/B horizon represents the transition zone depicted in Fig. 33.

ice movement has always represented a fundamental problem for other theoretical models as they should all lead to essentially continuous displacement. The fluctuation between essentially solid and liquid states should lead to a 'stick-slip' style of movement (c.f. Fischer et al., 1999). Lateral variations in subglacial conditions (e.g. water content, pore water pressure, drainage efficiency) means that this style of movement should be repeated across the sole of the glacier. The result should be that in one area the glacier will be moving, whereas in an adjacent area it may be essentially stationary. The glacier can, therefore, be thought of as 'shuffling' forward. More constant or even rapid ice movement may reflect more uniform subglacial conditions possibly even extending across the whole width of the glacier. The areas of active movement reflecting dilated sediment could either take the form of isolated patches or form a more coherent network (Fig. 35). However, with very high pore water contents a water-rich zone may develop at the ice-sediment interface leading to decoupling of the glacier from its bed, in turn leading to more rapid movement.

Although the dilated sediment should represent a zone of maximum displacement the resultant till should/could be massive, due to the fact that this layer/zone lacks a coherent deformable framework. Any observed

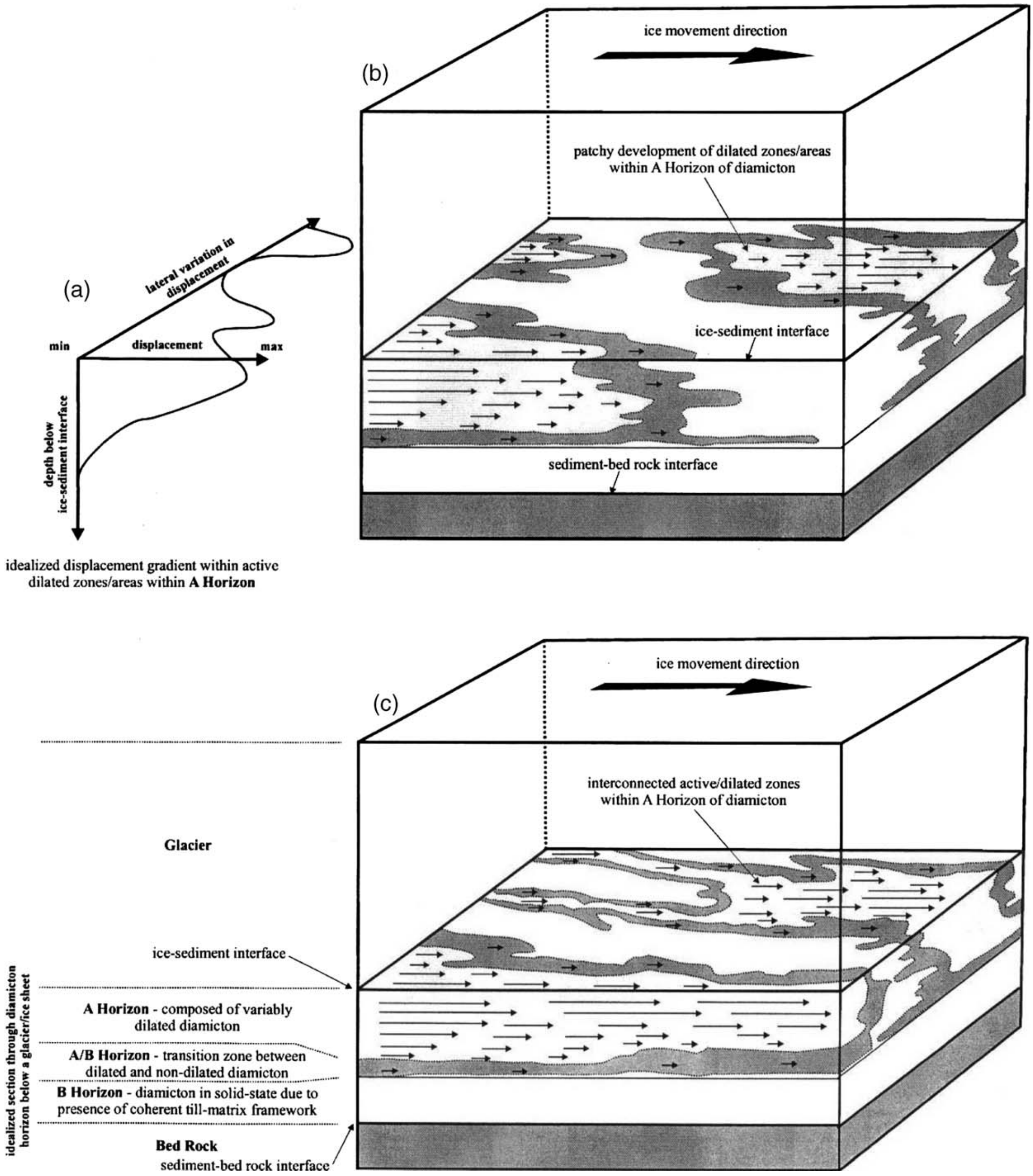


Fig. 35. Schematic diagram portraying the theoretical development of areas of active movement at the ice-bed interface due to dilating subglacial sediment. This takes place either in isolated patches (a and b) or as a more coherent network of interconnected zones (c). The length of the arrows reflects the relative displacement magnitude throughout the deforming sediment due to lateral variations in subglacial conditions (e.g. water content, pore water pressure, drainage efficiency). The net effect is that one area of the glacier bed will be moving, whereas in an adjacent area it may be essentially stationary. Note that the A horizon is not a tabular zone stretching across the whole glacier bed.

deformation would, therefore, probably reflect a relatively late phase that occurred when most of the pore water had been expelled, or record a much later, totally separate deformation event (e.g. proglacial deformation during active glacier retreat). Any earlier phases of deformation may have been largely overprinted as the sediment underwent renewed dilation. The presence of a dilated or even liquefied till layer would also reduce or even prevent transmission of the simple shear component of deformation, produced by the motion of the overlying ice, into the underlying sediments. Deformation, if any, at this relatively deeper structural level within the subglacial sedimentary sequence would be dominated by compression (orthogonal to bedding) or layer-parallel extension occurring in response to the ice overburden. However, during periods when the sediment is in a non-dilated/solid state (Table 1) a component of simple shear should/could be translated into the underlying sediments leading to the observed thrusting/folding at a deeper level within the subglacial sedimentary pile. Consequently, deformation should be expected to be partitioned to varying degrees throughout the substrate over time. A cumulative displacement profile through a subglacial till may therefore be more complex in detail than a simple vertical decrease in displacement as portrayed in the Breiðamerkurjökull case study (Fig. 36).

5.2. Formation of a till-matrix framework

Subglacial solid state deformation of the active till layer will only occur when a coherent till-matrix framework begins to develop as pore water pressure falls. Consequently, formation of such a framework accompanies dewatering and a change from dilated (plastic or liquid) to collapsed (semi-solid or solid) state (see Table 1).

At Breiðamerkurjökull the subglacial till can be divided into two horizons (Boulton and Hindmarsh, 1987; Benn, 1995). The upper A horizon of the till has a low shear strength and a porous, bubbly texture, but is structurally massive. In contrast, the lower B horizon has a higher shear strength, is compact and has a fissile, platy structure. The void ratios decrease downward through the till from *c*. 0.59 in the A horizon down to *c*. 0.45 in the lower B horizon (Benn, 1995). Evidence for the presence of A and B horizons has also been recognised within recent Icelandic subglacial tills (e.g. Benn, 1995; Evans, 2000a,b; Evans and Twigg, 2002). Consequently, the development of this bipartite internal stratigraphy may be considered to be the result of a commonly occurring subglacial process at least in the contemporary glacier snouts of Iceland.

