The composition and internal structure of drumlins: complexity versus commonality

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Abstract:

Investigation of drumlins is significant to both glaciology and palaeoglaciology but the sheer diversity of their composition and internal structure is often cited as a major obstacle towards a satisfactory explanation of their formation. Hypotheses that receive support in one location are all too easily falsified by data from drumlins elsewhere; but most observations are gleaned from rather small sample sizes, which may not be representative and, in extreme cases, may not offer a valid hypothesis test. This paper addresses this problem and presents the first systematic survey of the vast literature on the composition and internal structure of drumlins. The overall aim is to provide a concise summary of observations and identify any emergent patterns or trends (commonality versus complexity) that hypotheses of drumlin formation should be able to explain. Results confirm that investigations are often limited by availability of suitable sediment exposures (40% of studies report data from <5 drumlins and 44% do not specify sample size), although borehole data and geophysical techniques can alleviate this problem. It is clear that the constituents of drumlins are incredibly diverse in terms of their composition (e.g. a range of lithologies, clast shapes, sizes and fabrics); structure (e.g. sediments that are stratified, homogeneous, surface conformable, unconformable); and evidence of deformation (e.g. ranging from widespread, to partial, to absent). Despite this diversity, our review leads us to suggest that drumlin composition can be simplified to five basic types: (i), mainly bedrock, (ii), part bedrock/part till; (iii), mainly till; (iv), part till/part sorted sediments; and (v), mainly sorted sediments. This is a potentially significant step, in that it reduces the oft-cited complexity of drumlin composition and provides a more realistic goal for theories or numerical models of drumlin formation to target. These different types can occur within the same drumlin field, which leaves us with two possible implications for drumlin formation. (1) Different types of drumlin are formed by different processes, despite being morphologically similar (equifinality?) – investigation of drumlin composition may, therefore, reveal diagnostic processes/explanations for these different types of drumlin and we argue that bedrock 'drumlins' are a good example. (2) A single process occurs across large parts of the ice-bed interface to create drumlinised terrain in a variety of sediments – investigation of drumlin composition may, in this case, simply reflect pre-existing sediments but, importantly, the way in which the drumlin-forming mechanism modifies/is modified by them. We argue that the latter, simpler, explanation applies to the other four types of drumlin and conclude that the diversity in drumlin composition is not an obstacle to a single unifying theory.

1. Introduction

Drumlins are ubiquitous on former ice sheet beds and are probably the most extensively studied bedform produced beneath glaciers (e.g. Menzies, 1979a; 1984; Clark et al., 2009). The 'text-book' description of a drumlin typically describes them as streamlined oval-shaped hills with a long axis parallel to the orientation of ice flow and with an up-ice (stoss) face that is generally steeper than the down-ice (lee) face (cf. Menzies, 1979a; although see Spagnolo et al., 2010; in press). Analysis of a large sample of drumlins from Britain (>30,000) reveals that they are typically between 250-1000 m long, 120-300 m wide and between 1.7-4.1 times as long as they are wide (Clark et al. 2009).

Scientifically, investigation of drumlins is important for at least two main reasons. First, their alignment with former ice flow direction makes them an important (if not essential) ingredient in glacial geomorphological inversion models employed to reconstruct the dynamic behaviour of palaeo-ice sheets through time (e.g. Boulton and

Clark, 1990; Kleman and Borgström, 1996; Kleman et al., 1997; Greenwood and Clark, 2009a, b). For example, it has also been suggested that their shape and, in particular, their elongation ratio (length divided by width), is related to former ice velocities (Chorley, 1959; Hart, 1999; Stokes and Clark, 2002; Hess and Briner, 2009).

Second, drumlin formation results from subglacial processes that are difficult to investigate beneath modern-day ice sheets. Their form and composition, therefore, preserve important information regarding how ice flow interacts with its substrate and knowledge of such processes is crucial to understanding the dynamics of present-day ice sheets. Subglacial processes beneath present-day ice sheets are rather poorly constrained, but we do know that they produce bedforms (including drumlins), which has recently been confirmed by geophysical investigations of their existence and 'growth' beneath the Antarctic ice sheet (King et al., 2007, 2009; Smith et al., 2007). However, detailed investigation of drumlins beneath contemporary ice sheets, especially regarding their composition and internal structure, still represents a major logistical challenge. Thus, drumlins on deglaciated glacier forelands and palaeo-ice sheet beds can provide information crucial to our understanding of subglacial processes beneath ice sheets. This, in turn provides improved constraints for the development of physically-based numerical models of drumlin formation (e.g. Hindmarsh, 1998; Fowler, 2000) and ice flow dynamics. As Baranowski (1979: p. 435) notes: "… until the mechanism responsible for drumlin formation is fully understood, some of the key glaciological problems related to the glacier bed will remain obscure". In this respect, drumlins represent an important link between glaciology and palaeo-glaciology.

Despite the importance of drumlins to both glaciology and palaeoglaciology, their origin is enigmatic and controversial, with many competing (and sometimes radically different) ideas put forward to explain their formation (e.g. Fairchild, 1929; Smalley and Unwin, 1968; Smalley, 1981; Shaw, 1983; Boulton, 1987; Hindmarsh, 1998; Fowler, 2000). It has been pointed out that the lack of consensus regarding their formation is largely due to the large variability of both drumlin form and their internal composition (see excellent overviews in Menzies, 1979a; Patterson and Hooke, 1995; Benn and Evans, 1998). Observations that are used to support one hypothesis in one location are often not found in other locations. Moreover, both their morphometry and their composition have been used to develop theories of drumlin formation, with different workers often placing a greater emphasis on which they consider to be most important or diagnostic with regard to the drumlin-forming mechanism. For example, Boyce and Eyles (1991: p. 787) suggest that the lack of consensus regarding drumlin formation is "due fundamentally to a lack of detailed studies of the subsurface geology of drumlin fields"; whereas in another study, Fisher and Spooner (1994, p. 294) suggest that "drumlin form rather than internal sedimentology" be used to support their proposed mechanism of formation.

If there is a universal explanation for drumlin formation, which might be a reasonable goal given the unimodal distribution of their size and shape (cf. Clark et al., 2009; Spagnolo et al., 2010), the more robust hypotheses of their formation will be those that are able to withstand falsification by large datasets/observations of both their form and their composition. Recent advances in the spatial resolution of remote sensing products, particularly digital elevation models, have enabled rigorous analysis of large datasets of drumlin morphometry (e.g. 44,500 in Spagnolo et al., 2010; >37,000 in Clark et al., 2009; and >6,500 in Hess and Briner, 2009). Unfortunately, techniques that enable analysis of large sample sizes of their composition and internal structure are very rare, and investigations are traditionally based on localised field observations of a small number of sediment exposures (discussed in section 2). As Clapperton (1989) notes, the "lack of data on internal structures precludes tightly constrained testing of hypotheses of drumlin formation" (p. 397). Indeed, given the diverse range of drumlin constituents, we are often left wondering which sets of observations are more common and which are more unusual or obscure. A systematic study of a large sample survey would go some way in addressing these issues and we note that there are numerous reports of drumlin composition and structure in the literature (we estimate >200 papers) that date back to the 19th century (e.g. Upham, 1892).

1.1. Aims and scope

The overall aim of this paper is to systematically compile observations of drumlin composition and internal structure into a large sample in order to distil any patterns or trends that may provide new insights regarding drumlin genesis and act as a stimulus for further research. Given the often bewildering level of complexity surrounding drumlin constituents, we intentionally refrain from an in-depth discussion of the myriad of impressive sedimentological features that are reported (though that would also be a worthwhile effort) and focus instead on summarising various aspects of drumlin composition with the aim of evaluating whether any commonality exists that theories of drumlin formation should be able to explain. In doing so, we hope to reduce the oft-cited complexity that so often surrounds this subject and provide a comprehensive yet accessible review. In this sense, although the paper is reviewing sedimentological features, it is not written for sedimentologists but, rather, those who are unfamiliar with this body of literature and who are interested in solving the crucial puzzle of how drumlins form, and want to know what sediments and structures are found in drumlins that ought to be addressed by a successful theory.

