2

A Brief History of Till Research and Developing Nomenclature

> *With relief one remembers that, after all, the facts gathered with such infinite care, over so many years, are in no ways affected: their permanency is untouched, their value as high as ever. It is the interpretation which has gone astray.*
>
> Carruthers (1953, p. 36)

A benchmark publication in the development of till nomenclature was contained in the final report by the INQUA Commission on Genesis and Lithology of Glacial Quaternary Deposits, entitled '*Genetic Classification of Glacigenic Deposits*' (Goldthwait and Matsch, 1989; Figure 2.1). Most significant in this report was the paper by Aleksis Dreimanis (Figure 2.2), entitled '*Tills: Their Genetic Terminology and Classification*', a summary of the findings of the Till Work Group, which operated over the period 1974–1986. It was a synthesis of knowledge and a rationale for a unified process-based nomenclature but at the same time afforded the presentation of alternative standpoints on till classification, and hence delivered a selection of frameworks containing complex and overlapping genetic terms. More broadly, 'till' at this juncture was defined as:

> a sediment that has been transported and is subsequently deposited by or from glacier ice, with little or no sorting by water.
>
> (Dreimanis and Lundqvist, 1984, p. 9)

As a way forward, the Till Work Group, through Dreimanis (1989), arrived at a series of nomenclature diagrams (Figure 2.3), which aimed at an inclusive but at the same time simplified and unambiguous, process-based till classification scheme. More specifically, Dreimanis (1989), within the same volume, compiled a table of diagnostic characteristics for differentiating what he termed 'lodgement till', 'melt-out till' and 'gravity flowtill'. Although this book later advocates a fundamentally different set of sedimentological terms for the deposits being described by Dreimanis (1989), the contents of his summary table are nonetheless still highly relevant to the differentiation of subglacial versus mass flow origins for diamictons on the one hand and subglacial traction versus melt-out processes on the other, and hence are reproduced here in Table 2.1.

Prior to the production of the Goldthwait and Matsch (1989) volume, till nomenclature had developed out of a small number of local case studies, not all of which were based on modern process, as was reviewed by Dreimanis (1989). We shall return to the issue of process-based till nomenclature schemes throughout this book, but first it is important to provide historical context for the deliberations of the Till Work Group and beyond.

Till: A Glacial Process Sedimentology, First Edition. David J A Evans.

Figure 2.1 Symposium volumes compiled on the subject of tills during the 1970s to the early 1990s.

Figure 2.2 Researchers involved in the historical development of till sedimentology up to, and in some cases beyond, the late 1970s.

Table 2.1 The main criteria identified by Dreimanis (1989) as critical to the differentiation and classification of 'lodgement till', 'melt-out till' and 'gravity flow till'.

Criterion	Lodgement till	Melt-out till	Gravity flow till
Position and sequence in relation to other glacigenic sediments	Advancing glaciers – lodged over pre-advance sediments and glacitectonites, unless eroded. Retreating glaciers – lowermost unit if pre-advance deposits and advance till has been eroded. Locally underlain by meltwater channel deposits. May be overlain by any glacigenic sediments.	Usually deposited during glacial retreat over any glacially eroded substratum or over lodgement till. May be interbedded with lenses of englacial meltwater deposits. Locally underlain by syndepositional subglacial meltwater sediment and subglacial flow till.	Most commonly the uppermost glacial sediment in a non-aquatic facies association. Also associated locally with subglacial tills, where cavities were present under glacier ice or where the glacier had overridden ice-marginal flow till. May be interbedded or interdigitated with glacifluvial, glacilacustrine or glacimarine sediments.
Basal contact	Since both lodgement and melt-out tills begin their formation and deposition at the glacier sole, their basal contact with the substratum (bedrock or unconsolidated sediments) is similar in the large scale, being usually erosional and sharp. Glacial erosion marks underneath the basal contact and clast alignments immediately above the contact have the same orientation. Glacitectonic deformation structures formed by the till-depositing glacier may occur under both till types and strike transverse to the direction of local glacier stress.		Variable; seldom planar over longer distances. Flows may fill shallow channels or depressions. Contact may be either concordant or erosional, with sole marks parallel to the local direction of sediment flow. Loading structures may be present at the basal contact of waterlain flow till and the underlying soft sediment.
	Basal contact represents sliding glacier base and is generally planar if substratum is over-consolidated but may be grooved. Bedrock contact is usually abraded, particularly on stoss sides of protrusions. Sliding glacier base is a shear plane, so sheared and strongly attenuated substrate material may be deposited as a thin layer along this plane, and in places is sheared up into lodgement till. Clast pavements may be present along the basal contact but may also occur higher up in lodgement till. If lodgement till becomes deformed by glacial drag shortly after its deposition, the basal contact may become involved in the deformation with tight recumbent folding, overthrusting and shearing.	If the basal contact of glacier ice was tight with the substratum during melting, the pre-depositional erosional marks are well preserved under lodgement till. However, subsole meltwater may modify the basal contact locally, and produce convex-up channels and various other meltwater scour features.	

Thickness	Typically one to a few metres. Relatively constant laterally over long distances.	Single units are usually a few centimetres to a few metres thick, but they may be stacked to much greater thicknesses.	Very variable. Individual flows are usually a few decimetres to metres thick, but they may locally stack up to many metres, particularly in proglacial ice-marginal moraines and some lateral moraines.
Structure, folding and faulting	Typically described as massive but on closer examination a variety of consistently orientated macro- and microstructures indicative of shear or thrusting may be found. Folds are overturned, with anticlines attenuated down-glacier. Deformation structures are particularly noticeable if underlying sediments are involved or incorporated in the till, developing smudges. Sub-horizontal jointing or fissility is common. Vertical joint systems, bisected by the stress direction, and transverse joints steeply dipping down glacier, may be formed by glacier deforming its own lodgement till. The orientation of all the deformation structures is related to the stress applied by the moving glacier, and therefore it is laterally consistent for some distance.	Either massive or with palimpsest structures partially preserved from debris stratification in basal debris-rich ice. Lenses, clasts and pods of texturally different material preserve best, for instance soft-sediment inclusions of various sizes and englacial channel fills. Loss of volume with melting leads to the draping of sorted sediments over large clasts. Most large rafts or floes of substratum are associated with melt-out tills and they may be deformed by glacial transport and by differential settlement during melting.	Structures depend upon the type of flow and other associated mass movements, the water content and the position in the flow. Either massive or displaying a variety of flow structures such as: (a) overturned folds with flat-lying isoclinal anticlines; (b) slump folds or flow lobes with their base usually sloping down flow; (c) roll-up structures; (d) stretched out silt and sand clasts; (e) intraformationally sheared lenses of sediments incorporated from substratum, with their upper downflow end attenuated if consisting of fine-grained material, or banana shaped.
Grain size composition	Usually a diamicton, containing clasts of various sizes. Grain size composition depends greatly on the lithology and composition of the substrata up-glacier and the distance and mode of transport from there. Comminution during glacial transport and lodgement has produced a multimodal particle size distribution. Most resulting subglacial tills are poorly to very poorly sorted, described also as well graded, and their skewness has a nearly symmetrical distribution, except for those tills that are rich in incorporated pre-sorted materials.		Usually a diamicton with polymodal particle size distribution. Texturally similar to the primary till to which it is related, but with a greater variability in grain size composition, due to washing out of, or enrichment in fines, or incorporation of soft-substratum sediment during the flow. Some particle size redistribution takes place during the flow. Grain size composition depends greatly upon the type of flow and the position or zone within it. Sorting, inverse or normal grading may develop in some zones of flows, and parts of clasts may sink to the base of the flow.

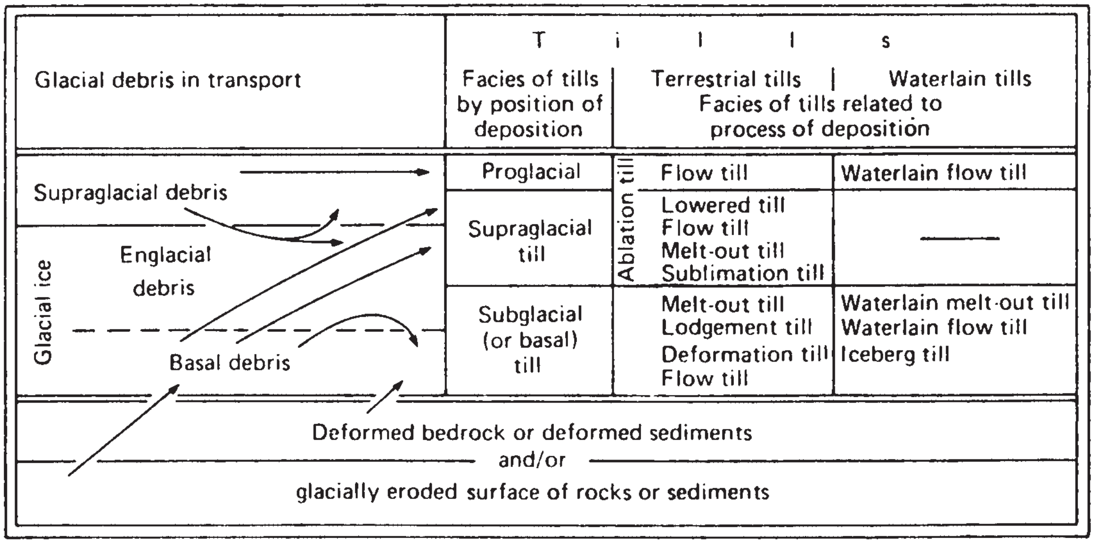
(*continued*)