The proposed 'active' or dilated layer may be largely confined to the A horizon in the upper part of the subglacial till, primarily as a result of an increase in the normal stress downward due to an increase in the load of the overlying ice (Fig. 37). This increase in the normal stress downward would require an even greater increase in the critical pore water pressure for dilation to occur. As a consequence of this, with increasing depth the sediment will begin to collapse leading to dewatering and the development of a till-matrix framework. Dewatering and collapse of the dilated layer may also

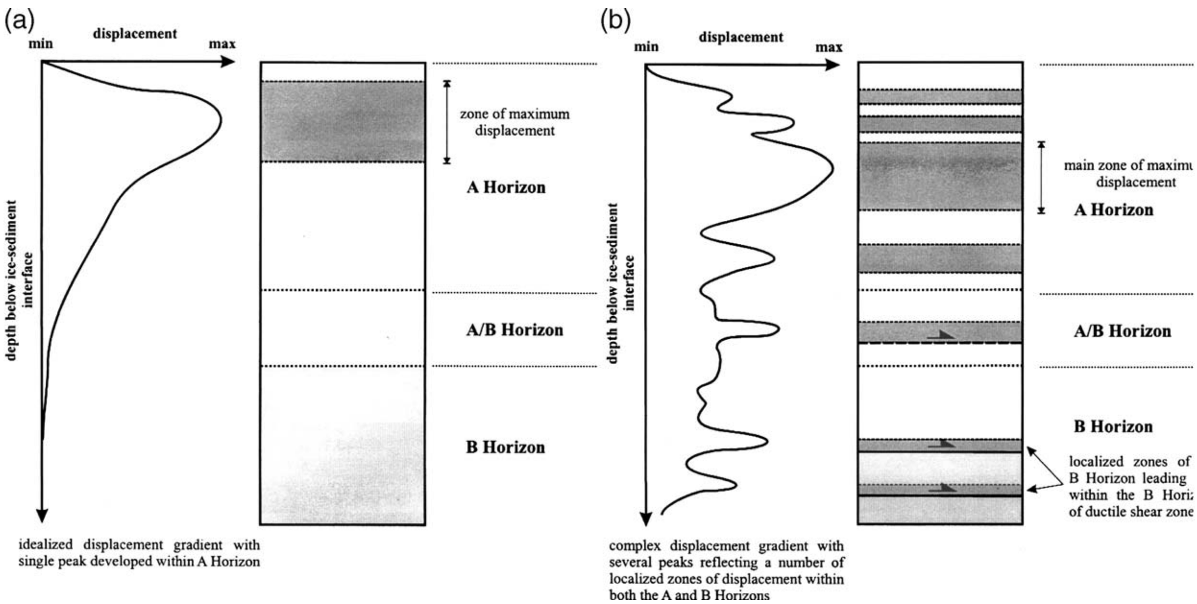


Fig. 36. Theoretical cumulative displacement curves through subglacially deforming till showing (left) a simple vertical decrease in displacement as portrayed in the Breiðamerkurjökull, case study (but incorporating field evidence of maximum displacements at depth in the till) and (right) complex curve depicting multiple failure loci due to deformation partitioning.

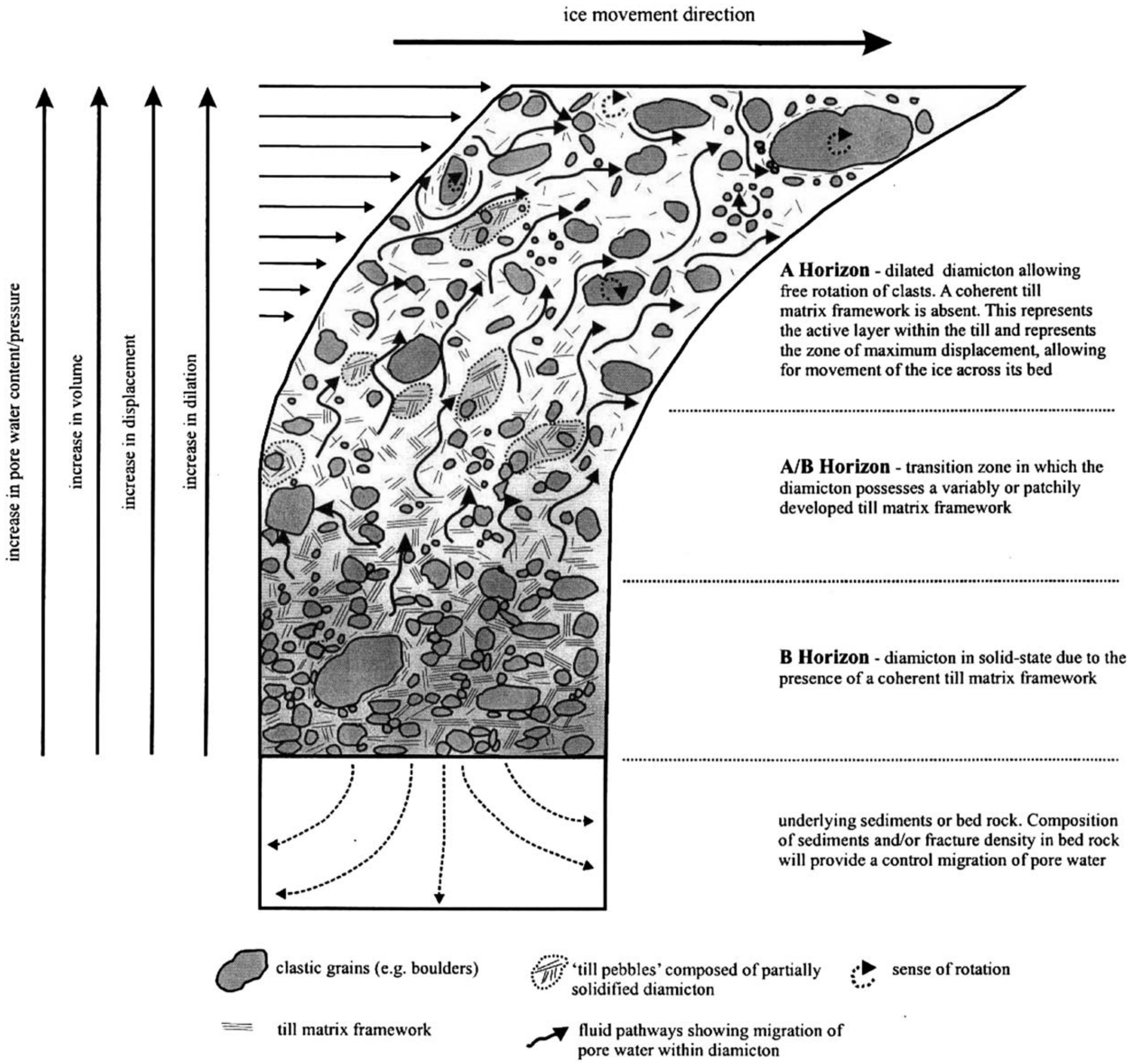


Fig. 37. Idealized reconstruction of the subglacial deforming till layer and the development of porewater migration pathways, till-matrix framework and till pebbles and their relationship to horizon development and geotechnical properties depicted in Fig. 33.

occur due to a fall in pore water pressure and/or increase in subglacial drainage. A till-matrix framework will begin to develop as dilation decreases, leading to a rise in inter-granular contact within the till, reflected in a fall in porosity and increase in density. As the sediment continues to collapse the rigidity of the framework increases as even more grains come into contact. This has the result of increasing the frictional strength of the till. As the sediment continues to dewater, porewater tension between clastic grains may lead to a further increase in till cohesion. The consequence of this process is that the amount of displacement accommodated by the till will decrease, solidification will occur and the sediment may begin to undergo solid state deformation. In an ideal situation the till-matrix framework will become progressively more developed downward through the till. The overall effect would be the deposition or accretion of a layer of solid till at its base (i.e. the B horizon) with a transition zone (the A/B horizon) separating the solid B horizon till from the overlying active A horizon (Figs. 34 and 37). In clay-rich tills the electrostatic forces between the charged clay particles may result in a rapid increase in till-matrix framework rigidity as a critical level of porosity is reached. This may, in theory, result in the rapid solidification and a relatively sharp boundary between 'dilated and 'solid' state till layers (i.e. a narrow A/B transition zone). If rapid solidification occurred throughout the dilated/active layer it may cause a locking of the system and potentially the localized cessation of movement of the glacier bed.

In theory, as the till-matrix framework begins to develop the sediment would begin to undergo solid state deformation. However, in the initial stages of development of the framework, any applied shear stress may result in failure and 'shear' induced re-liquefaction of the till. Once the framework has reached a critical point in connectivity between the grains, hence greater rigidity, the till may begin to deform (e.g. fold), even though it is not fully solidified (c.f. development of pre-full crystallisation fabrics in igneous rocks). If deformation does not occur, then the massive structure indicative of the originally dilated till will be preserved. This interpretation is supported by the preservation of massive A horizon subglacial tills in the geological record. Where deformation does occur, the framework will begin to distort (ductile deformation) or collapse resulting in further expulsion of pore water and, as a consequence, an increase in the rigidity of the framework. The expelled pore water may either drain into the underlying sediment or escape into the overlying active till layer. Where this layer is maintained, deformation or collapse of the framework would be mainly driven by the weight of the ice overburden. Framework collapse would be accompanied by clast rotation resulting in shape alignment of elongate, low sphericity grains, and the onset of foliation development within the till. As the till-matrix framework continues to form and collapse the intensity of the essentially bedding-parallel foliation will increase. The result will be the formation of the compact, platy fissility observed in the till B horizon. In clay-rich tills this foliation may also be represented by a plasmic fabric within the matrix. During unloading of the till as the glacier retreats this bedding-parallel fissility may be reactivated to form horizontal fractures within the till (Fig. 38).