We note that Menzies (1979a) also addresses the question of internal composition in his influential review on drumlins and we build on and update that work, benefiting from more recent studies and with a sole focus on drumlin composition and internal structure (whereas Menzies covered a number of other aspects such as location, morphometry, patterning, etc.). Our paper is not intended to be an exhaustive review of this vast body of work, although the reference list is deliberately extensive for those who wish to dig deeper; and nor is it intended to provide a critique of observations of internal structures or hypotheses regarding drumlin formation. Indeed, in striving for an objective synthesis of observations, we purposely refrain from subjectively 'updating' or 're-analysing' older observations within modern paradigms. As such, some descriptions need to be viewed through a temporal context (for example, with respect to various approaches to terms used to describe till and its stratigraphy: Menzies et al., 2006).

The structure is built around a series of fundamental questions which we regard as key questions to help inform or inspire formational theories for drumlins and which can be more fully answered by drawing on observations from numerous studies rather than specific case studies:

- What are drumlins composed of; are there different types of drumlin; and are some more common than others?

- How variable are the sediments inside drumlins; both within the same drumlin field and between drumlin fields?
- Where are drumlin sediments derived from and how do the sediments inside drumlins compare to those in inter-drumlin areas?
- What clast sizes, shapes, fabrics and deformation features are found within drumlins?

Section 2 provides a brief summary of the various techniques to investigate drumlin composition and sections 3 to 9 answer the above questions with reference to various aspects of drumlin composition such as the main constituents of drumlins (section 3), specific veneers and carapaces that have been reported (4), specific stoss and lee features (5), and features associated with subglacial deformation (6). Variability of drumlin composition is described in section 7, followed by a review of sediment provenance (8) and clast shapes, sizes and fabrics (9). As noted, the aim is to provide objective and concise summaries and identify any commonality that may exist across a broad range of studies. The paper culminates in a more subjective discussion (section 10) of two further questions, which are arguably the most important:

- How representative are observations of drumlin composition and internal structure?
- What does the variability of drumlin internal structure tell us about drumlin formation?

2. Techniques to Investigate and Sample Drumlin Sediments

2.1. Direct field observation of sediment exposures

By far the most common technique is that of direct field observation and sedimentary logging/analysis of sediments exposed in a drumlin. The majority of studies that use direct field observations report detailed logs of sediment exposures and often note clast shape, sizes and patterns in macro-fabric analyses (e.g. Dardis, 1985; Clapperton, 1989; Hart, 1995a; Meehan et al., 1997). Additional data have also been obtained using sediment geochemical analyses (e.g. Newman et al., 1990; Aario and Peuraniemi, 1992; Stea and De Piper, 1999) and, more recently, micromorphological analyses of sediment thin sections (e.g. Menzies and Maltman, 1992; Menzies et al., 1997; Yi and Cui, 2001; Menzies and Brand, 2007).

Bespoke trenches or excavations have been created for some studies (e.g. Nenonen, 1994), and are especially well-suited to small bedforms (e.g. Fuller and Murray, 2002), but drumlins are usually large and trenches and excavations can be expensive, difficult to dig, and may introduce problems of disturbance. Thus, most studies rely on providential natural exposures "wherever these were available" (Hill, 1971: p. 19). A potential disadvantage therefore, is that investigators are often restricted to a small 'window' into the drumlin interior and sometimes just a few metres of exposed sediments in a drumlin that might be 10s metres high. Moreover, it means that investigators have little or no control over a sampling scheme, i.e. in terms of which parts of the drumlin the sediments are exposed. Vertically, they may, for example, be restricted to sampling the basal sediments or surficial sediments. Longitudinally, they might be restricted to only the stoss or lee side of the drumlin and, laterally, they could be analyzing one flank of the drumlin but not the other. In some cases, however, it has been possible to investigate entire cross-sections through drumlins, usually as a result of aggregate extraction (e.g. Shaw, 1983; Hanvey, 1987; Sharpe, 1987; Menzies and Brand, 2007); road-building (e.g. Hill, 1971) or extensive lake/coastal erosion (e.g. Hanvey, 1989; Newman and Mickelson, 1994; Hart, 1995a; Menzies et al., 1997; Stea and Pe-Piper, 1999; Kerr and Eyles, 2007). A classic example of this latter case are the extensive drumlin exposures on the southern shore of Lake Ontario, which have attracted the attention of several workers (e.g. Slater, 1929; Menzies et al., 1997), including Fairchild (1907), who swam out into the lake to observe them from a distance.

Some studies systematically examine sediments at both the stoss and the lee of a drumlin (e.g. Yi and Cui, 2001; Fuller and Murray, 2002) but we note that continuous longitudinal sections (e.g. McCabe and Dardis, 1994) are relatively rare, compared to transverse cross-sections. The key advantage of any continuous cross section, of course, is that it is possible to observe the overall 2D architecture of drumlin sediments and how they relate to each other and, crucially, to the overall drumlin shape. However, the ideal condition of having one entire cross section running parallel to the drumlin and one entire cross section running perpendicular, see Figure 1, is impossible to attain in nature.

A further fundamental sampling issue, noted by Goldstein (1989: p. 241), is that "even where detailed structural, stratigraphic, and sedimentological studies have been carried out, […] they are usually based on observations at only one or a few exposures". Indeed, our review of the literature indicates that around 40% of papers report data from a small (<5) sample of drumlins from drumlin fields of hundreds (and sometimes thousands) of landforms, see Figure 2. Moreover, of the remaining studies, 44% do not specify the number of drumlins that were investigated. A potential drawback of the traditional field observation of drumlin internal structure, therefore, is that sampling is usually only possible from a limited number of drumlins within a much larger drumlin field. Whether a small sample of observations is representative of the whole drumlin field is often difficult to ascertain but we note the value of those studies that report larger than average sample sizes, e.g. 33 (Hart, 1997); >50 (Goldstein, 1989); 55 (Dardis et al., 1984); 76 (Hill, 1971) and 90 (Dardis, 1985).

In summary, direct field observation is by far the most common technique employed to investigate drumlin composition and internal structure. It has to be acknowledged, however, that this approach can suffer from inherent sampling problems, which most workers recognize as a major limitation. As Habbe (1992, p. 69) notes, "the relation between drumlin sediments and drumlin form have been a matter of discussion for more than 80 years due to the rareness of good exposures in drumlins".

2.2. Systematic borehole and surface sampling

In addition to field observation of sediment exposures, some studies have utilised borehole and/or shallow surface sampling techniques, which can greatly increase the spatial extent of observations and, crucially, introduce a more systematic sampling strategy (e.g. Goldstein, 1989; Boyce and Eyles, 1991; Ellwanger, 1992; Habbe, 1992; Wysota, 1994; Zelčs and Dreimanis, 1997; Rattas & Kalm, 2001; Jørgensen and Piotrowski, 2003; Rattas and Piotrowski, 2003; Raukas and Tavast, 1994). Boyce and Eyles (1991), for example, utilised almost 7,000 borehole logs which enabled them to detect a down-ice changes in the stratigraphy of drumlins along a 70 km flow-line in the Peterborough drumlin field, Ontario (Canada), further augmented by geophysical data and morphometric analysis of almost 1,000 drumlins. Likewise, Goldstein (1989) sampled surficial sediments (< few metres) from over 125 localities within the Wadena drumlin field, west-central Minnesota, in addition to around 20 pre-existing boreholes logs that extended to greater depths (up to 150 m). The texture, lithology, and mineralogy were systematically investigated in order to identify trends in drumlin internal structure.

As suggested by these examples, borehole and surface sampling allows spatial trends in drumlin composition and internal structure to be identified, which can be a distinct advantage. However, it is important to acknowledge that borehole results often rely on the assumption that the internal structure of a drumlin is homogenous enough to be described by one or two boreholes that may be randomly placed within the body of a drumlin. Indeed, a limited number of 1-dimensional boreholes are likely to be of less use than a limited number of sediment exposures, which do at least offer a 2-dimensional perspective.

2.3. Indirect (geophysical) investigation

Recent work has recognised the potential of using geophysical techniques (e.g. ground penetrating radar (GPR), seismic and electrical resistivity surveys) to investigate the internal structure of drumlins, circumventing the need for finding suitable sediment exposures (e.g. Kulessa et al., 2007; Hiemstra et al., 2008). Such techniques have the advantage of being able to provide 3-dimensional visualisations of drumlin content (e.g. Figure 1). It should be recognised, however, that interpretation of geophysical data can be difficult (e.g. differentiation between various till units: Kulessa et al. 2007), especially in the absence of exposed sediments to help constrain observations, and that this kind of investigation requires expensive equipment compared to more traditional field methods.