Table 2.1 (Continued)

Criterion	Lodgement till	Melt-out till	Gravity flow till
	Abrasion in zone of traction during lodgement produces silt size particles. Most lodgement tills have relatively consistent grain size composition, traceable laterally for kilometres, except for the lower 0.5–1 m that strongly reflects the local material. Clusters or pavements of clasts are common.	Winnowing of silt and clay size particles in the voids during melt-out may reduce their abundance in comparison with their lodged equivalents. Some particle size variability is inherited from texturally different debris bands in ice. Extreme variations in grain size may occur over short distances in the vicinity of large rafts and other inclusions of soft sediment.	
Lithology of clasts and matrix	Lithological composition tends to be less variable than in other genetic varieties of tills; most constant is the mineralogical and geochemical composition of the till matrix. Materials of local derivation increase in abundance towards the basal contact with the substratum.	Since glacial debris of distant derivation is more common in the englacial zone than in the basal zone of a glacier and since the englacial zone is more likely to be deposited as melt-out till rather than by lodgement, materials of distant derivation may be more abundant in the melt-out than in the lodgement component of the same till unit, particularly in supraglacial melt-out till. Great compositional variability occurs in the vicinity of incorporated megaclasts, rafts or floes of sub-till material. Soft-sediment clasts, for instance consisting of sand, may be found in melt-out till, but not in typical undeformed lodgement till.	Lithological composition is generally the same as that of the source material of the flowed till – a primary till or glacial debris, plus some substratum material incorporated during the flowage. Material of distant derivation dominates in flowed tills derived from supraglacial and englacial debris, but dominance of local materials indicates derivation from basal debris. Soft-sediment clasts derived from the substratum or from sediment interbeds in multiple flows are common.
Clast shapes and their surface marks	The following criteria apply where most clasts are derived from single cycle transport: sub-angular to sub-rounded shapes dominate, depending mainly upon the distance of transport in the basal zone of traction. Bullet-shaped (flat-iron, elongate pentagonal) clasts are more common than in other tills and non-glacial deposits and their tapered ends usually point up glacier. Some elongate clasts have a keel at their base. Glacial striae are visible mainly on medium to hard, fine-grained rock surfaces. Elongate clasts are striated mainly parallel to their long axes, unless they have been lodged or transported by rolling.		If present, soft-sediment clasts are either rounded or deformed by shear or dewatering. The more resistant rock clasts are in the same shape as they were in the source material when re-sedimented by the flowage. Therefore, the relative abundance of glacially abraded, sub-angular to sub-rounded clasts versus completely angular clasts in flowed tills in mountain glaciers will indicate the approximate participation of basal debris versus supraglacial debris in the formation of the flowed till. Some rounded, water-reworked clasts without striations may derive from meltwater stream deposits.

	The bullet-shaped and facetted clasts, also crushed and sheared clasts, are more common in lodgement tills than in other tills. Lodged clasts are striated parallel to the direction of the lodging glacial movement, and they have impact marks on both the upper and lower surfaces, but in opposite orientation; on the surface, the stoss end is up glacier, but on the underside the stoss end is down glacier. Clast pavements with sets of striae parallel to the direction of the latest glacier movement over them may occur at several lodgement levels. Their top facets are either parallel with the general plane of lodgement or they dip up glacier.	If, in an area of mountain glaciation, the source of supraglacial melt-out till is englacially or even supraglacially transported and supraglacially derived debris, then the clasts are angular. Most commonly, supraglacial melt-out till in such areas also contains an admixture of glacially abraded basal debris, also englacially transported.	
Macro- and microfabrics	Strong macrofabrics with the log axis parallel to the local direction of glacier movement in diamictons reported as either lodgement or melt-out tills. Occasionally transverse maxims have developed, associated with folding and shearing. Fabric strength may also vary, depending upon till grain size, the abundance of clasts and post-depositional modification. Lodgement till fabric may be of complex origin: produced by lodgement or by deformation of the already deposited dilated till under the same glacier. If both stress directions coincide, a strong fabric will develop; if not, the lodgement fabric becomes weakened. Typically, the a-b planes dip slightly up glacier if lodgement alone is involved. Microfabric is usually as strong as the macrofabric.	Melt-out till fabric is inherited from glacier transport. Where fabric dominates it is parallel to the direction of glacier movement, unless deformation changes it to transverse fabric locally. Melt-out process can, however, weaken the fabric, particularly the microfabric. Also, the dip inclination of clasts becomes reduced by the reduction of the volume of ice during melting.	Variable, and dependent greatly upon the type of flow and the position in the flow. May range from randomly orientated to strong fabric in thin flows. Fabric maxima are either parallel or transverse to the local flow direction, unrelated to glacier movement; the a – b planes are either sub-parallel to the base of the flow or they dip up-flow. Fabric maxima may also differ laterally over short distances.
Consolidation, permeability and density	Most lodgement tills, particularly the poorly sorted, matrix-supported varieties, are over-consolidated, provided there was adequate subglacial drainage. Their bulk density, penetration resistance and seismic velocity are usually high, and permeability low, relative to other varieties of till of the region.	Supraglacially formed melt-out tills are usually less (normally weakly) consolidated than the subglacially formed, commonly over-consolidated melt-out tills, provided there was adequate drainage of meltwater. Bulk density and penetration resistance may be lower and more variable than in related lodgement till. Permeability is also more variable.	Primarily normally consolidated and relatively permeable. If clayey, may become over-consolidated due to post-depositional desiccation. Density lower than in primary tills.

(*continued*)


Glacial debris in transport
T i l l s
Facies of tills by position of deposition
Terrestrial tills
Waterlain tills
Facies of tills related to process of deposition
Supraglacial debris
Englacial debris
Glacial ice
Basal debris
Proglacial
Supraglacial till
Subglacial (or basal) till
Ablation till
Flow till
Waterlain flow till
Lowered till
Flow till
Melt-out till
Sublimation till
Melt-out till
Lodgement till
Deformation till
Flow till
Waterlain melt-out till
Waterlain flow till
Iceberg till
Deformed bedrock or deformed sediments
and/or
glacially eroded surface of rocks or sediments