The progressive development of the till-matrix framework will lead to an increase in the shear strength of the till. The collapse of the framework will eventually lead to deformation induced over-consolidation and

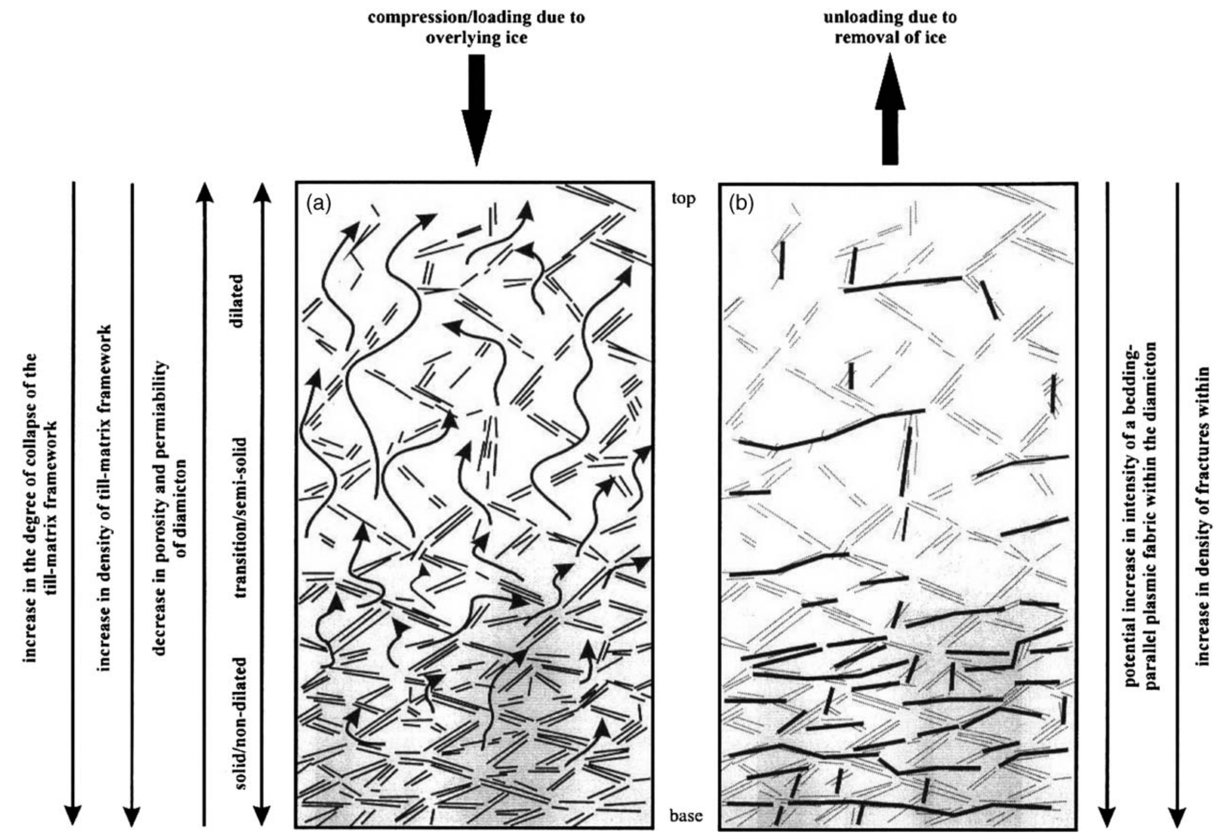


Fig. 38. Conceptual diagram to convey the impact of dilatancy on framework development in tills. Compression/loading (a) leads to an increase in density of the till-matrix framework with depth. Unloading (b) leads to the increase in intensity of bedding-parallel structures with depth.

strain hardening of the till B horizon. If the applied shear stress is high enough, the recently formed foliation may be folded (ductile deformation). However, if the strain rate is too high, failure (brittle deformation) may occur resulting in faulting, including displacement along the B horizon foliation surfaces.

In situations were till-matrix framework formation is accompanied by the dissipation of the active till layer it is possible that an increased component of simple-shear deformation may be transmitted into the underlying sediment. Consequently, asymmetrical shear related foliations (e.g. S–C fabrics, shear bands, Riedel shears, extensional crenulations, see Passchier and Trouw, 1996) and folds will be developed, recording the formation of a subglacial shear zone (van der Wateren et al., 2000).

In the proposed fluid flow model for the formation of massive subglacial tills and glacier displacement, lodgement will not occur until the till begins to solidify. As the till-matrix framework begins to develop the frictional force exerted on the clast will increase until a point where the moving clast will become 'locked' into the solidified till. During the final stages of movement, the force of the clast impacting into the developing till-matrix framework will lead to the increased collapse of this framework. This will lead to a slight increase in dewatering and localised solidification of the diamicton immediately in front of the clast and the development of a prow of sediment. The overall effect will be to speed up/assist the lodgement process.

5.3. Variation in pore water pressure during till-matrix framework development

Studies made of modern subglacial environments have shown that pore water pressure and content varies on a number of scales (see Clarke, 2005 for a review). These fluctuations will have a profound effect on the developing till-matrix framework. An increase in pore water pressure or content within the active zone of a partially formed till-matrix framework could lead to a re-inflation/dilation and eventual dissipation of this framework. This would have the effect of widening the active later, terminating till deposition and potentially resulting in the 'detachment' of the A horizon from the underlying B horizon. It is also possible that renewed fluid flow within the active A horizon may even lead to erosion of the B horizon. If preserved this could take the form of either a sharp planar contact ('detachment') or an irregular erosional boundary between the massive A horizon and underlying foliated, over-consolidated B horizon. Alternatively, a till may contain within it, or overlie, impermeable sediments (e.g. clay) or bed rock. In such a situation, the restriction on drainage efficiency may result in a further increase in pore water pressure exceeding the cohesive strength of the till. This would lead to liquefaction and either the decoupling of the glacier from its bed and/or hydrofracturing of the over-consolidated B horizon, the underlying sediments or even bedrock.

As pore water pressure begins to fall the till-matrix framework would once again begin to develop, followed by the deposition/accretion of a second layer of B horizon till. The repeated fluctuation in pore water pressure would result in the accretion of several layers of variably deformed B horizon till separated by planar (detachment) or erosion surfaces, underlying a single layer of massive A horizon till. This polyphase sequence is probably a more realistic model of B horizon till deposition and deformation, rather than a single continuous accretionary process.

5.4. Till composition

In many theoretical models, subglacial till is largely treated as if it were compositionally homogenous. However, in reality the density of pebble to boulder sized clasts and the sand-silt-clay content of the matrix (amongst other properties) varies both laterally and vertically within a single till unit. Such compositional variations will affect response of the diamicton to changes in pore water pressure and/or any imposed shear stress. For example, the relatively more sandy parts of the matrix will dilate more rapidly than adjacent clay-rich areas, resulting in vertical and/or lateral variations in till dilation. These clay-rich areas of the till will possess a relatively higher cohesive strength and also impede pore water flow through the diamicton. The potential result could be the partitioning of dilation, liquefaction and, therefore, flow displacement into a number of discrete zones within the till unit (Fig. 36). Consequently, rather than containing a single zone of flow displacement, the subglacial till could be composed of an anastomosing network of dilated/liquefied zones enclosing domains of partially solidified diamicton. Partitioning of dilation within diamicton may control the location of the zone of maximum flow displacement within the till. This zone could, therefore, occur at a deeper level within the subglacial environment, rather than immediately below the till-ice interface. The result could lead to a 'raft' of till being displaced over the underlying subglacial sediments without it actually being frozen to the overlying ice.

In contrast to the focusing of dilation and fluid flow into the sandier parts of the diamicton, the higher frictional strength of sand-rich lithologies means that in the solid state they are more competent and resistant to deformation. Consequently, any deformation will be partitioned into the less competent, weaker clay-rich parts of the sediment. The result may be that these relatively clay-rich parts of the till may exhibit an apparently higher intensity of deformation compared to the adjacent sandier horizons which may lack any obvious signs of deformation. Under the microscope for example, clay-rich parts of a deformed till may show strong birefringence in cross-polarised light. This phenomenon is referred to as plasmic fabric and is the direct result of clay platelets having aligned parallel to each other under the influence of (subglacial) shear stresses (see van der Meer, 1993). If deformation continues to be partitioned into the clay-rich parts of the till it could eventually result in strain hardening and brittle failure (faulting).