Significantly, geophysical techniques have also enabled investigators to detect bedforms beneath existing ice masses, at depths of almost 2 km below the ice surface (King et al., 2007; 2009; Smith et al., 2007; Smith and Murray, 2009). The major advantage of these studies is that ice dynamics are well-constrained, allowing investigators to link bedform characteristics to specific glaciological conditions (e.g. ice velocity, thickness and stress regime). Crucially, the surveys can also be repeated, so that temporal changes in bedform evolution (e.g. sediment erosion and deposition) can be identified. Repetition of seismic reflection lines on Rutford Ice Stream, West Antarctica, in 1991, 1997 and 2004, for example, revealed localised erosion rates of ~1 m a^{-1}, followed by the growth of a mound of sediment downstream (10 m high and 100 m wide) interpreted as a drumlin (Smith et al., 2007), but more recently recognised as a more elongate mega-scale glacial lineation (King et al., 2009). It is, of course, very difficult to sample sub-ice stream sediments directly, but the seismic data are of sufficient resolution to indicate that the mound of sediment is composed of one unit, interpreted by the authors to be an actively deforming sediment, emplaced on top of a harder, non-deforming substrate.

3. Types of Drumlin Composition and Internal Structure

This section provides a review of the observations of drumlin composition and internal structure in the literature but it is important to begin by simply outlining the different aspects that might potentially be most relevant to theories of drumlin formation, illustrated in Figure 3. Note that most studies simply refer to drumlin 'internal structure' but we make a distinction between drumlin 'composition', which only refers to the constituents, and drumlin 'structure', which only to the spatial arrangement of the constituents and their relationship to each other.

First, one might be interested in the composition of the sediments in a drumlin and whether they are unsorted (e.g. till), sorted (e.g. glaciofluvial) or simply composed of bedrock (or a combination). It might also be interesting to examine whether their content is distinct from the adjacent non-drumlinised terrain, although this is more difficult, in practice, because flatter inter-drumlin areas are even more likely to be devoid of exposures. Second, it would be important to note whether the sediments are homogenous, stratified or show structures that are conformable with the drumlin surface, hinting at possible depositional or erosional processes. Third, it might be interesting to consider the presence of deformation structures. These could be limited, partial or widespread and might reveal the nature of any glaciotectonic deformation before, during or after drumlin formation. The diagrams in Figure 3 are three simple end members of each aspect and it is known that more complex combinations exist. Additionally, there are several other aspects of drumlin composition structure that are potentially important and have attracted the attention of numerous workers. These include clast fabric analysis, veneers of superficial deposits, and specific stoss and lee-features (etc.), but the aspects shown in Figure 3 are, arguably, the most fundamental characteristics that formational theories would need to address.

Ideally, it would be possible to systematically review the literature and quantify the number of drumlins with a specific composition, structure, and style of deformation. In practice, however, we find that this is simply not possible, partly because of the problems associated with the nature of the observations themselves (e.g. availability of suitable sediment exposures, see section 2) but also partly because different papers tend to focus on particular aspects of drumlin composition or internal structure. Indeed, we find that most papers primarily report on the composition of the drumlin and it is for this reason that this component dominates our review and categorisation in this section, although we note observations of internal structures where they are reported.

In his seminal review of the location and formation of drumlins, Menzies (1979a) stated that “the internal composition of a drumlin varies from stratified sand to unstratified till to solid bedrock, with every possible permutation between” (p. 319). This mantra is often repeated in papers (e.g. Dardis et al., 1984) and textbooks (e.g. Benn and Evans, 1998) and has often been seen as a major obstacle to a unifying theory of drumlin formation. A recent paper by Kerr and Eyles (2007, p. 8), for example, states that “uncertainty [in drumlin formation] arises largely because of the sedimentological and stratigraphic variability of their cores”. Whilst it is undoubtedly true that drumlin composition is incredibly varied, our review of the literature suggests that the wide variety of observations can, in fact, be distilled into a limited number of basic types that are reported, which we categorise as:

1. Mainly bedrock
2. Part bedrock/part till
3. Mainly till
4. Part till/part sorted sediments
5. Mainly sorted sediments

These categories might be viewed as conjectural but we find that it is a relatively straightforward task to group all previously-reported observations of drumlin composition into one of these five basic types. We acknowledge the intrinsic limitation of any classification and the likelihood of a continuum of drumlin compositions, but we believe that the identification of these categories is a necessary move to simplify the complexity that has so often inhibited progress towards a satisfactory explanation of drumlin formation. This is a potentially significant step because recent advances have been made in the numerical modelling of drumlin formation (e.g. Hindmarsh, 1998, Fowler 2000) which, so far, have preferentially focused on validation against drumlin morphology. As Hiemstra et al. (2008, p. 46) note, "such theoretical studies have yet to provide a solution for the sedimentological and structural-architectural variability in drumlins as recorded in the field". If it can be demonstrated that the composition and internal structure of drumlins can be simplified to a few simple types, then it appears a far more attainable goal for numerical modelling to seek validation against these types, rather than numerous site specific observations.

Moreover, we note that a number of studies have already recognised some of these categories (e.g. Wysota, 1994). For example, 'till drumlins', 'glaciofluvial drumlins' and 'bedrock-cored drumlins' were distinguished within the same drumlin field in northern Latvia by Danilans (1973) and Straume (1979), both cited in Zelčs and Dreimanis (1997); and correspond to our 'mainly till', 'mainly sorted sediments', and 'part bedrock/part till' drumlins, respectively. Likewise, Raukas and Tavast (1994) describe a variety of drumlins on the Fennoscandian Shield, including "whaleback bedrock forms […], rock-cored drumlins, drumlins with cores of stratified deposits and/or older till, and drumlins which consist of entirely homogeneous till" (p. 374). It is important to state that these categories refer to the main constituents of the drumlin and do not include the thin carapaces or veneers that are often reported in conjunction with the bulk contents and which typically make up <10% of the drumlin at its highest point (e.g. Hart, 1995a; Menzies and Brand, 2007). Likewise, they do not incorporate specific stoss (e.g. Hart, 1995a) or lee sediments (Dardis et al.,1984; Ellwanger, 1992) which appear to require an obstacle (i.e. the drumlin) to form prior to their emplacement, such as stratified lee-side sediments (Dardis et al., 1984). Note that we do not include reports of ice-cored drumlins because they are transient features that will degrade into more permanent glacial topography such as hummocky moraine (e.g. Schomacker et al., 2006). The following sections provide a concise and objective summary of the characteristics of each of these drumlin types.

3.1. Mainly bedrock

There are several papers that report the occurrence of what are variously termed 'bedrock drumlins', 'rock drumlins' or 'tadpole rocks' (e.g. Fairchild, 1907; Linton, 1964; Glückert, 1973; Dionne, 1987; Raukas and Tavast, 1994; Evans, 1996; Heroy and Anderson, 2005; Kerr and Eyles, 2007). These are often described as streamlined landforms composed entirely of bedrock. It has been pointed out that they can be formed in a variety of rock types from Precambian shield rocks to younger sedimentary rocks (Dionne, 1987), although research on submarine glacial landforms on continental shelves characteristically reports 'bedrock' drumlins on harder, crystalline bedrock of the inner shelf areas (e.g. Heroy and Anderson, 2005; Graham et al., 2009).

Drumlins composed entirely of bedrock appear to be very similar to other types of intermediate-scale (1-10 km) streamlined erosional features (e.g. roche moutonée, whalebacks, etc.), which are often grouped together in text-book classifications of glacial erosion landforms (e.g. Sugden and John, 1986; Benn and Evans, 1998). Indeed, various names are often used interchangeably with the term 'rock drumlin' (cf. Bennett and Glasser, 1996), particularly the term 'whaleback'; although Evans (1996) points out that a whaleback is typically symmetrical in longitudinal cross section, whereas rock drumlins are asymmetrical, with a steeper stoss slope and gently tapering lee slope. The absence of a plucked lee face distinguishes these features from roche moutonée (Evans, 1996). It is for this reason that some workers have suggested that it would be helpful to differentiate between drumlins composed of entirely consolidated bedrock and those composed of unconsolidated sediments (e.g. Fairchild, 1907; Dionne, 1984; 1987). Dionne (1987), for example, recommends the term 'tadpole rock' be used. This would appear to be a valid point and we also argue that 'rock drumlins' should be distinguished from other drumlins and that the use of the word 'drumlin' to describe such bedrock features might be inappropriate and misleading (see discussion section 10.2.1.1).