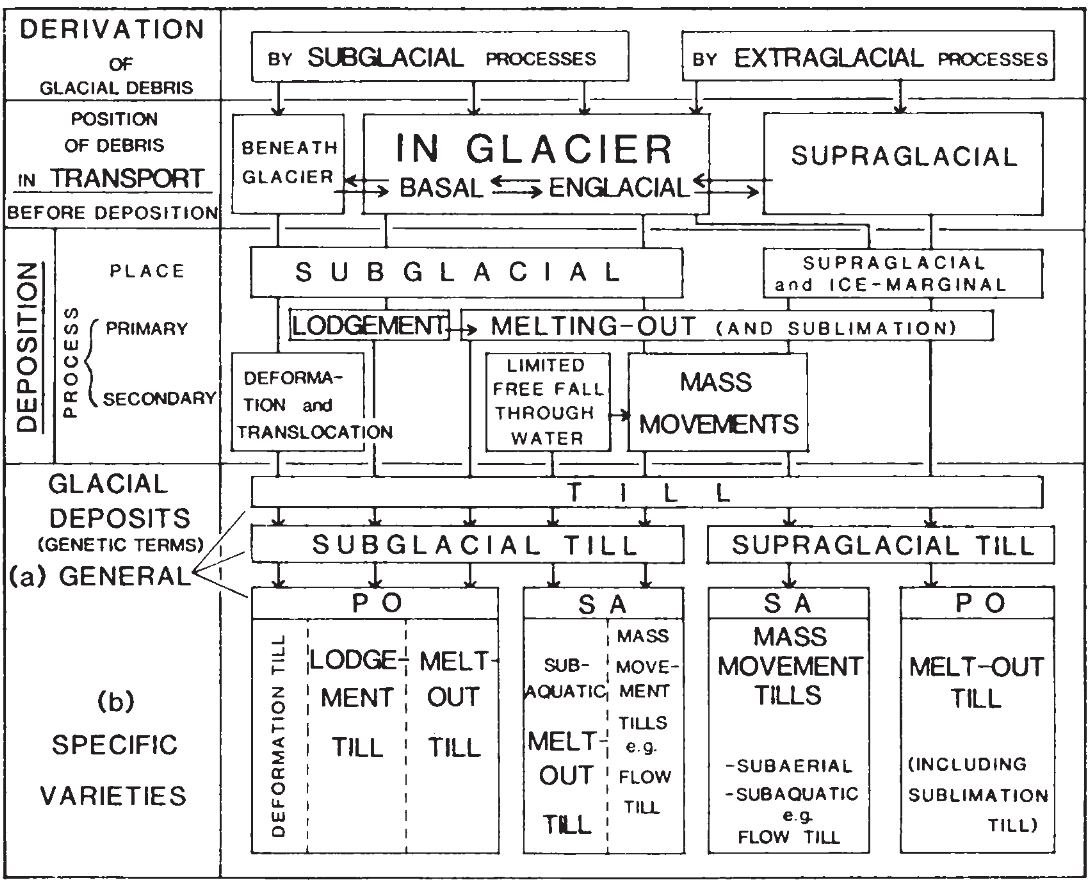

DERIVATION OF GLACIAL DEBRIS
BY SUBGLACIAL PROCESSES
BY EXTRAGLACIAL PROCESSES
POSITION OF DEBRIS IN TRANSPORT BEFORE DEPOSITION
BENEATH GLACIER
IN GLACIER
BASAL
ENGLACIAL
SUPRAGLACIAL
DEPOSITION
PLACE
PROCESS
PRIMARY
SECONDARY
SUBGLACIAL
SUPRAGLACIAL and ICE-MARGINAL
LODGEMENT
MELTING-OUT (AND SUBLIMATION)
DEFORMATION and TRANSLOCATION
LIMITED FREE FALL THROUGH WATER
MASS MOVEMENTS
GLACIAL DEPOSITS (GENETIC TERMS)
(a) GENERAL
TILL
SUBGLACIAL TILL
SUPRAGLACIAL TILL
(b) SPECIFIC VARIETIES
PO
SA
SA
PO
DEFORMATION TILL
LODGEMENT TILL
MELT-OUT TILL
SUB-AQUATIC MELT-OUT TILL
MASS MOVEMENT TILLS e.g. FLOW TILL
MASS MOVEMENT TILLS
-SUBAERIAL
-SUBAQUATIC
e.g. FLOW TILL
MELT-OUT TILL
(INCLUDING SUBLIMATION TILL)

Figure 2.3

RELEASE OF GLACIAL DEBRIS AND ITS DEPOSITION OR REDEPOSITION			DEPOSITIONAL GENETIC VARIETIES OF TILL		
I. ENVIRONMENT	II. POSITION	III. PROCESS	IV. BY ENVIRONMENT	V. BY POSITION	VI. BY PROCESS
GLACIO-	ICE-MARGINAL:	A. PRIMARY	TERRESTIAL	ICE-MARGINAL	A. PRIMARY TILL
TERRESTRIAL		MELTING OUT	NONAQUATIC TILL	TILL	
	-FRONTAL	SUBLIMATION			MELT-OUT TILL
		LODGEMENT			-SUBLIMATION TILL
	-LATERAL	SQUEEZE FLOW		SUPRAGLACIAL	
		SUBSOLE DRAG		TILL	LODGEMENT TILL
		B. SECONDARY:			DEFORMATION TILL
	SUPRAGLACIAL	-GRAVITY FLOW	SUBAQUATIC OR	SUBGLACIAL	OR
			WATERLAIN TILL	TILL	GLACITECTONITE
GLACIOAQUATIC		SLUMPING			SQUEEZE FLOWTILL
		SLIDING AND			B. SECONDARY TILL
	SUBGLACIAL	ROLLING			
					FLOWTILL
		FREE FALL			-GRAVITY FLOWTILL
	SUBSTRATUM				

Figure 2.3 A variety of till and till process classification schemes compiled by the Till Work Group of the INQUA Commission on Genesis and Lithology of Glacial Quaternary Deposits (from Dreimanis, 1989). The upper diagram is the groups' genetic classification of tills in 1979 (after Dreimanis, 1969, 1976) which attempted to summarise both the position and migration of debris during glacial transport on the left and the final deposits, firstly in relation to position of deposition (middle column) and secondly in terms of facies nomenclature on the right. Note that deformed materials (not including 'deformation till') occur along the base of a diagram that mimics the vertical stratigraphic succession related to any one glacial phase (Hambrey and Harland, 1981). The middle diagram is the summary in 1982 of the groups' deliberations on process–form relationships, with factors that influence till production in the top half and the till genetic classifications at the base (Dreimanis, 1982). The lower diagram is the 'depositional genetic classification of till' compiled by Dreimanis (1989), with debris release and deposition on the left and till type on the right (no horizontal correlation is implied).

The term 'till' was first used by the Scots to refer to rough and agriculturally impoverished ground conditions or stoney clay and as a consequence was then adopted by Archibald Geikie (1863) as a geological term to refer to glacial deposits, specifically those that appeared as 'stiff clay full of stones varying in size up to boulders produced by abrasion carried on by the ice sheet as it moved over the land' (Geikie, 1863, p. 185). Since that time, the term 'till' has always been associated with glacial debris, and hence the frequently used variant 'glacial till' is a redundancy. However, 'till' was soon replaced by the term 'boulder clay', mostly by British geological mappers, a map unit classification that has remarkably endured on many British geology maps despite its grain-size implications being applicable predominantly only to lowland settings. Classification schemes for glacial and glacifluvial deposits were originally proposed by Chamberlin (1894a), who subdivided what was called 'glacial drift' into stratified and unstratified categories and also, together with Upham (1892), first used the term 'lodge'. The genetic qualifiers of 'lodgement' and 'ablation' were proposed for till by some early workers, such as Upham (1891a, b, 1894b), Chamberlin (1894a, b), Salisbury (1902), Tarr (1909) and Shaw (1912), after the sedimentological observations of Torell (1877). The characteristics of till were remarkably well described by James Geikie (1894), when he documented features such as 'broken' (glacitectonised) and plucked bedrock, bedrock rafts in contorted drift (previously highlighted by the British regional geologists C. Reid, S.V. Wood, J.L. Rome and F.W. Harmer), lee-side bedding, 'stone lines' (clast pavements), crude stratification, crag-and-tails and clast wear features like striae, facets and uneven edge rounding. Striated clast pavements, in places accompanied by slickensided or striated clay matrixes, were first documented by Stoddard (1859). Although till fabric analysis was not developed until the mid-twentieth century, Hind (1859) and then Miller (1884) appear to be the first to have identified non-random clast distribution in tills. Miller identified fissility in what he called 'fluxion structure', a signature of shearing in fine matrixes. Observations on the modification of clasts during glacial transport were first elucidated by T.C. Chamberlin (in Upham, 1894a) where he states the following:

> the material on the surface and slopes of a considerable number of glaciers … [are] … invariably of sharp, angular, unworn forms. … The englacial material that comes to the surface on the terminal slope of the Rhone glacier. … I found to be altogether angular and entirely without any evidence that it had been at the bottom of the glacier. … The basal material of the same glacier was, however, well rounded, and the moraines just below contained large quantities of this rounded material.
>
> Chamberlin (in Upham, 1894a, p. 85).

Although the term 'boulder clay' was widely applied to tills in the late nineteenth and early twentieth centuries based upon their massive appearance and fine-grained matrix, the apparently stratified nature of the deposits was a subject of some significant investigations, particularly by George Lamplugh (1881a, b, c, 1882, 1884a, b, 1890, 1919) in Britain but also by Crosby (1890, 1896) in the eastern USA. Lamplugh's detailed sketches of the large coastal exposures on the Holderness coast of eastern England (Figure 2.4) indicated that the depositional processes involved in the production of 'boulder clay' in the lowland glaciation record were strongly influenced by subaqueous or glacifluvial mechanisms.

The inappropriateness of the term 'boulder clay' was inherent within the definitions of its early proponents as perceived by Flint (1957) when he stated that it:

> is not a good designation for the range of deposits we know as till. It is not good because some till contains no boulders, some contains little or no clay, and some … contains neither boulders nor clay, but only silt, sand and pebbles.
>
> Flint (1957, p. 109)

At the same time, Charlesworth (1957) acknowledged that 'boulder' represented all size grades larger than pebbles (>15 cm diameter) and that the matrix, rather than exclusively always clay, varied according to the bedrock source:

> on sandstones … it is liable to be loose and sandy; on granites, gneisses and quartzose schists … it is stoney, coarse and gravelly and often hardly distinguishable from decayed rock in situ. In these cases, the term 'clay' is less appropriate than in areas of limestone, clay or shale.
>
> Charlesworth (1957, p. 377)

Hence, 'typical boulder clays' were regarded as prevalent in areas of relatively softer or finer-grained bedrock, whether that was in slate upland settings like the northern English Lake District or on coastal lowlands such as the post Cretaceous bedrock terrain around the western margins of the North Sea (cf. Lamplugh, 1881a, b, c, 1882, 1884a, b, 1890, 1919). Boulder clay matrix characteristics also displayed regional patterns, which were broadly interpreted (cf. Charlesworth, 1957) as the result of the generation of finer matrix by progressive wear over distance (i.e. from ice sheet dispersal centre to margin). The matrix generated, even over relatively short distances, was termed 'rock-flour', immediately evident in the milky, turbid nature of streams draining glaciers on hard beds. The relationship between crushing and abrasion processes and fine-grained matrix production in tills was later elucidated through the concept of 'terminal grade' (see Chapter 5). It is worth noting in this respect