Further microscopic evidence of the heterogeneity of subglacial sediment and its associated non-uniform response to subglacial deformation comes from the common occurrence of rounded, soft sediment inclusions in till. These mm-to cm-scale structural elements are known as intraclasts or 'till pebbles' (cf. van der Meer, 1993) and may be composed of sediment that is similar to, or texturally and compositionally distinctly different from the host diamicton. The presence of such features suggest small-scale variations in composition, grain size and/or water content, which, in the formation of a heterogeneous till-matrix framework (see Fig. 37), would give rise to a situation where angular, irregular or even diffuse patches or fragments solidify in a matrix that overall would still be in a dilated or liquefied state. During renewed or continuing flow within the liquefied layer these till pebbles would become rounded or even deformed (folded) (*c.f.* mudstone clasts within a mud-clast conglomerate). If the formation of the till-matrix framework is more advanced then an increase in pore water pressure may lead to hydrofracturing and fragmentation of the framework rather than localised re-inflation. In both cases the till pebbles will be similar in composition to the host sediment, but may internally possess a plasmic fabric(s) that is unrelated to any structures seen within the enclosing matrix. The latter may even show no evidence of solid state deformation. Any earlier formed deformation structures (including plasmic fabrics) present within the till pebbles will be re-orientated due to rotation of the clasts. Evidence of plastic deformation of the till pebbles may provide an indication of the rigidity and the relative timing of re-inflation/dilation of the till-matrix framework. Any increase in the rigidity of the framework and/or over-consolidation of the diamicton would require a greater increase in pore water pressure for disruption to occur. As a result brittle fracturing of the till, rather than reactivation of the liquefied till layer, is more likely to occur.

5.5. Clast a-axis macro fabric development within tills

Although clast macro fabric has been employed relatively widely in the differentiation of subglacial till types, particularly deformation tills (e.g. Benn, 1994a,b, 1995; Hicock and Fuller, 1995; Benn and Evans, 1996; Hicock et al., 1996; Evans et al., 1998, 1999; Evans, 2000a,b), there remains significant scepticism about the applicability of the technique in evaluations of till genesis and more specifically strain signatures (e.g. Hooyer and Iverson, 2000; Benn, 2002; Iverson and Hooyer, 2002). For example, Boulton et al. (2001) state *"…we are sceptical about the empirical basis of much fabric analysis as a powerful discriminator of till genesis, and would agree with* Bennett et al. (1999) *that it 'offers little quantitative support in the interpretation of glacigenic sediments' "*. However, it is widely accepted that subglacial tills that have been subject to high cumulative strains, particularly lodgement till, will display strong clast fabrics. Coulomb plastic behaviour in deforming subglacial till involves slippage between clasts and the surrounding, faster advecting matrix (Ildefonse and Mancktelow, 1993). This results in the more elongate clasts assuming a minimum obstacle size and therefore orientating their a-axis parallel to the main stress direction. Providing the stress direction does not change, the clast *a*-axes remain in an ice-flow parallel position and the clast fabric strength is then proportional to the total strain in the till at low strains, the relationship then becoming exponential at higher strains.

Despite this, a range of clast fabric strengths have been reported from "typical" subglacial tills. Although this variability of clast fabric strengths has been used to question the value of the technique in deciphering deformation patterns and quantifying bed shear strains, it is likely that it in fact reflects the heterogeneity of subglacial beds and their concomitant responses to glacier shear stress. For example, Piotrowski et al. (2001) suggest that the Jeffery type rotation of clasts in viscous tills seems incompatible with a deforming bed. Moreover, March type rotation through plastic deformation has been identified as the dominant mode of clast orientation in deforming till in both field (Benn, 1995; Benn and Evans, 1996) and laboratory (Hooyer and Iverson, 2000) investigations. However, numerous studies have concluded that weakly developed fabrics do characterize deforming bed tills (e.g. Hicock, 1992; Hart, 1994, 1997; Clark, 1997), suggesting that, at least locally, particles are free to rotate in a viscous medium. Fabric strength may also be affected by clast collisions in coarser grained tills (Ildefonse et al., 1992). Inhomogeneous or unsteady deformation may therefore produce a wide range of clast fabric strengths and localized fabric patterns will reflect the deformation history and local strain conditions of the enclosing sediment. For example, Boulton et al. (2001) propose that deforming till becomes stiffer with depth and therefore clasts will glide rather than rotate, thereby explaining clast pavements at the bases of deformation tills. Macrofabrics reported by Larsen and Piotrowski (2003) from multiple tills in Poland are uniformly strong throughout the sequence, and although strengths do vary over short distances, the authors propose that the fabric strength supports a plastic rather than viscous model of subglacial sediment deformation. In an attempt to verify the applicability of the technique, we here review the characteristics of clast macro fabrics in tills and clarify the relationships between fabric strength and rheological properties of subglacial materials.

The intensity and style of clast *a*-axis macro fabrics developed within tills will vary depending upon the flow and subsequent solid state deformation history. Macro fabrics from massive dilatant A horizon tills are highly variable and tend to exhibit a wide range of dip values (anisotropic) and weak to moderate preferred orientations (low elongation) (Dowdeswell and Sharp, 1986; Benn, 1995; Hart, 1994). In contrast to A horizon fabrics, *a*-axis macro fabrics developed within B horizon tills possess a low isotropy and moderate to high elongation parallel to the direction of ice movement (Hart, 1994; Benn, 1995; Benn and Evans, 1996). Hart (1994, 1995) argued that there is a relationship between the strength of the *a*-axis fabric (S1 values) and the thickness of the 'deforming layer'. However, no consistent relationship has been observed in other studies (Benn, 1995; Benn and Evans, 1996). Benn and Evans (1998), therefore, preferred to interpret *a*-axis macro fabric characteristics in terms of 'strain type', rather than the thickness of the postulated deforming layer.

The clear differences between clast *a*-axis macro fabrics from A and B horizon tills can be interpreted as reflecting development of the preferred orientation within a liquid and solid state, respectively (c.f. Benn and Evans, 1998). The range of *a*-axis fabric shapes recorded from modern and ancient subglacial tills are similar to those from debris flows. This is primarily because the processes of particle orientation during flow in both situations is very similar, the only difference being that in the subglacial situation, flow is constrained by the overburden pressure and direction of movement of the overlying ice. The latter results in the more spatially defined nature of macro fabrics from subglacial tills parallel to the direction of flow (ice movement), in comparison to the highly variable or even divergent pattern of debris flow fabric maxima. The variability of *a*-axis fabrics seen within A horizon subglacial tills reflects the fluidised, dilated state of the till matrix enabling the clast to rotate in any direction. As a consequence the clast may respond rapidly to localised variations in the pattern of flow; for example around localised perturbations within the bedrock or stationary ('lodged') boulders. These highly mobile clasts may also move up or down through the liquefied layer with the 'buoyancy' of the clasts possibly being aided by flow within the till matrix. The effect would be to align the *a*-axis of the clast within the direction of flow, but due to high clast mobility the orientation of the *ab* plane would vary (Fig. 39). The latter would result in the observed variation in clast dip in A horizon tills. Rotation of clasts within the dilatant/fluidised layer could also be aided by the development of a water-rich film enclosing the pebble or boulder, essentially decoupling it from the till matrix.

Due to the formation of a till-matrix framework with increasing depth this type of flow-related rotation will decrease as the sediment begins to solidify, and 'solid state' rotation will begin to take over. In the simplest case this rotational process will be controlled by loading due to the overlying ice, i.e. resulting in compaction. The angle of dip of the *ab* plane would decrease, with the clasts becoming increasingly aligned parallel to bedding and the developing foliation within the B horizon (Fig. 39). Continued movement of the overlying ice as the till dewaters may lead to the transmittal of a component of simple shear into the underlying sediment deforming the till-matrix frame work. As a result of this deformation the clast *a*-axis will continue to rotate (solid and/or semi-solid state rotation) into the direction of shear, i.e. the direction of ice movement. Consequently, the resultant clast *a*-axis macro fabric is more likely to record the direction of ice movement, displaying a more pronounced alignment and lower angle of dip (i.e. comparable to clast fabrics developed within B horizon tills).