3.2. Part bedrock/part till

Several studies report drumlins that are composed of a combination of bedrock and till (Crosby, 1934; Hill, 1971; Gluckert, 1973; Dionne, 1987; Moller, 1987; Boyce and Eyles, 1991; Nenonen, 1994; Fisher and Spooner, 1994; Raukas and Tavast, 1994; Hart, 1997; Meehan et al., 1997; Zelčs and Dreimanis, 1997; Yi and Cui, 2001; Fuller and Murray, 2002). The proportion of bedrock and till in such a drumlin is, of course, variable, although Dionne (1987) suggested that the till should account for at least 25% of the entire drumlin volume to distinguish it from more bedrock dominated forms (e.g. described in section 3.1).

Some part bedrock/part till drumlins possess a core of consolidated rock, surrounded and entirely covered by unconsolidated sediments that include one or more units of till and/or glaciofluvial sediments (Boyce and Eyles, 1991; Nenonen, 1994; Fisher and Spooner, 1994; Meehan et al., 1997; Yi and Cui, 2001), hence the often used terms of 'rock-cored' drumlins. This core can be positioned at the stoss (Gluckert, 1973; Boyce and Eyles, 1991; Tavast, 2001), middle (Tavast, 2001) or lee (Tavast, 2001) of the drumlin, although it appears that most of the reported rock-core drumlins have the bedrock towards stoss end (e.g. Boyce and Eyles, 1991; Yi and Cui, 2001; Fuller and Murray, 2002). We also note that the relative position of the core has also been shown to vary within a single drumlin field (Raukas and Tavast, 1994; Fisher and Spooner, 1994). Figure 4 (a) shows an example of bedrock-cored drumlins in the northern part of the Peterborough drumlin field, Ontario, Canada.

The sediments found in association with a bedrock 'core' are diverse. At the simplest level, a rock cored drumlin may be surrounded by a single unit of till, such as the one that Meehan et al. (1997) describe in NE Ireland that attains a maximum thickness of 5.4 m. They also report that the weathered sandstone bedrock has been sheared up into the overlying till. In contrast, Fuller and Murray (2002) report evidence of two till units in association with a rock cored drumlin in Iceland and Fisher and Spooner (1994) report an homogenous till in association with gravel and sand veneers (particularly in the lee-side) and stratified glaciofluvial sediments in the Bow Valley, Alberta. It is also clear that part bedrock/part till drumlins are often found in the same swarm as those that do not, apparently, have a component of bedrock (cf. Hill, 1971;

Newman and Mickelson, 1994). In other cases, part bedrock/part till drumlins appear to be the dominate type. Möller (1987: p. 116), for example, reported that “a field check of 96 streamlined ridges revealed one or more visible rock cores at 81% of the sites visited” in the Åsnen area of Sweden. Likewise, Crosby (1934) estimated that at least 25% of drumlins in the Boston Basin, Massachusetts, have rock cores.

It should be acknowledged that in some cases it might not be possible to ascertain the full extent of the bedrock ‘core’ and, depending on the extent of the exposure, it may even be possible to misinterpret large boulders (especially crystalline) as bedrock. We also note that, in their review, Patterson and Hooke (1995) pointed out that in some drumlinised areas, small bedrock protuberances are present in drumlin fields that are not associated with drumlins (e.g. citing Fairchild, 1907; Aronow, 1959; Gluckert, 1973; Gillberg, 1976).

Finally, the term ‘crag and tail’ is often used interchangeably with part bedrock/part till drumlins but this term is usually used (cf. Dionne, 1987) to describe landforms where the bedrock occupies the entire stoss portion of the landform and is exposed at the surface, with unconsolidated material forming an obvious tail it its shadow. In contrast, where the exposed bedrock occurs in the lee of the landform, the term ‘pre-crag’ has been used (cf. Haaviston-Hyvärinen, 1997).

3.3. Mainly till

A third type of drumlin commonly reported in the literature are those composed mainly of till (e.g. Lincoln, 1892; Fairchild, 1907; Sharp, 1953; Wright, 1957; Aronow, 1959; Wright, 1962; Harris, 1967; Hill, 1971; Gravenor, 1974; De Jong et al., 1982; Dardis, 1987; Piotrowski, 1987; Dardis and McCabe, 1987; Clapperton, 1989; Goldstein, 1989; Stea and Brown, 1989; Newman et al., 1990; Habbe, 1992; Aario and Peuraniemi, 1992; Nenonen, 1994; Newman and Mickelson, 1994; Raukas and Tavast, 1994; Wysota, 1994; Hart, 1995a; Hart, 1997; Menzies et al., 1997; Stea and Pe-Piper, 1999; Nenonen, 2001; Rattas and Piotrowski, 2003). In some cases, the whole drumlin appears to consist of a homogenous unit or single till (e.g. Wright, 1962), which may, essentially, be structureless (e.g. Habbe, 1992). In other cases, there are clearly conformable layers of stratified structures with well-developed fissility and shear planes (Nenonen, 1994, see Figure 5. In yet other cases, the single unit may show evidence of widespread deformation. Menzies et al. (1997) report this sub-type in the New York State drumlin field, along the shore of Lake Ontario. Here, drumlins appear to be composed of a mélange of deformed sediment that shows various features characteristic of both brittle and ductile deformation throughout the drumlin and to thicknesses of up to 50 m. In other cases, the entire unit has been described as a 'lodgement till' (e.g. Wysota, 1994; although note more recent work questioning the use of this term, e.g. Menzies et al., 2006).

Two or more till units are also commonly reported (e.g. Hill, 1971; Stea and Brown, 1989; Newman et al., 1990; Aario and Peuraniemi, 1992; Wysota, 1994; Zelčs and Dreimanis, 1997; Stea and Pe-Piper, 1999). In North Down and Co Antrim, Northern Ireland, Hill (1971) found that the vast majority of drumlins in his study area were composed of till but that many drumlins contained more than one unit that were distinguishable on the basis of a combination of colour, texture, etc. Some contained just one 'lower' till unit, with the upper till unit only forming a thin carapace; whereas others contained only the 'upper' till unit or were composed of a core of the lower till unit surrounded by the upper till unit, see Figure 6. Hill (1971) also noted that, where the lower unit was overlain by an upper till unit, the upper till unit tended to be thinnest on the main crest of the drumlin and thicker along the flanks. Some drumlins were also formed of three till units (Figure 6). Similar observations were also reported by Rattas and Piotrowski (2003) who identified some drumlins with only a 'young' till resting directly on bedrock; some with a thin 'old' till and thick young till; and some with an old till, a core of outwash, and the young till.

It is important to note that Hill's (1971) systematic study of the Irish drumlin swarm also revealed a small number of drumlins with a core of bedrock (section 3.2.) and some with sands and gravels (section 3.4), emphasising the variability in drumlin internal structure within a single field.

Studies that report 'older' till cores, often suggest that different subglacial processes account for their deposition at different times (e.g. Newman et al., 1990; Aario and Peuraniemi, 1992; Wysota, 1994; Stea and De Piper, 1999). Aario and Peuraniemi (1992), for example, describe a densely-packed underlying till covered by a less dense till unit and suggest that the former was deposited by lodgement and melt-out and that the latter results from melt-out and flow processes during deglaciation. Zelčs and Dreimanis (1997) also described drumlins with a core of densely compressed massive till, which differs from the surface till and which they suggested is an older till. Likewise, Wysota (1994) reported different types of drumlins, one of which was characterised by drumlins composed entirely of till, overlying an older till core. Interestingly, Newman et al. (1990) investigated weathering profiles in two tills in Boston, Massachusetts, and suggested that the lower till unit was subjected to a long period of subaerial exposure and probably pre-dates the last glaciation.