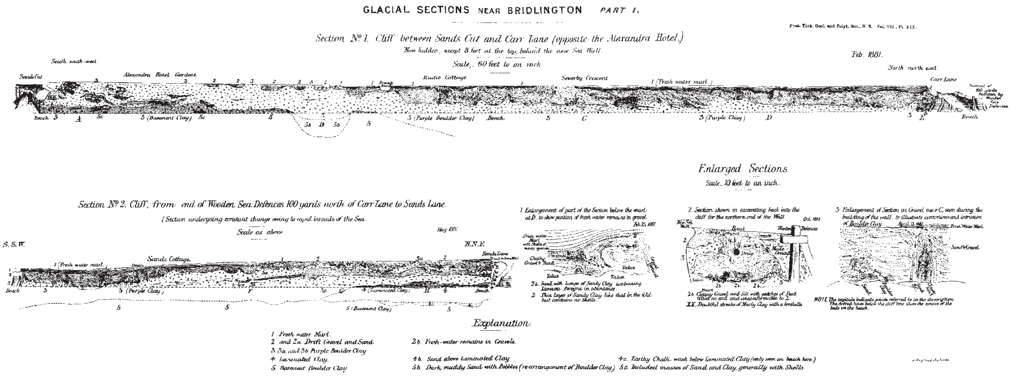


Figure 2.4 Examples of section sketches of the coastal exposures through the East Yorkshire coast tills at Bridlington, England by Lamplugh (1881a). The extent of stratified sediments and their deformation are well illustrated and were influential in Lamplugh's (1911) use of surging Svalbard glacier snouts and their proglacial deformation of foreland deposits as a modern analogue in his interpretations of till genesis.

that Lamplugh (1911) associated the clay-rich matrix of the English east coast 'boulder clays' with cannibalisation of offshore muds by the advancing North Sea glacier, akin to the processes around surging snouts he had observed on Svalbard (cf. Garwood and Gregory, 1898). The importance of matrix generation locally in this way was acknowledged by early workers (e.g. Salisbury, 1900) and was quantified by Flint (1947), who concluded that 75–90% of boulder clays had not travelled further than 80 km and long-distance erratics must have travelled mostly supraglacially or englacially and/or been reworked from earlier deposits.

By the time Dreimanis (1989) had reported on the findings of the Till Work Group, it was clear to all glacial researchers that 'till' was an extremely diverse deposit, and due to its similarities with other poorly sorted materials, it had great potential to be widely mis-identified or mis-classified. Problems continue to arise wherever the term 'till' is applied to a wide range of material types merely because they are associated with glaciation. This stratigraphic approach is particularly suited to terrain mapping where poorly sorted surficial materials are classified as till units, such as 'till plains', 'ground moraine', 'till and moraine', and so on, a procedure that can be justified if the most recent process to act upon a till is not used to genetically classify it; for example, mass movement deposits developed in till can be classified as 'flow till'. Even sedimentologists, for example, Harland *et al*. (1966) used the terms 'till' and 'tillite' for all diamictic (poorly sorted) sediment containing glacially transported material. Such an approach may avoid semantic arguments but hamper attempts to delve into the process sedimentology of glacier beds. More appropriate is the employment of a non-genetic, descriptive classification prior to genetic labelling, as is standard procedure in other realms of sedimentology. At landform and landscape scales, especially in relation to mapping, the ancient term 'drift' still has applicability despite its linkages with diluvial theory; it merely communicates that the ground surface is covered by debris of likely glacial provenance (e.g. drift mound, drift ridge, drift belt, drift limit) and continues to be employed as a non-genetic descriptor, especially in the British Isles, although alternative non-genetic terms such as 'discrete debris accumulation' (Harrison *et al*., 2008; Whalley, 2009) are becoming popular. In sedimentology, a similar procedure has long been employed by using the descriptive term 'diamicton' or 'diamict' ('diamictite' for lithified materials) for poorly sorted sediment with a wide range of grain sizes (Flint *et al*., 1960; Harland *et al*., 1966; Flint, 1971; Eyles *et al*., 1983a; Evans and Benn, 2004). Other terms proposed included 'glacial conglomerates' under the group of 'cataclastic rudites' (Pettijohn, 1949), 'conglomeratic mudstones' (Miller, 1953; Crowell, 1957; Wayne, 1963), 'paraconglomerates' (Pettijohn, 1957) and 'mixtites' (Schermerhorn, 1966; Martin *et al*., 1985; Spencer, 1985). For engineers, the term 'diamicton' when unqualified has restricted utility because it does not convey the grain size characteristics of what is a hugely variable material, which ranges from clast-supported and gravelly to matrix-supported and clay-rich deposits. Hence, Eyles *et al*. (1983a) initiated the procedure of facies codes that communicated diamicton characteristics using qualifiers (e.g. matrix-supported or clast-supported, massive or stratified diamictons or laminated diamictons, etc.).

Particularly problematic in the analysis of glacial depositional process–form regimes has always been the ubiquitous appearance of stratified material or stratified diamictons (e.g. Lamplugh, 1879), a subject that was creatively addressed by Goodchild (1875) and Carruthers (1939, 1947, 1953). Whereas thin bands of stratified sediment were readily acknowledged as the product of thin films of water created at the ice–till interface (Charlesworth, 1957), the more substantial stratified inter- and intrabeds that were associated with many outcrops of 'boulder clay' appeared to require far more subaqueous sedimentation than was compatible with the 'lodgement' process *per se*. Even the early three-fold classification scheme of Chamberlin (1883) recognised subglacial till, upper (englacial or superglacial) till and subaqueous till. The thickness of many such till sequences, and also thick massive tills, is not only a subject of significant debate developed throughout this book but also a

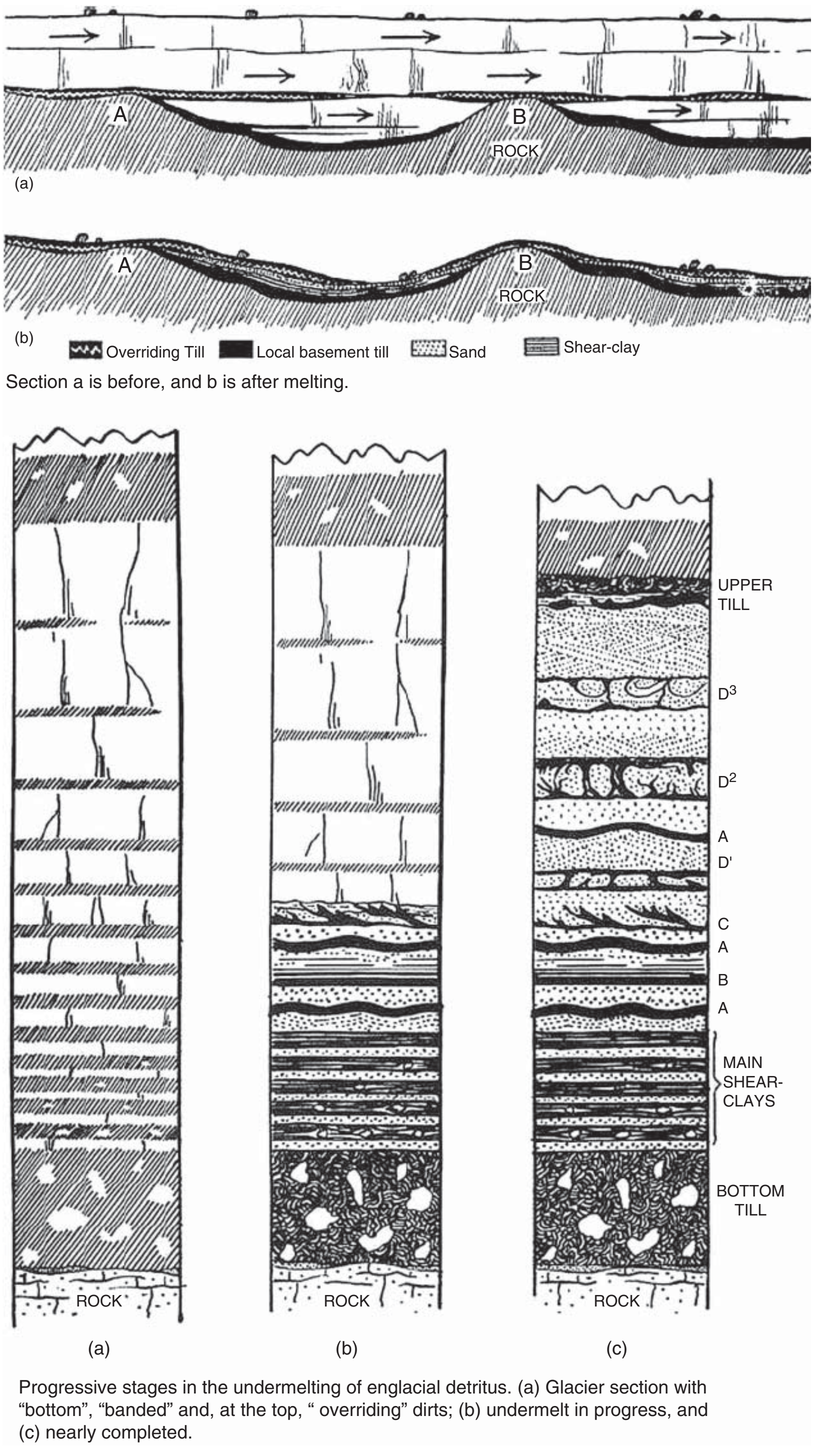


Figure 2.5 Diagrams produced by Carruthers (1947–1948, 1953) to explain his undermelt theory.

problem that emerged early on in the study of glacigenic deposits. Early studies by Penck (1882), Heim (1885), Drygalski (1897, 1898) and Wahnschaffe (1901) questioned whether or not thick 'boulder clays' could be transported as subglacial materials, and Crosby (1900) proposed only thin layers of till deposition based upon the volume of sediment emerging from beneath contemporary glacier snouts. Shaler (1870) hypothesised that the maximum depth of till that could be transported beneath glacier ice was 30 m, but the importance of englacial debris (e.g. Chamberlin, 1895; Crosby, 1896) in the formation of thick 'till' sequences was soon identified as a potential source of debris released during final glacier melt (Upham, 1891a, b, 1892; Hershey, 1897). Thus was born the problematic and controversial 'melt-out' concept.