An important point to be made here is that B horizon tills will have previously undergone a phase of liquefaction, i.e. they began life as a dilated A horizon till prior to solidification. Consequently, rather than being a completely separate process, solid state rotation will be superimposed upon a till which already

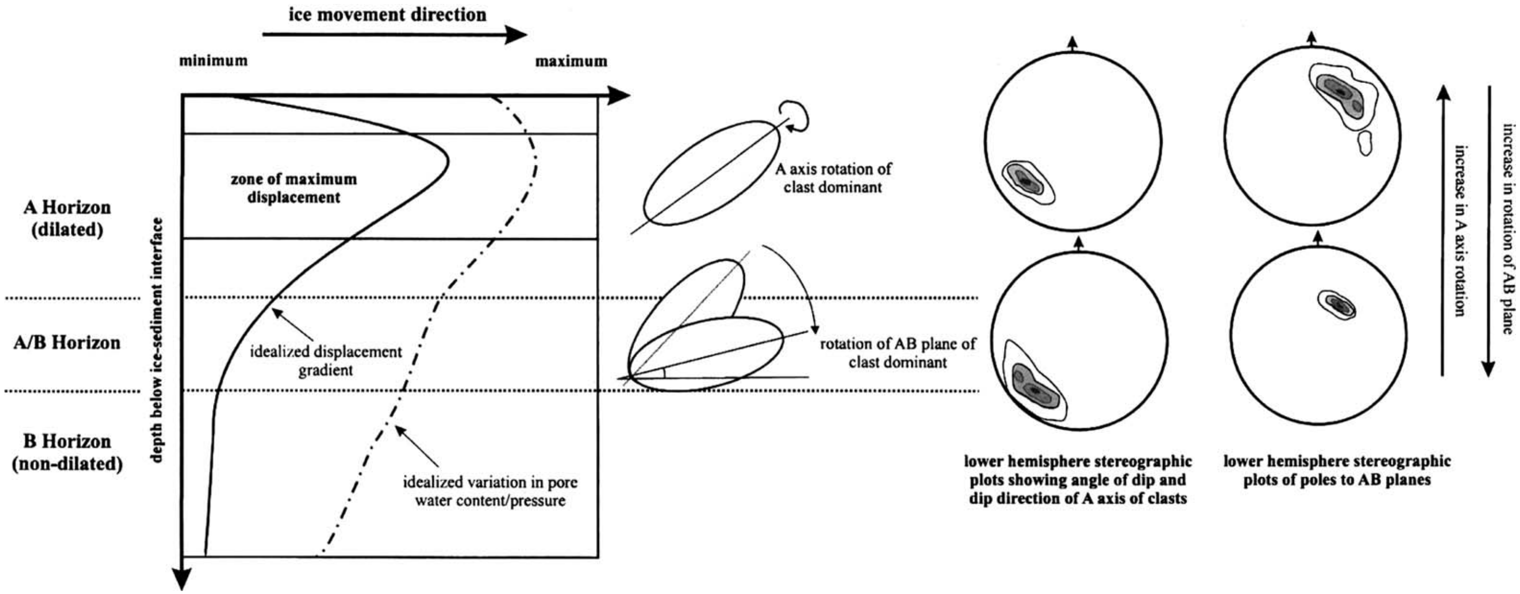


Fig. 39. Potential impact of A and A/B horizon developments on clast fabrics.

possesses a preferred clast alignment that developed during earlier fluid flow. In many cases the direction of flow of the till will coincide with the direction of shear as both are controlled by movement of the overlying glacier. Consequently, even at low strains a pronounced *a*-axis macro fabric may be developed within the B horizon till. As a result the strength of the clast macro fabric is not directly proportional to the intensity of solid state deformation and, therefore, may lead to an over estimation of the shear strains involved. Furthermore, the density of clasts within the till may affect the intensity of *a*-axis fabric developed during either liquid or solid state rotation. For example, where the clasts are isolated within the deforming, finer grained matrix they are able to 'freely' rotate and align within the direction of shear. If the clast density is sufficiently high then nearest neighbour effects may restrict clast rotation and, therefore, impede the development of the clast macro fabric.

6. Patterns of till deposition

In their review of entrainment and transport of basal sediment in glaciers, Alley et al. (1997) provide schemata for subglacial processes (Fig. 2). These schemata have implications for the spatial and temporal distribution of subglacial till deposition and help us to place interpretations of till sequences into the context of a process-form continuum.

Firstly, they emphasize the fact that glacifluvial transport is extremely efficient, giving rise to the removal of sediment and erosion of bedrock along drainage channels at the glacier bed. This effectively transports large volumes of sediment beyond the glacier system into proglacial areas where it can be reworked during more extensive glacier advances (see second point). The nature of drainage networks (ie. channelized versus distributed systems) has a significant impact upon sediment availability and till deposition/moraine construction at glacier margins (Swift, 2002; Swift et al., 2002; Spedding and Evans, 2002).

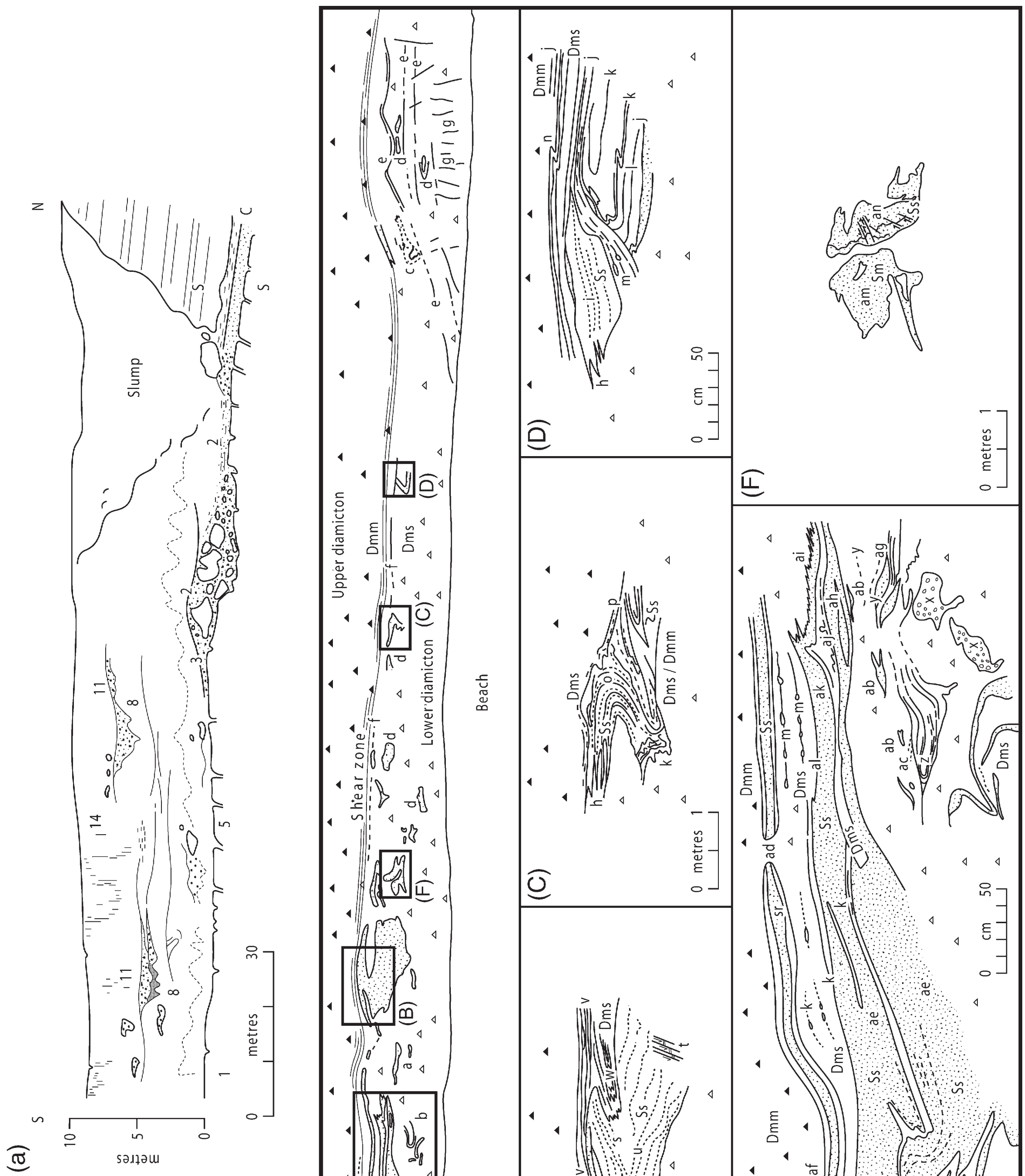
Secondly, the long distance transport of sediment is reliant upon glacier advance and marginal fluctuations. The wide range of sediment transport mechanisms in a glacier (Fig. 2) are typically more active in marginal and sub-marginal locations. This results in the concentration of debris in marginal zones through net adfreezing (Weertman, 1961; Boulton, 1972; Hubbard and Sharp, 1989; Knight, 1997) supercooling (Alley et al., 1998; Lawson et al., 1998; Evenson et al., 1999; Alley et al., 1999, 2003), debris-rich ice thickening by thrusting, folding and overriding (e.g. Goldthwait, 1951; Souchez, 1967; Hooke, 1973a,b; Hooke and Hudleston, 1978; Evans, 1989; Knight, 1989, 1994) and the concentration of glacifluvially reworked sediments. An advancing glacier will therefore transfer sediment over long distances as its marginal zone migrates over the landscape. Additionally, a stationary ice margin will soon exhaust its supply of local sediment in contrast to a fluctuating margin that will be able to access fresh stores of material. Alley (2000) alludes to the importance of sediment supply to the deformation process when he states that "till continuity comes first" and "history matters"; the fine-grained nature and thick beds of the southern Laurentide tills can be explained by the deforming layers' inheritance of extensive proglacial lake sediments (Alley, 1991).