It has also been noted that the layering of different till units may not necessarily conform to the drumlin surface, with some workers describing a 'layer-cake' stratigraphy (e.g. Stea and Brown, 1989). Stea and Brown (1989) described a layer-cake of till units in drumlins in southern and central Nova Scotia, which they interpreted as erosional remnants. Similarly, in drumlins in upper New York State, a tripartite sequence of two till units, separated by glaciolacustrine sands, were attributed to an erosional origin by Kerr and Eyles (2007). In other cases, however, their arrangement is clearly conformable (Fairchild, 1907; Fairchild, 1929; Newman and Mickelson, 1994; Stea and Pe-Piper, 1999). The till units have also been reported to be separated by thin units of glaciofluvial sediments, which may represent subglacially or proglacially derived sediments (e.g. Wysota, 1994; Raukas and Tavast, 1994; Hart, 1997; Kerr and Eyles, 2007). Wysota (1994) noted a category of drumlin characterised by an 'older' till core, overlain by glaciofluvial deposits and then lodgement till. In some cases, the lower units show evidence of being glaciotectonically deformed upwards and into the units above (Wysota, 1994). In other cases, the contact is sharp and there is little evidence of material from the lower unit becoming incorporated into the overlying unit (Stea and Pe-Piper, 1999). Similarly, Stea and Pe-Piper (1999: p. 311) described a "knife-sharp" contact between two tills exposed in a drumlin near Halifax, Nova Scotia.

The degree to which till units (or any sedimentary units for that matter) are conformable with the drumlin surface seems to be a key issue (Fig. 3b). Where they are shown to conform to the drumlin surface, investigators have often suggested that they were incrementally deposited over time (Fairchild, 1929; Newman and Mickelson, 1994) and it is fair to presume that such sedimentary build up is linked to drumlin formation. In contrast, till units that are clearly not conformable to the surface of the drumlin, are often used to suggest an erosional origin for the drumlin shape.

3.4. Part till/part sorted sediments

Another type of drumlin commonly reported in the literature are those which have been shown to be composed of large amounts of both till and sorted sediments (e.g. stratified glaciofluvial sediments), an example of which is illustrated in Figure 7 (e.g. Hill, 1971; Whittecar and Mickelson, 1977; Whittecar and Mickelson, 1979; Aario, 1977; De Jong et al., 1982; Dardis and McCabe, 1983; Dardis et al., 1984; Dardis, 1985; Sharpe, 1985; Dardis, 1987; Krüger, 1987; Sharpe, 1987; Dardis and McCabe, 1987; Clapperton, 1989; Goldstein, 1989; Hanvey, 1989; McCabe, 1989; Boyce and Eyles, 1991; Ellwanger, 1992; Habbe, 1992; Hanvey, 1992; Menzies and Maltman, 1992; Goldstein, 1994; Nenonen, 1994; Wysota, 1994; Dardis and Hanvey, 1994; Fisher and Spooner, 1994; McCabe and Dardis, 1994; Newman and Mickeson, 1994; Raukas and Tavast, 1994; Hart, 1995a; Hart, 1997; Knight and McCabe, 1997; Zelčs and Dreimanis, 1997; Menzies et al., 1997; Raunholme et al., 2003; Jørgensen and Piotrowski, 2003; Rattas and Piotrowski, 2003; Kerr and Eyles, 2007; Heimstra et al., 2008). The location of the sorted sediments may vary from a centrally-positioned core or 'pod' (e.g. Rattas and Piotrowski, 2003) to an underlying unit (e.g. Clapperton, 1989; Habbe, 1992; Jørgensen and Piotrowski, 2003), which in some cases is eroded/deformed upwards into the till (e.g. Wysota, 1994) and which in other cases is not (Habbe, 1992; Menzies and Maltman, 1992; Jørgensen and Piotrowski, 2003) An In yet other cases, as noted above, sorted sediments may occur in between two till units (e.g. Habbe, 1992; Wysota, 1994; Kerr and Eyles, 2007) and sometimes inter-bedded with till or vice versa (e.g. Whittecar and Mickelson, 1979; Goldstein, 1994). It is also the case that a till units can be capped by a layer of sorted sediments (e.g. Hart, 1995a; Haaviston-Hyvärinen, 1997; Fisher and Spooner, 1994), although in most of these cases, the sorted sediments are then assumed to be formed during deglaciation and after drumlin formation (see section 4.2). A key issue with this sequence would be to determine whether the sorted sediments were conformable or unconformable with the drumlin surface, with the latter unlikely to formed during deglaciation.

Goldstein (1994) described drumlins in the Puget Sound field (Washington) as characterised by a fluvio-lacustrine core, related to meltwater or proglacial lake activities, overlain by a till layer up to 10 m thick. Similarly, Hart (1995a) reported drumlins in NW Wales that appear to have more resistant cores of glaciofluvial sediment, surrounded by till. Interestingly, some of the cores also show evidence of deformation structures, whereas others did not and she also noted that the till unit comprised only a thin carapace of deforming till and/or a stacked sequence at the ice proximal (stoss) end of the drumlins (see section 5). A gradational/smudged contact between cores of outwash and a surrounding till matrix were also reported by Rattas and Piotrowski (2003).

Similar observations were also presented by Boyce and Eyles (1991) who found varying degrees of deformation of stratified sands and gravels that were truncated by a mantle of till (Figure 4). This till mantle was characterised by a massive or crudely bedded till facies between 1 and 10 m thick but which thickened in inter-drumlin areas. The contact between the basal part of the till mantle is strongly erosive and marked by glaciotectonic deformation structures, such as drag folds. The basal part of the till mantle also contain abundant rafts and lenses of underlying sediments, which become progressively more attenuated upward in the section. Indeed, observations of an upwardly intensifying pattern of deformation is reported in several other studies, especially where drumlins are associated with or overlie pre-existing glaciofluvial sands and gravels (e.g. Ellwanger, 1992: Figure 7). Ellwanger (1992) noted that erosion of the underlying sediments appears to have taken place preferentially on the stoss slope of the drumlins he studied, with re-deposition of down-dipping material in the lee side.

It is also worth noting that several authors (e.g. Hanvey, 1989) have drawn attention to stratified sediments preferentially occurring towards the lee-side of drumlins and, where this has been reported (e.g. Dardis et al., 1984), it is often suggested that the sediments were laid down in a lee-side cavity that required the presence of an obstacle (e.g. the drumlin). As such, they appear to be a specific type of lee-side features, rather than forming the bulk of the drumlin (see section 5). Conversely, Kupsch (1955) described one drumlin in Saskatchewan, Canada, as being characterized by a stoss of stratified sand and gravel and a probable tail of till.

3.5. Mainly sorted sediments

It has been known for a long time that some drumlins are simply composed entirely of sorted sediments (or possibly with only a very thin veneer of till) and lack any substantial evidence for widespread deformation (De Jong et al., 1982; Shaw, 1983; Shaw and Kvill, 1984; Sharpe, 1987; McCabe, 1989; Zelčs and Dreimanis, 1997; Menzies and Brand, 2007). An example of this type of drumlin is schematically illustrated in Figure 8. Menzies and Brand (2007) observed undeformed proglacial and deltaic sediments in an extensive exposure of a drumlin at Port Byron, New York State. They suggested that calcium carbonate precipitation cemented the stratified sediments, which acted as an obstacle around which a thin veneer of till was subsequently emplaced. Significantly, there appears to be only limited erosion at the contact between the till and the underlying stratified sediments, which they interpret as indicative of basal decoupling with shearing within the thin till veneer not transferred to the underlying sediments. In other cases (e.g. Shaw, 1983), the presence of undisturbed stratified/sorted sediments has been used to argue that drumlins might represent infillings into subglacial cavities, produced during subglacial floods.

4. Drumlin Veneers/Carapaces

Numerous papers in the literature report the existence of a thin ‘veneer’ (also termed ‘carapace’ or ‘mantle’) of sediments surrounding the main drumlin constituents (e.g. Wiśniewski, 1965; Finch and Walsh, 1973; Garnes, 1976, all cited in Karczewski, 1987; Whittecar and Mickelson, 1979; Karczewski, 1987; Rouk and Raukas, 1989; Boyce and Eyles, 1991; Wysota, 1994; Hart, 1995a; Knight and McCabe, 1997; Stea and Pe-Piper, 1999; Menzies and Brand, 2007), including ice-cored drumlins (Schomacker et al., 2006). In many (but by no means all) of these studies, the authors point out that the sedimentary processes that produced the veneer are probably not related to the drumlin-forming process. The perception of a unit as a veneer arises from finding a thin unit conformable to the drumlin shape but distinct from the underlying contents on the basis of sediment properties (e.g. grain size) or structures (e.g. a conformable veneer atop horizontally bedded units). It is for this reason that we describe these features in a separate section, although we acknowledge that the distinction in some cases might be more arbitrary. This means that there is no precise distinction between, for instance, a rock-cored drumlin and a bedrock drumlin with veneer, although, as noted earlier, Dionne (1987) recommends that a bedrock cored drumlin (our part bedrock/part till type) should be composed of at least 25% unconsolidated material. The risk is that authors might have used different terms for the same drumlins. Nevertheless, there appear to be two main types of veneer reported in the literature: a thin veneer of primarily glaciofluvial sediments (e.g. Hart, 1995a) or a thin veneer of till (e.g. Menzies and Brand, 2007).