The grandfather of the melt-out concept is widely acknowledged to be J.G. Goodchild (1875), as he was the first to propose that at least some 'boulder clays' were derived from the melting of debris-rich ice similar to that being observed at that time in Svalbard and Greenland. The principle that a subglacial till could be overlain by an englacially derived till was popular amongst those (e.g. Torell, 1877, Hitchcock, 1879; Upham, 1891a, b, 1895, Russell, 1895; Salisbury, 1896, 1902, Tornquist, 1910; Shaw, 1912) who had observed sequences of lower, dense and compact tills ('typical boulder clay') overlain by coarser and loosely packed 'upper tills', the two tills often separated by stratified deposits. From such vertical sequences came the genetic terms 'lodgement till' and 'ablation till'. What some regarded as a more extreme variant of the melt-out concept was the 'undermelt theory' of George Carruthers (1939, 1947–1948, 1953), designed to explain the more problematic clay-rich tills ('typical boulder clays') and their intra- and interbeds of stratified sediments, typified by the Holderness tills of the Eastern England coast. Although his model implied, we now understand implausibly, that even the most delicate sedimentary bedforms and laminations ('shear clays') could be perfectly preserved after englacial melt-out (Figure 2.5), Carruthers was advocating nothing more than a more passive variant of the melt-out process that was championed by earlier geologists with their 'ablation till'. What Carruthers had succeeded in articulating were the sedimentological attributes necessitated by the melt-out theory if it was to be used to explain thick, partially stratified sequences of clay-rich tills. That the model was a step too far (i.e. it was an outrageous geological hypothesis that could be falsified; Davis, 1926) was demonstrated by the fact that his last offering on the theory in 1953 had to be self-published as a pamphlet (cf. Wordie, 1950; Anderson, 1967; Bennett and Doyle, 1994). Nevertheless, the concept of passive melt-out was to return for a fresh airing in the 1970s and continues to be debated by glacial sedimentologists (see below). Additionally, the final stage in the undermelt process (Figure 2.5) depicted a style of stratigraphy that was already widely observed in the ancient glacial record (lower and upper tills separated by stratified sediments) and which was to be addressed through the application of modern Arctic analogues to ancient till stratigraphies in the late 1960s to 1970s.

After the early recognition by Torell (1877), Chamberlin (1883, 1894a, b), Upham (1891a, b, 1895), Salisbury (1902), Tarr (1909) and Shaw (1912), amongst others, that glaciers appeared to produce both basal 'lodgement' and supraglacial 'ablation' tills, it was accepted that a specific set of processes operated during the subaerial release of debris from glacier ice, leading to flowage and resedimentation (Sharp, 1949; Flint, 1957; Harrison, 1957). The introduction of the term 'flow till' by Hartshorn (1958) to classify this type of sediment was a significant benchmark in glacial sedimentology, providing a genetic label for those glacial diamictons not created by lodgement or melt-out. A significant step was then taken in the late 1960s and early 1970s when Geoffrey Boulton reported on his systematic observations on sedimentary processes operating on some Svalbard glacier snouts. His widely used conceptual model (Figure 2.6a, b; Boulton, 1972a) conveyed a process sedimentology that acknowledged the overwhelming importance in polythermal glaciers of supraglacially reworked

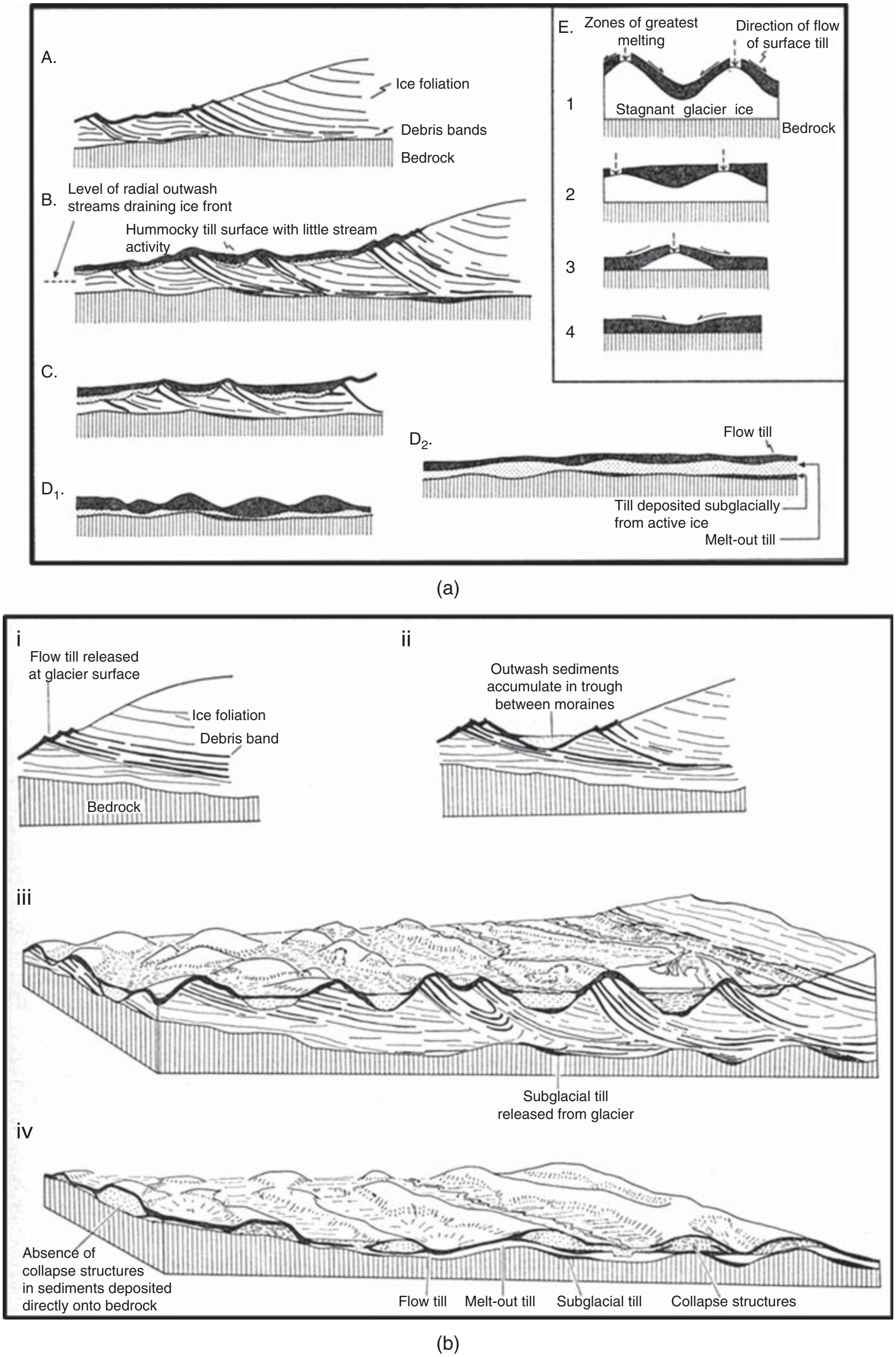


Figure 2.6 (*Continued*)