Third, overdeepenings near glacier margins are maintained by the freeze-on of rising and supercooling meltwater exiting the depression in addition to the deformation of sediments and their removal from the depression.

Fourth, continuous deforming beds are most likely to occur in ice-marginal locations. This is especially the case where pre-existing sediment (e.g. glacilacustrine or glacimarine sediments) blankets bedrock obstacles or potential sticky spots.

Finally, we should expect both spatial and temporal separation of all subglacial mechanisms. This is aptly illustrated by what takes place in the vicinity of subglacial drainage channels where till squeezes into the low pressure cavities until till patches become isolated from the drainage system (Boulton and Hindmarsh, 1987; Alley, 1989a,b, 1992; Walder and Fowler, 1994). Temporal variability is demonstrated in circumstances where tunnel or canal fills of stratified sediment occur in subglacial till sequences (e.g. Eyles et al., 1982; Alley, 1991; Clark and Walder, 1994; Evans et al., 1995; Boyce and Eyles, 2000; Fig. 40).

The above schemata of Alley et al. (1997) suggests that sediment availability increases at the glacier margin and the transport of subglacial sediment results in the excavation of overdeepenings in sub-marginal settings. This 'conveyor belt' transport of sediment logically leads to the marginal thickening of till sequences and sediment excavation and/or bedrock erosion of upglacier regions, up to the area of the glacier that lies in the vicinity of the equilibrium line. This has been modelled by Boulton (1996a,b) for glaciers beneath which the predominant transport process is deformation (excavational deformation of Hart et al., 1990; Hart and Boulton, 1991; Hart, 1995). Boulton suggests that the maximum deposition rate occurs in the sub-marginal zone of the glacier where till sheets thicken and are


(a)
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1

superimposed (constructional deformation of Hart et al., 1990; Hart and Boulton, 1991; Hart, 1995). The model recognizes that advance and retreat tills are superimposed, although complex till stacks can be constructed by rheologic superposition (Hicock, 1992; Hicock and Dreimanis, 1992b; Hicock and Fuller, 1995). As the tills in such complex sequences display discrete lithological provenance, deformation/displacement signatures and cannibalized rafts of non-till sediments, they clearly record ice marginal fluctuations and/or changing ice lobe influence at particular locations. The lithologically distinct tills may also be separated by stratified interbeds that record changes in subglacial drainage conditions and ice-till coupling (Boyce and Eyles, 2000; Fig. 41).

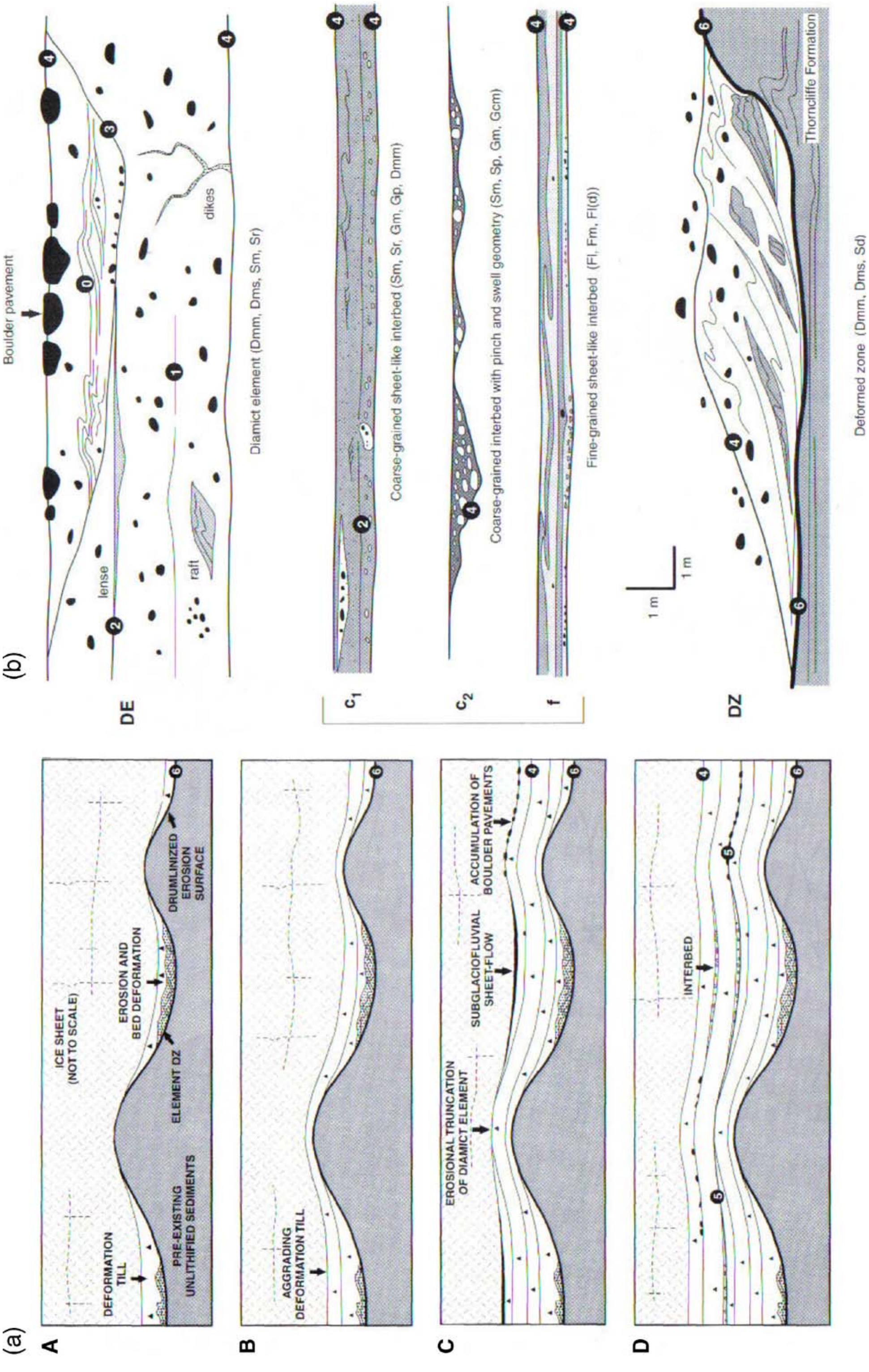
The localized thickening of subglacial tills beneath modern glacier margins has been related to a range of processes and substrate conditions in Icelandic glacier research. Evans and Hiemstra (2005), elaborating on the work of Krüger (1996), identify a seasonal cycle of marginal re-freezing and melt-out of tills advected from up ice by a combination of lodgement, deformation and ice keel and clast ploughing (Fig. 32). This explains the stacking of up ice thinning till wedges at stationary glacier snouts. Further variability in the thickness of such till wedges is described by Kjær et al. (2003), who link localized thickening of deforming subglacial tills with lower substrate permeability.

If till deformation and/or ploughing, as defined by Tulaczyk et al. (2001), is significant in the net down glacier transfer of subglacial sediment then till should thicken towards glacier and ice sheet margins (Haeberli, 1981). This thickening should be visible at former ice sheet margins, providing that the snout was stable over a period of time that was sufficient for incremental stacking of till. For example, Piotrowski and Kraus (1997) highlight the fact that tills are not at their thickest near the former margin of the Scandinavian Ice Sheet in Germany but maintain the same thickness well within the margin. Evans and Ó Cofaigh (2003) describe a situation where till thickens well within the limit of the LGM in the Irish Sea Basin and offer an explanation that appears to satisfy the palaeoglaciology of the British Ice Sheet as a whole; the ice sheet occupied its southernmost limit for a short period of time and may even have advanced to its limit during a surge.