4.1. Veneer of till

Several papers report drumlins mantled by a thin veneer of till (e.g. Karczewski, 1987; De Jong et al., 1982; Knight and McCabe, 1997), see Figure 9. This veneer is often interpreted as an ablation/melt-out till that has been draped over the landscape (e.g. over both drumlins and non-drumlinised terrain) during deglaciation (e.g. Whittecar and Mickelson, 1979; Dardis et al., 1984; Karczewski, 1987; Aario and Peuraniemi, 1992). For example, Whittecar and Mickelson (1979: p. 357) describe a "retreat till" 1-3 m thick, which truncates all internal structures. In other cases, the till veneer may be thicker and not necessarily the product of deglaciation but might simply have been emplaced by a different ice flow phase, following drumlin formation (e.g. De Jong et al., 1982; Knight and McCabe, 1997). In yet other cases, the veneer is simply emplaced over more resistant sediments, such as the one described by Menzies and Brand (2007) at Port Byron, New York State (USA) (Figure 8). As noted above, they interpreted limited erosion at the contact between the till veneer and the main drumlin constituents, other than a minor drag fold, and invoke thin-skinned deformation of this layer, as revealed by thin section microstructures. A similar conclusion was reached by Habbe (1992), who noted minimal glaciotectonic disturbance of underlying units beneath a thin skin of till over drumlins in the southern German Alpine foreland. Likewise, Boyce and Eyles (1991) noted a veneer of till mantling drumlins cored with stratified proglacial outwash in the Peterborough drumlin field, north of Lake Ontario. Unlike the thin-skinned deformation reported by Menzies and Brand (2007), Boyce and Eyles (1991) found numerous glaciotectonic deformation structures at the lower contact of the till mantle and the incorporation of abundant rafts and lenses of the underlying proglacial sediments. Similar evidence for glaciotectonic deformation of glaciofluvial sediments underneath a thin (0.5 - 3 m) veneer of till were also described by Wysota (1994) and Whittecar and Mickelson

(1979). Thin till veneers have also been noted overlying lee-side stratified deposits (Dardis et al., 1984).

4.2. Veneer of glaciofluvial sediments

The other main type of veneer commonly reported in the literature is made up of primarily glaciofluvial sediments, which most investigators attribute to deposition during withdrawal of the ice margin across the drumlin (e.g. Hart, 1995a). Hart (1995a), for example, noted a stratified bed consisting of a lower laminated sand, silt and clay deposit (0.5 m thick) on the proximal side of a drumlin at Lleiniog, North Wales, see Figure 10, which she suggested may have been deposited in small lakes during glaciomarine incursion. Stratified sandy units (< few metres) have also been reported to cap the main drumlin/pre-crag sediments southerwestern Finland and are thought to have been deposited during the final deglaciation phase (Haavisto-Hyvärinen, 1997).

It has also been noted that whilst it is typical for such veneers to cover the entire drumlin, some are restricted to certain parts of the drumlin. Fisher and Spooner (1994), for example, reported stratified gravel veneers on the lee side of drumlins in Alberta, Canada. Indeed, some sedimentary packages have commonly been reported at the stoss or lee of a drumlin and these are described in the next section.

5. Drumlin Stoss and Lee Features

Specific features at the stoss and lee side of drumlins are also reported in the literature. They are generally described as stoss side features dipping up-ice (e.g. Hart, 1995a) and lee side features dipping down-ice (e.g. Hanvey, 1987; Ellwanger, 1992; Dardis et al., 1984). Most workers (e.g. Dardis et al., 1984) argue that the formation of such features appear to require an obstacle (i.e. the drumlin) and that they may not necessarily be related to the primary drumlin-forming mechanism.

5.1. Stoss side features dipping up-ice

Several workers have noted up-ice dipping features on the stoss side of drumlins (e.g. Hanvey, 1992), sometimes apparent as thrust structures (e.g. Hart, 1995a; Hart, 1997) and sometimes characterised by two or more till units accreted one on top of the other. Hart (1995a) noted prominent fold and thrust features in two drumlins in north Wales that preferentially developed on the stoss side of the drumlin (Figure 10) and McCabe and Dardis (1994) also described brecciated bedrock that had been sheared over the proximal end of one drumlin at Kanrawer, western Ireland.

5.2. Lee side features dipping down-ice

Lee-side depositional features which have attracted the most attention in the literature are lee-side stratified sediments. The occurrence of undeformed stratified sediments in drumlins has long been recognised (section 3.5) and a large body of work has drawn attention to their presence, specifically at the lee-side of drumlins (e.g. Dardis and McCabe, 1983; Dardis et al., 1984; Dardis, 1987; Dardis and McCabe, 1987; Hanvey, 1989, 1992; Dardis and Hanvey, 1994; Fisher and Spooner, 1994).

Investigating a relatively large sample of drumlins (55 in total) compared to most studies, Dardis et al. (1984) describe several lee-side stratified sequences, see example in Figure 11. These deposits occur as a wedge shaped unit which thickens down-ice (before thinning towards the lee end) and are composed predominantly of steeply dipping (15-30°) cross-bedded gravels (80%), sands and silts (20%) of varying thickness but with a tendency to increase down-slope. They noted that the stratified sequences tend to be associated with drumlins that lack the distinctive steep stoss- and tapering lee-ends. They also reported that the majority (90%) of stratified sediments infill embayments excavated in the lee-side of barchanoid drumlin forms and that the remainder are superimposed on drumlins with a more whaleback form. Interestingly, Dardis et al., (1984) note the presence of a thin till veneer (cf. section 4.1) draped on top of the stratified sequences and which appears to be related to the till in the main body of the drumlin that is often interbedded with the stratified sequences. They also point out that not all drumlins in the study area are associated with lee-side cavity fills.

In addition to lee-side stratified sediments, Ellwanger (1992) reports down-dipping layers of till that are parallel to the surface of an exposed drumlin in the Bodanrück drumlin field, southern Germany, see Figure 9c.

6. Deformation Features

One aspect of drumlin composition that has attracted much attention is the extent to which the sediments show evidence of having undergone high levels of strain as a result of glaciotectonic/syndepositional deformation (Hart, 1997). Indeed, this issue has proved quite contentious in the literature (e.g. Evans et al., 2006). It is not the aim of this paper to evaluate the arguments for and against these various interpretations of deformation (pervasive versus non-pervasive versus absent), but it is clear from our review that they certainly do exist; and with almost every possible permutation in between. For example, there are numerous reports of drumlin sediments showing high levels of strain, as evidenced by diverse descriptions of deformation features, such as faults, folds, fissures and joints that may result from either ductile or brittle deformation (Kupsch, 1955; McGown et al., 1974, cited by Menzies, 1979a; Whittecar and Mickelson, 1979; Sharpe, 1985; Stea and Brown, 1989; Boyce and Eyles, 1991; Hart, 1997). Examples of such deformation features can be seen in Figures' 7, 9 and 10.

Deformation features might occur extensively and throughout the entire thickness of the drumlin sediments (e.g. Menzies et al., 1997) or they may be more restricted to a 'thin skin' just a few centimetres thick at the drumlin surface (e.g. Menzies and Brand, 2007). Bringing together field data from 33 drumlins from various locations, Hart (1997) recognised the many different styles of deformation associated with drumlins and their cores and suggested that there is a continuum from stoss-side deformation, compressive core deformation, through to subglacial folds and finally to extensional deformation. It should be noted at this point that, where deformation features are found throughout the whole depth of the drumlin, it does not necessarily imply that deformation occurred throughout the entire depth at the same time, because is also possible that the deformation structures developed incrementally over a long time period and resulted from several episodes of deformation at different depths (Evans et al., 2006).