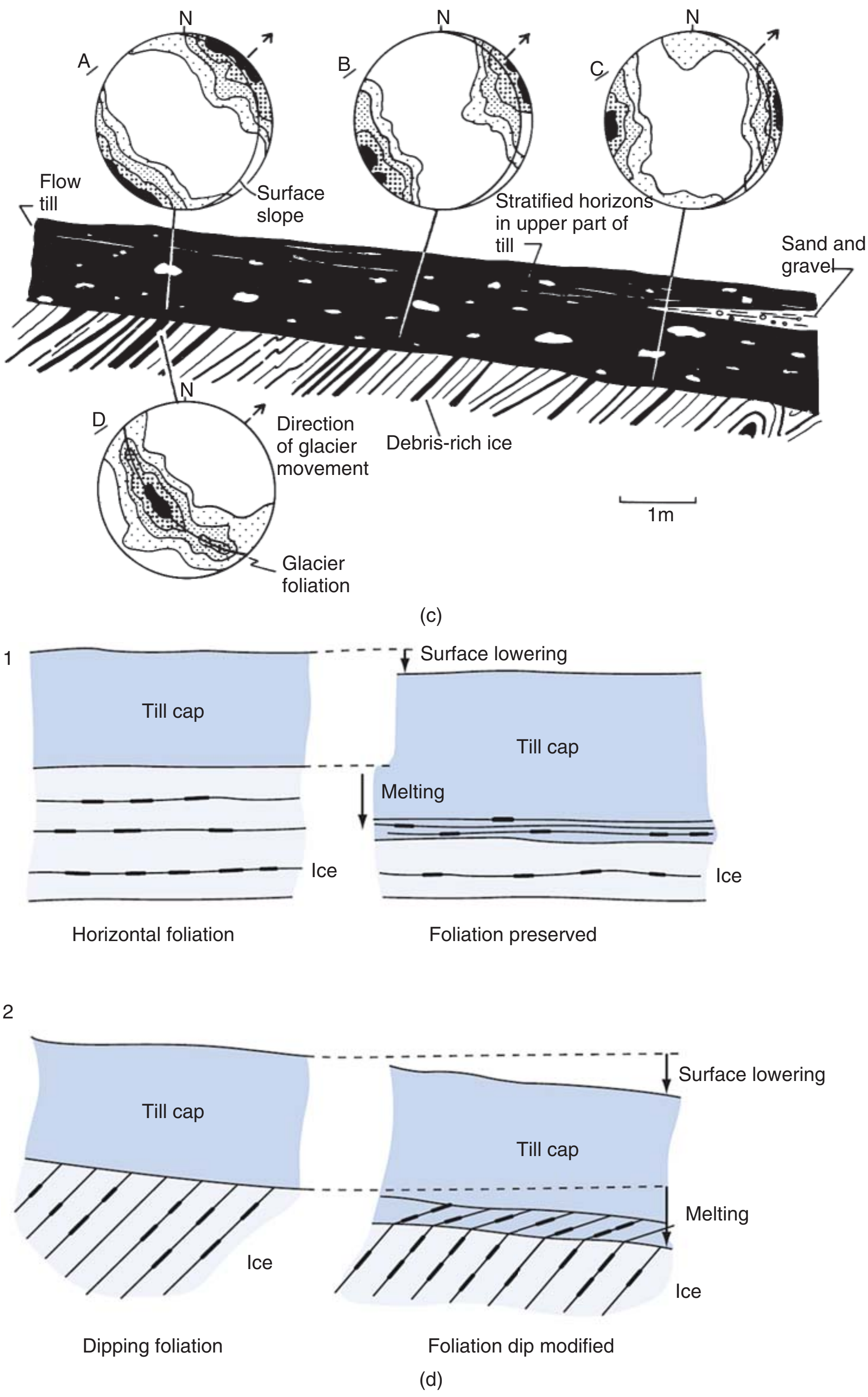


Figure 2.6 (*Continued*)

debris or 'flow tills' (Figure 2.6c; Boulton, 1967, 1968) as well as elucidating on the melt-out process in debris-rich basal ice sequences, re-affirming the broad concepts of englacial till production of Goodchild (1875) and Carruthers (1939, 1947–1948, 1953) and introducing for the first time the term 'melt-out till' (Figure 2.6d; Boulton, 1970a). The subglacial or lodgement component of the till stratigraphy in these glaciers was subordinate (Boulton, 1970a, 1971), but nevertheless combined with Boulton's melt-out and flow tills to form a tripartite sequence of till emplacement relating to one phase of glaciation, a stratigraphic model that he applied to a thick glacigenic sediment sequence at Glanllynnau, North Wales (Figure 2.7; Boulton, 1977; cf. McCarroll and Harris, 1992), which strongly resembled the final stage of the undermelt process proposed by Carruthers (1953; Figure 2.5).

A publication benchmark in till sedimentology was the release in 1971 of R.P. Goldthwait's edited volume entitled *Till: A Symposium* (Figure 2.1), wherein Boulton (1971) delivered one of his two seminal pieces on the tripartite till sequence and a range of other contributions on till sedimentology focussed on aspects such as macrofabrics, grain size and minerology of basal and 'ablation' tills; the concept of melt-out till had not been fully embraced by the glacial community at this stage even though Boulton's paper was already substantiating it. Even the knowledge base on subglacial till production processes was regarded as being in its infancy by Goldthwait (1971b) in his introduction to the volume. He summarised the state of the art on subglacial deposition as follows: (1) particles collect one by one due to frictional interference with bumps on the bed; (2) sheets of till or ice–debris mixes can be emplaced and sheared over when basal ice flow velocity drops to zero; (3) continuous basal melt brings material to the bed by the release of particles from debris-rich ice, as demonstrated in the seminal offering by Nobles and Weertman (1971) in the same volume, who developed ideas by Robin (1955), Gow *et al*. (1968) and Weertman (1964) on the melting beneath ice sheets due to thermal gradients beneath thick ice and frictional melt beneath sliding ice. On the basis of this, Goldthwait (1971b) proposed that Flint's (1957) term 'lodgement till', derived from Chamberlin's (1894a, b) term 'lodge', was most appropriate for the material produced by the combination of processes at the ice–bed interface. Goldthwait also offered three more state-of-the-art pointers that signposted future developments in subglacial deformation: (1) macrofabrics may be re-orientated within soft tills (e.g. MacClintock and Dreimanis, 1964; Evenson, 1971); (2) ice flowing over saturated tills might produce wave-like structures from which till could be injected into folds of moving ice (cf. recent proposals that till is subject to instabilities that create subglacial bedforms like drumlins and ribbed terrain; Dunlop *et al*., 2008; Fowler, 2000, 2009, 2010; Sergienko and Hindmarsh, 2013; Stokes *et al*., 2013); (3) till flows into corrugations in the ice base in sub-marginal locations (e.g. Ramsden and Westgate, 1971). Finally, Goldthwait acknowledged the importance of englacial debris in the delivery of material to thick till sheets by the final melt-out of debris-rich sub-polar ice.

Figure 2.6 Results of field observations on till production on Svalbard glacier snouts by Geoffrey Boulton: (a) diagrammatic sequence of depositional events related to the downwasting of debris-charged ice. A-D_1 depicts the development of hummocky terrain due to the continuous topographic inversions created by flowage of debris once melted out from discrete debris-rich ice folia. A-D_2 depicts the alternative scenario of till plain production due to more fluid 'flow till'. E shows the process of topographic inversion and till flowage due to uneven surface melting (from Boulton, 1972a); (b) the classic supraglacial process–form (landsystem) model of Boulton (1972a), showing the spatial relationships between subglacial, melt-out and flow tills and associated glacifluvial sediments due to the downwasting of a polythermal, debris-charged glacier snout; (c) field sketch and macrofabric data of 'flow till' observed to be accumulating on the surface of a debris-charged polythermal glacier on Svalbard by Boulton (1971); (d) simplified diagram to show the development of melt-out till as observed on Svalbard polythermal glaciers (from Boulton, 1971).

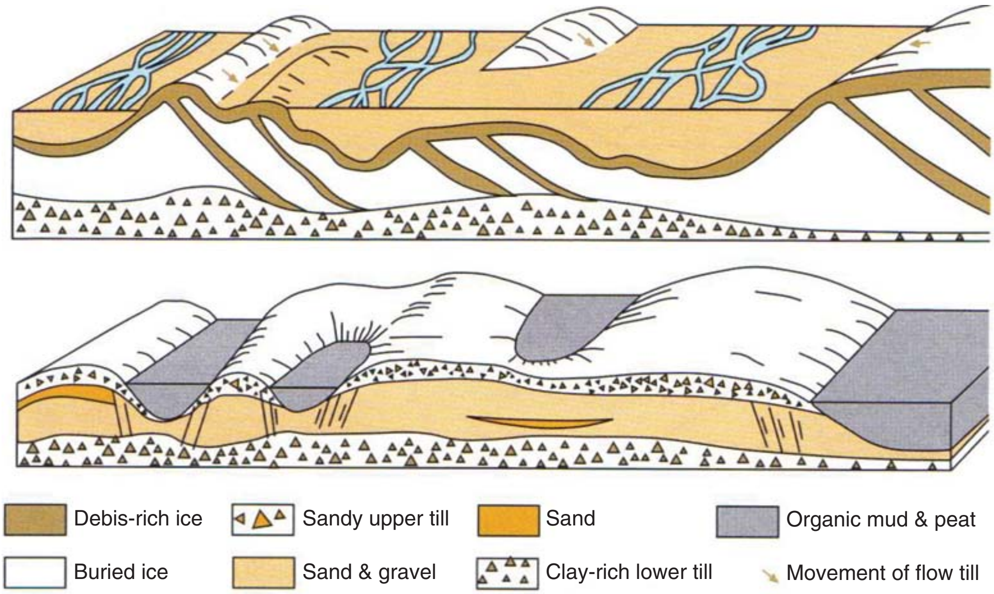


Figure 2.7 Schematic diagram interpreting the complex glacigenic sediments at Glanllynnau, North Wales (lower panel), guided by the process–form relationships observed in Svalbard (upper panel) and conveying the principle of tripartite (till-stratified sediments-till) sequences relating to one glacial advance (from Boulton, 1977).