The overall effect of fluid flow within the A horizon of a till is for diamicton to be transported towards the glacier snout, leading to a thickening of the deposited subglacial till in this direction. In the up glacier situation, any sediment below the ice will be cannibalised (i.e. eroded), disaggregated due to dilation and then incorporated into the actively moving diamicton. In reality, glaciers move by a process of 'stick-slip' with movement occurring in short bursts rather than a continual 'conveyer belt' process. The length and magnitude of these displacement events will be dependent upon ice-sediment boundary conditions. The result of stick-slip mode of glacier movement will be that the sediment transport mechanism for moving diamicton forward towards the snout will be switched on and off. The episodic nature of this transport mechanism may result in several phases or pulses of diamicton injection/deposition occurring towards the snout of the glacier.

During periods of no forward motion of the glacier (still stand) the transport of diamicton towards the front of the glacier will be slower and driven by loading of the

Fig. 40. Sedimentary structures in subglacial tills indicative of subglacial meltwater activity: a) Sandy Bay, NE England (from Eyles et al., 1982). S = Carboniferous sandstone; C = coal and shale band; 2 = glacitectonize bedrock; 3 = rubbly (comminution) till; 5 = intrusion of till into bedrock joints; 8 = stratified sediments in subglacial channels (canals); 11 = erosional upper contacts of canal fills, with deformed inclusions of stratified sediment, cannibalized from the canal fills, in overlying till; 14 = vertical joint patterns; b) Skipsea Till Formation, eastern England (after Evans et al., 1995), where subsequent ice movement has glacitectonized the stratified sediments deposited in canals at the ice-till interface. A = overview of section face showing Skipsea Till and associated intrabeds of stratified sediments; B–F = details of structures outlined by boxes in A with labels locating the following structures: a) deformed stratified, poorly-sorted, coarse and pebbly sands; b) concentrations of chalk clasts; c) concentrations of rounded pebbles; d) deformed sand lenses; e) crude lamination in the till due to subtle grain size variations; f) major discontinuity in the till, marking the top of the zone of deformed sand lenses; g) strongly developed vertical joints; h) interdigitation of till and sand; i) crudely planar stratified sands; j) laminated till comprising red, grey-brown and buff lamina derived from cannibalized soft bedrock; k) chalk stringers; l) laminated till; m) laminated till with chalk stringers; n) chevron fold; o) stratified sand with interstratified minor diamicton beds < 10 mm thick; p) till with weak stratification at base and chalk stringers subparallel to lower contact; q) dark brown till with chalk stringers; r) sand with stratification parallel to base of overlying till; s) cross-stratified sands; t) normal faulted sands; u) gentle folds; v) light brown stratified diamicton with sandy intercalations; w) folded stratified diamicton; x) concentrations of subrounded chalk pebbles, some of which are deformed into stringers within the surrounding till; y) sand stingers in till; z) sandy diamicton interstratified with cm thick beds of clayey sand folded into a recumbent fold; aa) deformed stratified clayey sands; ab) stratified sand lenses (dm wide) with convex tops and flat bases; ac) shears in till lined with sand; ad) laminated till grading into massive till; ae) moderately to well sorted, coarse to fine sands; af) rippled medium sands; ag) deformed lenses of rippled sands; ah) fine to very coarse, poorly sorted clayey sands containing pebbles towards the top; ai) stratified diamicton interdigitated with sandy clay; aj) chalk stringer deformed by a diaper; ak) coarse to fine sands with low-angled cross-stratification deformed by small normal faults; al) smooth base of laminated till parallel to the laminations of the underlying sands; am) massive to moderately well-sorted coarse sands; an) faulted, stratified, poor to moderately sorted, medium to fine sands.


(a)
A
DEFORMATION TILL
PRE-EXISTING UNLITHIFIED SEDIMENTS
ICE SHEET (NOT TO SCALE)
EROSION AND BED DEFORMATION
ELEMENT DZ
DRUMLINIZED EROSION SURFACE
B
AGGRADING DEFORMATION TILL
C
EROSIONAL TRUNCATION OF DIAMICT ELEMENT
SUBGLACIOFLUVIAL SHEET-FLOW
ACCUMULATION OF BOULDER PAVEMENTS
D
INTERBED
(b)
DE
Boulder pavement
lense
raft
dikes
Diamict element (Dmm, Dms, Sm, Sr)
Coarse-grained sheet-like interbed (Sm, Sr, Gm, Gp, Dmm)
Coarse-grained interbed with pinch and swell geometry (Sm, Sp, Gm, Gcm)
Fine-grained sheet-like interbed (Fl, Fm, Fl(d))
DZ
1 m
1 m
Thorncliffe Formation
Deformed zone (Dmm, Dms, Sd)

glacier as it 'sinks' into its bed. This process may result in ponding of liquefied diamicton below the ice or limited discharge at the glacier snout. The gravity driven expulsion/transport of the diamicton will continue until the till has sufficiently dewatered to become solid. The 'sinking' of the glacier into the underlying sediment will result in the collapse of the till-matrix framework assisting the solidification of the underlying diamicton and decelerating/retarding further movement. In some locations evidence of the foundering of outwash deposits into underlying diamicton (e.g. Evans et al., 1995; Fig. 42) may be indicative of gravity-induced loading of liquefied tills deposited during the early stages of deglaciation when the glacier had been decoupled from its deformable substrate.

Fig. 42. Gravel pendant structures at the top of the Skipsea Till, Yorkshire, England, possibly the product of foundering of glacifluvial sediments into subglacial till during immediate decoupling of the glacier from its soft bed.

7. Conclusion—towards a new subglacial till nomenclature

7.1. Rationale

It is clear that the subglacial processes of deformation, flow, sliding, lodgement and ploughing coexist at the base of temperate glacier ice. They act to mobilize and transport sediment and deposit it as various end members, ranging from glacitectonically folded and faulted stratified material to texturally homogeneous diamicton. The dominance of any one subglacial process varies both spatially and temporally, giving rise to the possibility that a till or complex till sequence contains a superimposed signature of former transportation/deposition at the ice-bed interface. Therefore, we recommend that, while glacial geologists and geomorphologists should be able to recognize the sedimentary imprints of various subglacial processes, genetic fingerprinting of subglacial tills should be less process-specific (e.g. deformation till, lodgement till, melt-out till). This is particularly appropriate in the majority of till studies where the process signatures cannot be differentiated or have been intensely superimposed and the use of a genetic label can be a matter of personal preference (c.f. Dreimanis, 1989; Ruszczynska-Szenajch, 2001); as Alley (2000) points out, although subglacial tills clearly deform by some mechanism or other they are polygenetic. Any till classification scheme must reflect the range of products encompassed by the subglacial till production continuum (Fig. 43) but at the same time avoid attaching specific genetic labels that communicate a far greater level of understanding than our tentative linkages between process and form can presently justify.

Because subglacially formed, deformed and deposited sediments occupy positions on a process-form continuum and cannot be unequivocally classified according to specific process using sedimentological criteria, we here propose a classification scheme that incorporates and reconciles all of the diagnostic criteria presented in this paper. The scheme also assimilates the presently available process measurements on modern glacier beds. We conclude that glacial geologists can presently unequivocally identify glacitectonite and subglacial traction till, the latter incorporating the former classification of lodgement till, deformation till and comminution till and including also sliding bed deposits and lee-side cavity fills. We further suggest, somewhat controversially but as a hypothesis for further rigorous testing, that subglacial melt-out till and sublimation till remain predominantly theoretical

Fig. 41. A model of till and interbed deposition (from Boyce and Eyles, 2000): a) the conceptual model involving: A) erosion and deformation of pre-existing unlithified sediments to form drumlinized surface; B) conformable aggradation of deformation tills on drumlinized surface; C) subglacial fluvial reworking of diamicton to form sheet-like interbeds and boulder pavements; D) continued aggradation of deformation tills and stratified interbeds; b) schematic illustration of architectural element types with typical bounding surfaces as represented by interbeds. DE = diamict element, where tabular beds separated by planar to gently undulating bounding surfaces with occasional clast pavements are deposited by aggradation of deformation till; I = interbeds comprising coarse (I-c) and fine (I-f) ice-bed separation deposits; DZ = deformed zone comprising glacially deformed pre-existing strata. Numbers in black dots refer to bounding surfaces whereby 6th order surface = mappable stratigraphic unit, 5th order surface = laterally continuous erosion surface and 4th order surface = boundary between architectural elements, 3rd order surface = laterally discontinuous minor erosion surface, 2nd order surface = boundary defining dissimilar lithofacies; 1st order surface = boundary separating similar lithofacies; 0 order surface = laminae (see Boyce and Eyles, 2000 for details).