It is also clear that deformation structures do not always extend from the drumlin surface downwards, but are also observed to extend from the drumlin base upwards. Observations of an underlying unit being deformed upwards and entrained into an overlying unit are commonly reported (cf. Boyce and Eyles, 1991; Wysota, 1994) and investigators have also reported large rafts of underlying sediment that have been deformed upwards en masse (e.g. Boyce and Eyles, 1991; Zelčs and Dreimanis, 1997), including bedrock (McCabe and Dardis, 1994; Zelčs and Dreimanis, 1997). As noted above, however, there are also reports of underlying material not being entrained into overlying units (Habbe, 1992; Menzies and Brand, 2007; Fuller and Murray, 2002) and, in some cases, the sediments within the drumlin show no evidence of any deformation features anywhere. These drumlins are commonly, although not exclusively, associated with well-sorted sediments e.g. 'stratified' drumlin sediments described in section 3.5 (e.g. Shaw and Freschauf, 1973; Whittecar and Mickelson, 1979; Shaw, 1983). As noted above, however, there are also drumlins with stratified sediments that do show evidence of deformation and/or which may simply be truncated (Habbe, 1992; Menzies and Maltman, 1992; Jørgensen and Piotrowski, 2003).

In summary, deformation features are found in all of the main types of drumlins summarised in this paper (section 3), apart from purely bedrock features, and some drumlins clearly show very little evidence of ever having been deformed. Where present, deformation features range from minimal and localised to widespread and throughout the entire drumlin thickness.

7. Variability of Drumlin Composition and Internal Structure

It is very clear from a review of the literature that drumlin composition and internal structure vary significantly and even within a single drumlin field (cf. Hill, 1971; Danilans, 1973 cited in Zelčs and Dreimanis, 1997; Straume, 1979, cited in Zelčs and Dreimanis, 1997; De Jong et al., 1982; Dardis, 1985; Boyce and Eyles, 1991; Wysota, 1994; Raukas and Tavast, 1994; Knight and McCabe, 1997; Rattas and Piotrowski, 2003). Indeed, Raukas and Tavast (1994) identify four of the five main types of drumlin described in this paper in a sample of several thousand drumlins in Estonia and northern Latvia. Likewise, Miller (1972) described drumlins in the New York field as variously containing gravel, till, finely bedded sand, fine-grained lake deposits, interbedded till and fine sand, and bedrock. To illustrate this point, Figure 12 shows the location of drumlins with different internal structures in North Down and South Antrim (Ireland) from Hill (1971). He detected four main types and, whilst most drumlins contained either a single unit of till or two units, he also found a few drumlins with rock cores and others composed mainly of stratified and sorted sands and gravels. Such variations are commonly reported but few studies have attempted to quantify the relative proportion of different drumlin constituents within a drumlin field. One of the few is by Hart (1995b), who investigated recent drumlins in the foreland of Vestari-Hagafellsjokull glacier, central Iceland and found that 15% constitute rock drumlins, 8% were till drumlins, 46% were rock-cored drumlins with a till veneer and that others appear to be more analogous to crag-and-tails.

In some cases, investigators (e.g. Flint, 1971; Dardis, 1985) have noted how some of the main types of drumlin composition reported in this paper (section 3), may actually represent a continuum of forms from bedrock drumlins to part bedrock/part till, through to drumlins of mainly till, although this sequence is rarely reported down a drumlin field. On the other hand, Boyce and Eyles' (1991) investigation of drumlins in the Peterborough drumlin field, Ontario, revealed systematic changes in their internal structure along an ice flow-line (Figure 4). Up-ice, they found elongate drumlins constructed of massive crudely bedded clast-rich till facies that rest directly on bedrock and are widely space apart, often forming in the lee of limestone scarps (cf. section 3.2). Further down-ice, drumlins appear to be less streamlined and more closely spaced and are composed of a core of proglacial outwash erosively truncated by a mantle of till (cf. section 3.4). Boyce and Eyles (1991) interpreted this down-ice trend as simply reflecting the function of time available for subglacial deformation, during ice advance, i.e. the duration of deforming bed conditions was greatest up-ice and this is where pre-existing sediments were completely eroded.

8. Provenance of Drumlin Sediments

An interesting question with respect to the composition of drumlins is: where are the sediments derived from? A large number of studies note that the material that constitutes the drumlin is derived locally (e.g. Shaler, 1893; Martin, 1903; Gravenor, 1953; Flint, 1957; Harrison, 1957; Embleton and King, 1968; Dreimanis and Vaigners, 1971, all cited by Menzies, 1979a; Miller, 1972; Gravenor, 1974; Clapperton, 1989; Hanvey, 1989; Zelčs and Dreimanis, 1997), which might imply minimal sediment transport distances. Indeed, Goldstein (1989) performed extensive and comprehensive sampling of the lithology of drumlins in the Wadena drumlin field, Minnesota, and found a dominant contribution from locally derived material that was transported no more than a few kilometres. However, Goldstein (1989) also noted that the occurrence of locally-derived material tended to diminish upwards, where assemblages of far-travelled erratics were more common. The mixing zone between the local and far-travelled material ranged from <10% of the drumlin thickness to almost its entire height. The same pattern was found by Stea and Brown (1989), who found far-travelled material (up to 100 km) tended to be more common in the surficial till layers. Similarly, Lincoln (1892) mentioned the presence of 'good-sized travelled stones' thickly covering the upper portions of some drumlins in the Finger Lake region of New York State.

Other studies have reported the presence of substantial components of far-travelled material (Jørgensen and Piotrowski, 2003), especially in comparison to other subglacial bedforms and moraines (e.g. Nenonen, 2001). Aario and Peuraniemi (1992) studied dispersal trains from a variety of landforms in Finland (end moraines, Rogen/ribbed moraines, drumlins, flutings, etc.) and used measurements of grain size, clast roundness and pebble lithology to infer the distant derivation of material in the drumlins, compared to the other landforms, although local material was also present. Haavisto-Hyvärinen (1997) also noted far travelled erratics from over 100 km in 'pre-crag' landforms in southwestern Finland. He makes an important point, however, by acknowledging that far-travelled material could have been transported in several ice flow episodes over a relatively long-time scale, rather than implying high sediment transport distances during landform genesis. Further support for the idea that drumlin sediments can be transported from different source areas is found in Stea and Pe-Piper (1999), who used whole rock geochemistry to locate the source of igneous erratic material in two drumlins on the Atlantic Coast of Nova Scotia. Their provenance analysis suggests that the drumlins they investigated are palimpsest features composed of material that was delivered to them by two ice flow phases with different source areas (cf. Stea and Brown, 1989), see Figure 13.

In common with the variable characteristics of the internal structure of drumlins, the characteristics of the material underneath drumlins have also been shown to vary and, again, even within the same drumlin field (Ellwanger, 1992). Ellwanger (1992), for example, reported drumlins from the Rhine area, Germany, that rest on both bedrock and on top of stratified sands and gravels. Boyce and Eyles (1991) also reported drumlins that rest directly on bedrock and note that they seemed to be more widely spaced apart than those that formed on unconsolidated sediments. In Patterson and Hooke's (1995) review, it is reported that drumlin substrate is highly variable and the conclusion is drawn that drumlin development is not obviously linked to the lithology of the substrate (cf. Greenwood and Clark, 2010), although some workers have drawn attention to variations in drumlin form (Phillips et al., 2010). In contrast, there are some regional investigations that report drumlin formation preferentially down-ice from easily erodible, fine-grained, sedimentary bedrock (Bouchard, 1989; Coudé, 1989; Aylsworth and Shilts, 1989).