The next symposium volume dedicated entirely to till was Legget's (1976) edited book entitled *Glacial Till: An Inter-disciplinary Study* (Figure 2.1). In terms of till sedimentology, this volume contained a review of till origins and properties by Dreimanis (1976) and a brief application of the tripartite till classification scheme to geotechnical properties by Boulton (1976); otherwise the chapters were aimed at engineering practicalities. Significant in the Dreimanis paper was the modification of his till classification scheme (Figure 2.3; upper panel) in which Boulton's (1970a, b) subglacial melt-out tills were firmly established, but the term 'melt-out' was applied to two variants, 'ablation melt-out till' and 'basal melt-out till', the former previously having been termed '(superglacial) ablation till'. Beyond Legget's (1976) collection, a number of case studies firmly established the 1970s as a decade of progress in till sedimentology in two main realms. First, Boulton's (1967, 1968, 1970a, 1972a, b) concept of 'melt-out till' was rapidly verified and consolidated by studies on modern Alaskan glaciers (Mickelson, 1971, 1973; Lawson, 1979a, b) and assessments of complex diamicton and stratified sediment sequences in ancient deposits (Shaw, 1972, 1979). Stemming from this, the benchmark study of melt-out till in modern and ancient settings was that of Shaw (1982), followed up with detailed studies by Haldorsen and Shaw (1982) and Shaw (1983). Second, the process–form regime involved in basal or 'lodgement' till production was investigated directly at the glacier bed in pioneering studies by Geoffrey Boulton, following on from his more holistic studies of till types on Svalbard (Boulton, 1974, 1975, 1979, 1982; Boulton *et al*., 1974, Boulton and Dent, 1974; Boulton and Jones, 1979). From this work came Boulton's (1974) 'critical lodgement index' whereby increasing effective pressures bring about increasing frictional resistance and concomitant grain-by-grain lodgement at the sliding ice–bed interface. Notions amongst till researchers that the subglacial bed could deform and could also initiate lodgement due to clast ploughing (e.g. Boulton, 1975, 1976, 1982) were converted into firm understandings during the late 1970s with daring experiments on soft glacier beds.

Although the subglacial deformation paradigm (Boulton, 1986) is widely acknowledged as having been initiated in the late 1970s to 1980s (the paradigm status is specifically related to contributions of deformation to glacier flow), the sedimentological signatures of till deformation were proposed much earlier in the late nineteenth and early twentieth centuries by some very perceptive observers. For example, McGee (1894) speculated on the possibility of 'differentially moving ground moraine'. Shortly afterwards, Geinitz (1903) and then Hollingworth (1931) alluded to viscous drag in subglacial materials by proposing a vertical deformation profile that increased in magnitude from the base of the deforming layer to a zone of maximum displacement near the top, after which the displacement again dropped off towards the ice – till boundary; this pattern of vertical displacement is now widely recognised in subglacial tills as we shall discuss at various places throughout this book. Other features indicative of subglacial deformation were Geinitz's (1903) and Hollingworth's (1931) 'lee tails' and 'pre-crags' (pressure boudins), Alden's (1905) cleavage slip planes or fissility, and Reid's (1885) crushed clasts. The juxtaposition of lodgement and deformation was also proposed by Virkkala (1952), and the till classification scheme of Elson (1961) clearly acknowledged the subglacial crushing and deformation processes in his terms 'comminution till' and 'deformation till', the former relating to densely crushed and ground bedrock and the latter to the partially homogenised upper layers of glacitectonically disturbed pre-existing materials. In an attempt to explain the genesis of drumlins, Smalley (1966) and, classically, Smalley and Unwin (1968) explored the discipline of soil mechanics to make till sedimentologists aware of the importance of dilatancy (expansion and contraction in response to porewater pressure changes) in the deformation of granular materials in addition to constant-volume deformation. The implications of this behaviour were clearly demonstrated in the celebrated subglacial experiments at Breiðamerkurjökull, Iceland, as reported by Boulton (1979) and Boulton and Jones (1979) and then later by Boulton and Hindmarsh (1987). At the same time, Engelhardt *et al*. (1978) identified a deforming substrate beneath Blue Glacier in Washington, USA. The Breiðamerkurjökull experiment identified a two-tiered structure in the subglacial deforming diamicton, comprising a low-strength, high-porosity upper layer (A horizon) and a stronger, higher-density lower layer (B horizon), thought to represent ductile and brittle deformation, respectively. Despite the importance of Boulton's (1970a, b, 1979) observations on subglacial deforming till, his was the only paper in the *Journal of Glaciology*'s (1979) glacier-bed processes special issue that was on the topic of deformable beds; Iverson (2010) has more recently reflected on this apparent early reticence by glaciologists to recognise till deformation, suggesting that it was an intellectual bias whereby

> experts on the flow and thermodynamics of ice were perhaps predisposed to not muddy the sliding problem with dirt.
>
> Iverson (2010, p. 1104).

Although glacial sedimentologists did not fully understand till deformation until the 1970s, glacitectonic deformation of materials was widely recognised (e.g. Torell, 1872, 1873; Johnstrup, 1874; Merrill, 1886; Sardeson, 1906; Fuller, 1914; Slater, 1927a – e; Kozarski, 1959; Elson, 1961; Moran, 1971; Rotnicki, 1976; Banham, 1977; Berthelsen, 1978), and till classification schemes at that time (e.g. Dreimanis, 1976) included 'deformation till', defined as:

> characterized by an abundance of glacio-dynamic structures such as folds, overthrusts, shear planes, injections, breccias, and mylonites formed by differential movement or compressive stresses during … lodgement processes.
>
> (Dreimanis, 1976, p. 37).

The definition arrived at by the Till Work Group was summarised by Elson (1989; cf. 1961) as follows:

> Deformation till comprises weak rock or unconsolidated sediment that has been detached from its source, the primary sedimentary structures distorted or destroyed, and some foreign material admixed.
>
> (Elson, 1989, p. 85).

This clearly referred to pre-existing materials deformed by overriding ice, although Elson (1961) originally used the term to refer to a continuum that included the deformed pre-existing materials as well as the more homogenised shear zone developed within them, which he later (Elson, 1989) compared to the deforming bed of Boulton and Jones (1979). Indeed, it was not until the recognition of subglacial deforming till layers in the late 1970s that the term 'deformation' till was applied more to tills rather than glacitectonised substrates. This application of the term 'deformation till' to subglacial deforming diamicton necessitated a development and expansion of the sedimentological nomenclature, an outcome that was extensively and exhaustively debated in the Goldthwait and Matsch (1989) volume, specifically by Dreimanis (1989), Elson (1989), Pedersen (1989) and Stephan (1989), and which strongly features Banham's (1977) term 'glacitectonite'. This was defined by Pedersen (1989) as:

> a brecciated sediment or a cataclastic sedimentary rock formed by glaciotectonic deformation.
>
> (Pedersen, 1989, p. 89).

It became clear at this time that a complex nomenclature designed to capture every nuance of a deforming glacier bed was in reality an attempt to draw sharp dividing lines within a sediment continuum and hence was increasingly of limited utility and certainly difficult to exercise in sedimentological practice. Pedersen (1989) advocated the adoption of Banham's (1977) term 'glacitectonite' instead of 'deformation till' and highlighted that Banham's scheme contained an internal nomenclature that recognised a continuum of deformation intensity (Figure 2.8); 'exodiamict glacitectonite' was sheared material that retained some primary parent structure and 'endiamict glacitectonite' was material sheared to the point where all primary structure was destroyed. Deformation till was from this time to become the homogenised or cannibalised upper contact of glacitectonites or, in other words, the endiamict glacitectonite.

Despite the fact that glacially deformed material has long been recognised, and more recently 'glacitectonite', or at least 'deformation till', is an established genetic glacial sedimentological term, there are still significant shortfalls in establishing diagnostic criteria for the description and interpretation of complex diamictons. As discussed above, terms such as 'glacial conglomerate'/'cataclastic rudite', 'conglomeratic mudstone', 'paraconglomerate' and 'mixtite' have all been proposed but tend to underplay some of the most significant common attributes of diamictons such as discontinuous stratification, pseudo-lamination, inter- and intra-bedding, soft-sediment rafts and a range of deformation structures from low-strain soft-sediment deformation to high-strain shear structures and fissility. Consequently, as we will see in the following chapters, glacial diamictons at their most heterogeneous display an often bewildering array of structures and sedimentary attributes (Figure 1.3), an appearance that some glacial researchers (e.g. Aber, 1982) have described as a 'mélange'. Although this term has genetic connotations in metamorphic rocks (Hsu, 1974), it can be employed as a non-genetic descriptive label and hence sedimentologically is a sound foundation for objective field investigations (see Chapter 4).

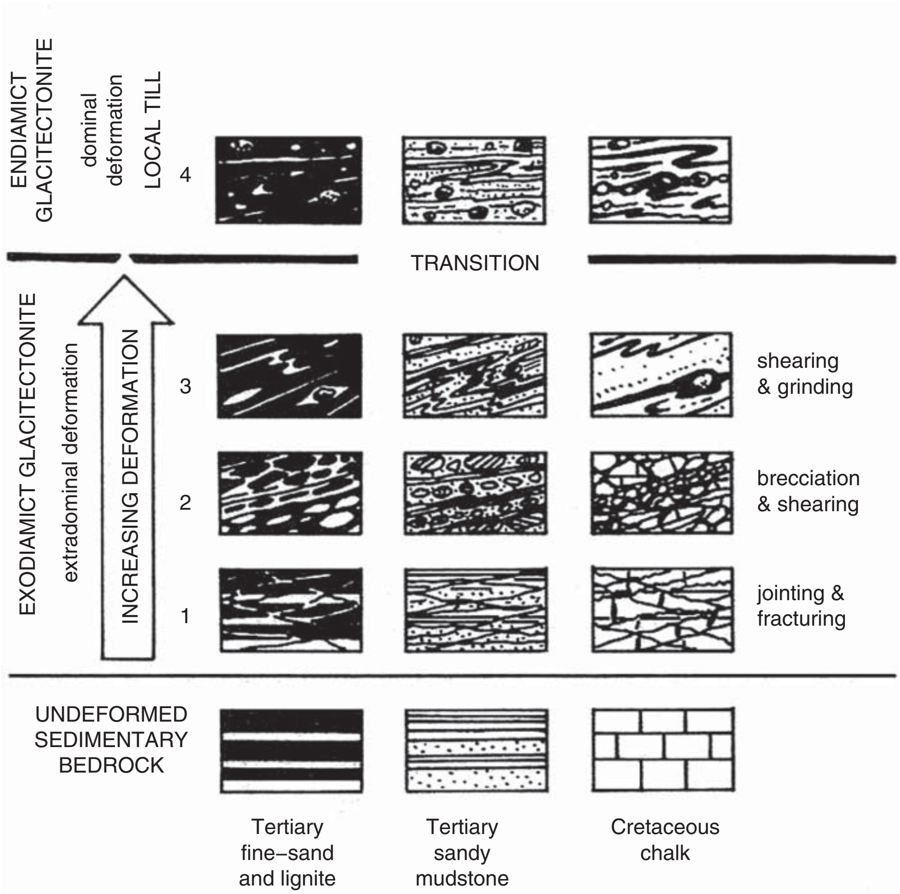


Figure 2.8 A classification scheme for glacitectonite compiled by Pedersen (1989) using the previous proposals of Banham (1977) and Berthelsen (1978).