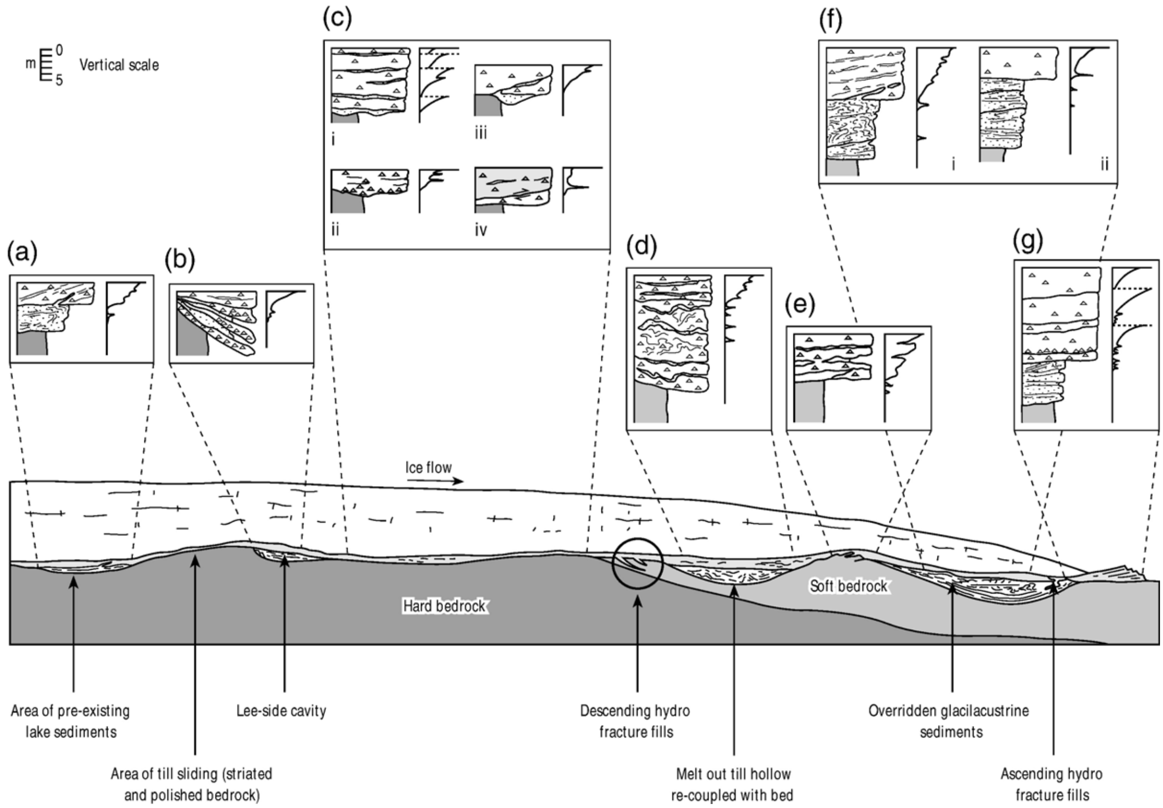


Fig. 43. Conceptual model of the full spectrum of till production and depositional mechanisms resulting in a continuum of till formation. The processes depicted are those that would be expected beneath a large, predominantly temperate outlet glacier with a seasonally frozen snout. The shaded area of the glacier bed represents the subglacial traction till (STT). The final thickness of a till deposit does not reflect the thickness of the subglacial traction/deforming layer at any one point in time. Not all the process-form products would necessarily be coeval and signatures may be overprinted due to glacier advance and retreat cycles. The graphs to the right of each vertical profile log indicate the likely relative pattern of cumulative strain. The process-form products are: a) pre-advance lake sediments capped by STT; b) lee-side cavity fill diamicts and stratified sediments capped by STT where ice has recoupled with the bed due to cavity closure. In a and b the tops of the lake sediment and cavity fill sequence are classified as glacitectonite which is locally cannibalized and dragged into the base of the deforming till layer after folding/thrusting is induced by ice keel ploughing, clast ploughing and/or migrations in the locus of failure planes in subglacial sediment aided by cyclical changes in porewater pressure. This produces a crudely laminated diamicton; c) sheared tills with partially to intensively glacitectonized stratified intra- and interbeds produced over hard beds where, i) STT and stratified interbeds (canal fills) are continually aggraded due to continuous replenishment of deformable sediment from up ice, ii) large clasts are lodged to produce a clast pavement at the base of a thin STT in which finer grained material is continuously advected down ice, iii) a single STT with associated glacitectonized canal fill at a site where aggradation is restricted by poor till continuity, iv) regelation of STT (grey shade) leads to the stacking of tills which later melt-out (note the similarity with sequences produced by marginal incremental thickening in g); d) pre-advance or remobilised melt-out till overlain by STT. The top of the melt-out till is classified as glacitectonite and is locally cannibalized and dragged into the base of the deforming till layer after folding/thrusting is induced at the STT/melt-out till interface and/or the loci of failure planes migrate through the subglacial sediment pile to produce a crudely laminated diamicton; e) glacitectonized soft bedrock grades upwards into STT with bedrock rafts (“comminution till”); f) glacitectonite (glacially overridden lake sediments) overlain by deforming STT where, i) the glacitectonite has been locally cannibalized and dragged into the base of the deforming layer after folding/thrusting is induced at the STT/stratified sediment interface and/or the loci of failure planes migrate through the subglacial sediment pile to produce a crudely laminated diamicton. This may be assisted by seasonal migration of the freezing front or cyclical changes in porewater pressures, ii) the top of the glaciteconite is eroded by the base of the STT. The contact between the two sediment bodies is essentially a fault gouge; g) glacifluvial outwash or lake sediment, glacitectonized in its upper layers and overlain by a stacked sequence of macroscopically massive STT’s. Incremental stacking occurs where the glacier margin is stationary and slabs of STT freeze on and melt-out every year.

constructs and the severe limitations on their preservation potential (Paul and Eyles, 1990) suggests that they are most likely to be manifest in the geological record as spatially restricted and both crudely stratified and macroscopically massive diamictons displaying a wide range of gravity induced disturbance structures. In order to be interpreted as melt-out till, a deposit must be devoid of subglacial traction features otherwise it is classified as a glacitectonite or subglacial traction till according to the criteria set out below.

7.2. Glacitectonite

The definition preferred here is that proposed by Benn and Evans (1996):

> Rock or sediment that has been deformed by subglacial shearing (deformation) but retains some of the structural characteristics of the parent material.

The range of materials involved in glacitectonite production reflects the infinite variety of parent materials, from bedrock to previously deposited Quaternary sediments. Comminution till also falls under the umbrella of the glacitectonite classification because the term glacitectonite covers sediments formed from subglacial reworking of bedrock, both in-situ or as displaced blocks and slabs. The deformation structures displayed within glacitectonites reflect their strain history and the rheology of individual sedimentary beds. Glacitectonites can be subdivided into Type A, which display evidence of penetrative deformation, and Type B, which have undergone non-penetrative deformation and so pre-deformational sedimentary structures are merely folded and faulted.

7.3. Subglacial traction till

Although somewhat complex the following definition includes the range of inter-related and inextricable processes and forms known to occur in the traction zone at the base of a glacier:

> Sediment deposited by a glacier sole either sliding over and/or deforming its bed, the sediment having been released directly from the ice by pressure melting and/or liberated from the substrate and then disaggregated and completely or largely homogenised by shearing.

This definition necessarily combines the subglacial process-form relationships associated with lodgement and deformation and addresses the widely cited problem of both processes being inextricable. It also includes localized lee-side cavity fills on hard beds and stratified sediments deposited by water films and channels at the ice-bed interface and within deforming subglacial sediment by Darcian and pipe flow. The effects of substrate ploughing by both ice and clasts are also incorporated in this definition. As observations on contemporary glaciers reveal that their beds are most likely to be mosaics of deformation and sliding and warm based and cold based conditions, the patterns of which change temporally and spatially, it is extremely unlikely that subglacial till end members in the geological record will be anything but hybrids produced by the range of known processes in the subglacial traction zone.

7.4. Subglacial melt-out till

Based upon the theoretical construct presented in the literature the subglacial melt-out till definition presented above remains appropriate but the process of sublimation needs to be recognized:

> Sediment released by the melting or sublimation of stagnant or slowly moving debris-rich glacier ice, and directly deposited without subsequent transport or deformation (modified from Benn and Evans, 1998).

Due to the severe limitations on their preservation potential we suggest that melt-out tills may rarely inherit and replicate the foliation and structure of their parent ice and will occur in the geological record as both crudely stratified and macroscopically massive diamictons displaying a wide range of gravity induced disturbance structures. In situations where melt-out deposits have been overrun by glacier ice or re-coupled with the glacier bed due to re-activation of ice flow, they will contain subglacial traction features and will therefore be classified as a glacitectonite.

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