Stratified, predominantly diamictic deposits have also long been recognised by glacial researchers (e.g. Geikie, 1894; Tarr, 1897; Kindle, 1924; Miller, 1953; Armstrong and Brown, 1954) and were classified by Harland *et al.* (1966) for those geologists working with the hard rock record as 'pseudo tillites', in contrast to the directly glacially related 'ortho tillites'. Harland *et al.* (1966) also coined the term 'para till' to cover ice-rafted debris. The lack of a suitable term for what appeared to be the submarine equivalents of terrestrial tills prompted Miller (1953) to use the term 'Yakatagite' for pre-Quaternary till-like stratified materials on Middleton Island, Alaska. Dreimanis (1969) later introduced the term 'waterlaid till' ('waterlain till' *sensu* Francis, 1975) to be used for 'a crudely stratified variety of till deposited in water' (Dreimanis, 1976, p. 39). A wide range of terms were then introduced for such deposits including 'subaquatic/subaqueous till', 'aqua till', 'underwater till', 'lacustro-till', 'marine till', 'iceberg (dump) till' and 'subaquatic ablation till' (see Dreimanis, 1976 and references therein) but were treated as unsatisfactory at the time by, for example, Flint (1971) and Boulton (1976). A process-based nomenclature has since been developed for such stratified sediments deposited clearly in deep water (cf. Evenson *et al.*, 1977; Dreimanis, 1979; Gravenor *et al.*, 1984; Powell, 1984), which gradually has moved away from using the term 'till' (e.g. 'dropstone

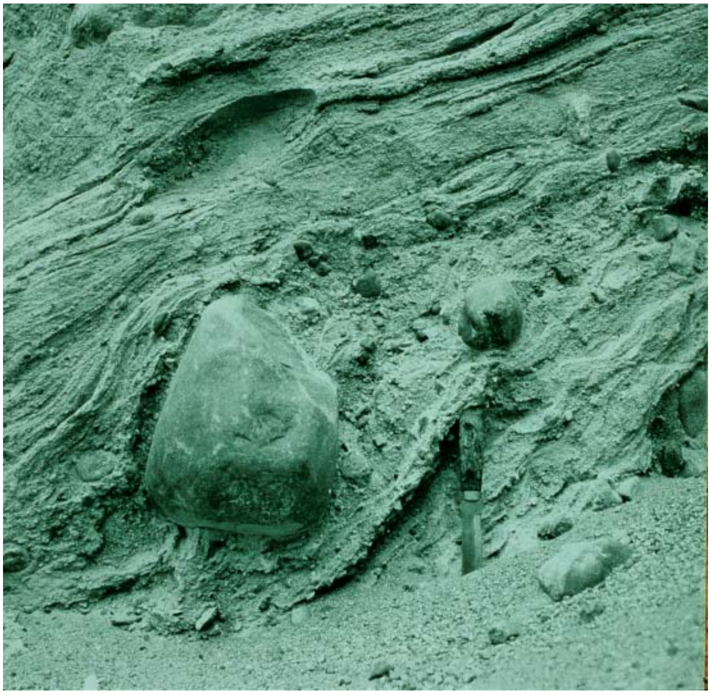


Figure 2.9 Photograph of the typical features of the Sveg till (J. Lundqvist).

diamicton', 'undermelt diamicton'), but the origins of many exposures through partially stratified and pseudo-stratified diamictons pose significant difficulties for glacial sedimentologists, especially at the complex interface between subglacial and subaqueous depositional environments. A classic example is that of the Catfish Creek Drift Formation in Ontario, Canada, a complex stratigraphic sequence of interbedded diamictons and stratified sediments, including the 'waterlaid Catfish Creek till' of Dreimanis (1976), which have been variously interpreted as subaqueous mass flow deposits, ice shelf undermelt and subaqueous flow deposits and alternating subglacial tills and meltwater cavity infills (cf. Evenson *et al.*, 1977; Gibbard, 1980; Dreimanis, 1982; Dreimanis *et al.*, 1987; Hicock, 1992, 1993; Boyce and Eyles, 2000; Dreimanis and Gibbard, 2005). Similarly, regionally significant 'stratified' till types like the 'Kalix' and 'Sveg' tills of Scandinavia (Figure 2.9) have been variously interpreted as subglacially deformed and/or waterlain (cf. Beskow, 1935; Hoppe, 1959; Lundqvist, 1969a, b; Virkkala, 1969; Shaw, 1979). In such settings, and more particularly in deep water marine settings, thick sequences of extensive massive and stratified diamictons were first highlighted by Craddock *et al.* (1964) as potentially constituting a particular problem for glacial sedimentology, because their origin as subglacial till/glacitectonite versus subaqueous rain-out is often notoriously difficult to demonstrate, as we shall see throughout this book.

This chapter has concentrated briefly on the history of till sedimentology, predominantly up until and including the deliberations of the Till Work Group, as published in Dreimanis (1989), as well as the general findings of the benchmark subglacial deformation experiments of the late 1970s. The deliberations of the INQUA 'Till Work Group' on genetic classifications for till were summarised by Dreimanis (1989; Table 2.1), identifying terrestrial and aquatic environments of deposition and the three forms of process-related till labelling (lodgement, melt-out and flow) championed by Boulton's

Svalbard observations. It is important to note that not all glacial sedimentologists were entirely convinced by the breadth of sediment types being called 'till', as demonstrated by the seminal work of Dan Lawson (1979a, b, 1981a, b, 1982) on sediments evolving around the margin of the Matanuska Glacier, Alaska. After observing the development of glacigenic diamictons in supraglacial and englacial settings, Lawson (1979a) regarded till as:

> a sediment deposited directly from glacier ice that has not undergone subsequent disaggregation and resedimentation.
>
> (Lawson, 1979a, p. 28)

Nevertheless, Table 2.1 has been employed to derive complex till types whose names reflected environment, position and process of deposition, transport process and derivation (supraglacial or subglacial). For example, Dreimanis (1989) highlighted 'glacioterrestrial subglacial melt-out till, of basal transport and subglacial derivation', from which the term 'subglacial melt-out till' would presumably suffice, because even Dreimanis acknowledged that the names 'are long and they appear cumbersome'. In their assessment of Dreimanis's (1989) genetic classification scheme for tills, Benn and Evans (2010) concluded that:

> In reality, field and laboratory techniques are not actually capable of refined assessments of the exact genesis of tills, making complex classification schemes such as that proposed by the Till Work Group difficult to apply in practice; more specifically, such schemes give a false sense that the glacial research community has accomplished a foolproof forensic procedure for the reconstruction of ancient process–form relationships.
>
> (Benn and Evans, 2010, p. 369)

Far simpler to use visually as well as communicatively was Dreimanis's (1989) tetrahedron or end member pyramid (Figure 2.10), which conveyed the three Svalbard till types of lodgement, melt-out and flow till in tandem with the more recently proposed deformation till, implying at the same time that melt-out invariably led on to lodgement, deformation or mass flows.

The preceding review forms a context for the significant details of modern till sedimentology, which is now covered in the remainder of this book. Although we will from here on concentrate on modern, or at least the most recent, studies of till sedimentology, it is appropriate also to digest in greater detail some older literature that remains pertinent today but which has been reviewed very briefly in this chapter.

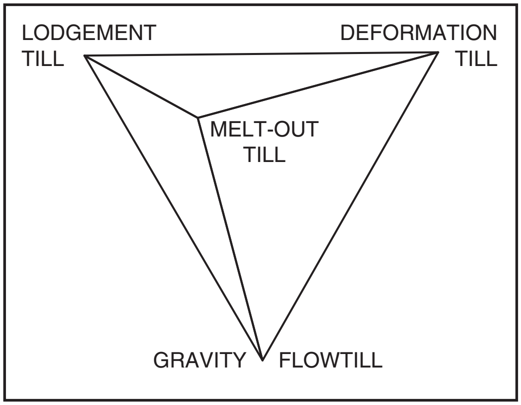


Figure 2.10 Till type tetrahedron (from Dreimanis, 1989).