It is also interesting to examine whether sediments from within drumlins are substantially different from the sediments in the inter-drumlins areas. However, studies that compare drumlin and inter-drumlins sediments are relatively rare, presumably because it is far more difficult to find exposures in the low-relief areas between drumlins. Of the few studies that do compare the two, Clapperton (1989) noted that 'deformed' till in inter-drumlin areas was generally thinner (1-2 m) compared to that in drumlins (up to 6 m). In contrast, Hill (1971) noted that, where a lower unit was overlain by an upper till unit, the upper till unit tended to be thinnest on the main crest of the drumlin and thicker along the flanks. Similarly, Boyce and Eyles (1991) described a till (1-10 m thick) mantling drumlins with a core of proglacial outwash being thicker in inter-drumlin areas. Fuller and Murray (2001) found waterlain clay deposits in the uppermost till units of drumlins in front of an Icelandic surge-type glacier which were absent from the equivalent till layers in the non-drumlinised terrain. They suggested that this indicates the presence of ponded water (and ice bed decoupling) over the drumlins but not over the non-drumlin areas, where they infer greater ice-bed coupling. Zelčs and Dreimanis (1997) also noted a difference between sedimentary structures in drumlins in Latvia, compared to the non-drumlinised terrain. The glacial sediments in the drumlins range from 10-40 m thick and they note that drumlins tend to have "more stratified beds, including till units of the last glaciation, [compared to] the inter-drumlin depressions" (Zelčs and Dreimanis, 1997: p. 75).

There are also studies, however, that report no obvious differences between the sediment composition of drumlins and inter-drumlin areas (e.g. Kerr and Eyles, 2007). Lincoln (1892), for example, described the drumlinised area near Geneva, in New York State, as a continuous sheet of till, of which the drumlins are merely a surface irregularity. Similarly, Rattas and Kalm (2001) describe till in an Estonian drumlin field as relatively uniform, without distinguishing between drumlin and inter-drumlin sediments. Menzies (1979b) also noted that till found within drumlins is similar in most aspects to the till in non-drumlinised areas in the Glasgow area of the UK.

Whilst it is sometimes the case that workers cite special sedimentary conditions within drumlins that may cause them to form in a particular location (e.g. a core of bedrock; more resistant or well-drained material: Hart, 1995a), Patterson and Hooke (1995) make the important point that in many cases, similar cores may exist in a drumlin field that did not lead to drumlin formation, e.g. topographic perturbations that did not lead to drumlin formation (cf. Fairchild, 1907; Aronow, 1959; Gluckert, 1973 and Gillberg, 1976, all cited in Patterson and Hooke, 1995).

Finally, with notable exceptions such as Aario and Peuraniemi (1992), very few studies have compared the internal sediments and structures of drumlins to other subglacial landforms that might be nearby such as eskers, flutes, moraines, etc. Significantly, one study by Sharpe (1987) did attempt such comparisons and concluded that landform internal structure was remarkably consistent, the implication being that they can only be differentiated by their different morphology.

9. Clast Sizes, Shape and Fabrics of Drumlin Sediments

9.1. Clast sizes and shapes in drumlins

Reflecting their varied composition (section 3), it is no surprise that clast sizes found in drumlins vary enormously and this has been noted in previous reviews (e.g. Menzies, 1979a). The grain size of sediment has been shown to range from fine clays (Wysota, 1994), through sands, and up to coarser material such as gravel, cobbles and large boulders (Hanvey, 1992), in addition to those with bedrock cores described earlier. Moreover, it has also been found that variable clast sizes often occur within individual drumlins (e.g. Gravenor, 1974; Hanvey, 1989, 1992; Fisher and Spooner, 1994). For example, Gravenor (1974) analyzed 150 drumlins in Nova Scotia and reported a 1-4% of clay, 26-47% of silt, 34-50% of sand and 20-33% of pebble/boulders. Likewise, Piotrowski (1987) and Piotrowski and Smalley (1987) studied drumlins in the Woodstock drumlin field (Ontario) and found variable percentages of clay (15-27%), silt (44-55%) and sand (18-41%) and Fisher and Spooner (1994: p. 291) reported a range of clast sizes from "granules to small boulders" inside drumlins in Alberta, Canada.

Hanvey (1992) reports variable boulder concentrations within drumlin tills in western Ireland and identified three main types of boulder concentration, which range in clast size and arrangement within the drumlin. The first type consists of a 'single clast' boulder lag embedded within a compact till and with a distinctive concentric arrangement which closely corresponds to drumlin morphology, see Figure 14. These are interpreted to be of glacigenic origin, perhaps laid down during lodgement processes. In contrast, the other two types of boulder concentration are denser, with an off-lapping arrangement that dip towards the lee end of the drumlin at an angle of 10-20 degrees. They also appear to be associated with massive or planar laminated coarse sand, and Hanvey (1992) interpreted their origin to be related to an aquatic influence and debris flow deposits. She argued that such a diverse clast size within and between these drumlins implies that quite different processes acted to shape the final drumlin form.

Menzies (1979a) also noted that a number of studies have found drumlin cores that contain clast sizes that are different from the rest of the drumlin (e.g. Upham, 1892; Fairchild, 1907, Wright, 1912; Fairchild, 1929; Slater, 1929; Hill, 1968, 1971). Slater (1929), for example, found a core of cohesive clay-rich till surrounded by a till unit with a lower clay content.

It follows that clast shapes in drumlins are also highly variable, although sub-angular and faceted clasts are commonly reported as being dominant (e.g. Clapperton, 1989). Nevertheless, rounded and angular clasts are also reported from within the same drumlin field and even the same drumlins. Fisher and Spooner (1994), for example, report a range of clast shapes (angular to rounded) from drumlins in Alberta, Canada, and also noted that around 10% were striated.

9.2. Clast fabrics in drumlins

A large body of work has reported that clast fabrics in drumlin sediments are generally orientated approximately parallel with the long axis of the landform (e.g. Hoppe, 1951; Wright, 1957; Wright, 1962; Gravenor and Meneley, 1958, cited by Menzies, 1979a; Evenson, 1971, cited by Menzies, 1979a; Hill, 1971 (Figure 6), Minell, 1973, cited by Menzies, 1979a; Shaw and Freschauf, 1973; Walker, 1973, cited by Menzies, 1979a; Gluckert, 1973; Gravenor, 1974; Menzies, 1976, cited by Menzies, 1979a; Karczewski, 1987; Piotrowski & Smalley, 1987; Aario and Peuraniemi, 1992; Goldstein, 1989, 1994; Wysota, 1994; Nenonen, 1994 (Figure 5); 2001; Jørgensen and Piotrowski, 2003; Menzies and Brand, 2007). It has also been reported that the plunge of the long axis of clasts (typically <20°) is preferentially orientated in an up-ice direction (Wright, 1957; 1962; Jørgensen and Piotrowski, 2003; Schomacker et al. (2006)). Interestingly, whilst Schomacker et al. (2006) found this pattern in the till mantling an ice-cored drumlin (0-14º), they report that the plunge direction of clasts in the inter-drumlin areas was generally down-glacier (principal vector 4º).

In those studies where vertical profiles have been taken, it has also been pointed out that the fabrics in the surficial layers of the drumlin are stronger than those at greater depths (e.g. Gravenor and Meneley, 1958; De Jong et al., 1982; Goldstein, 1989; Wysota, 1994; Menzies and Brand, 2007), although not always (e.g. Clapperton, 1989). Menzies and Brand (2007), for example, found strong clast macro-fabrics that matched the long axis trend of drumlin in a thin till veneer and suggested that it probably reflects high shear stress in thin skin deformation around the more resistant drumlin core (cf. Hart 1994; 1997; Iverson et al., 1998; Hooyer and Iverson, 2000). Likewise, Goldstein (1989) reported clast macro-fabrics from the Wadena drumlin field in Minnesota and found that fabrics towards the surface of the drumlin were stronger than those found at depth. He also reported fabrics in lateral positions that seem to indicate ice flow towards the drumlin axis. Similarly, Savage (1968), obtained sixteen fabrics from a drumlin in Syracuse, New York, which showed divergence around the stoss end, convergence around the lee end, and nearly parallel patterns along the lateral flanks, see Figure 15. The conclusions drawn from these studies is that the drumlins may have formed through an accretionary mechanism and that ice flow around the growing drumlin varied as the form was built up and hence, the final form of the drumlin does not resemble earlier phases of formation. Other studies have also reported fabrics from the flanks of the drumlins pointing towards the central crest (Clapperton, 1989; Aario and Peuraniemi, 1992) and Rouk and Raukas (1989) reported that drumlins in Estonia are characterized by clast fabrics on the flanks that rise up-slope towards the lee end. They interpreted this as evidence of till movement according to the dominant stress gradient.

Other studies (e.g. Andrews and King, 1968), however, have found only very weak fabrics in drumlins and some have argued that this may reflect the pervasive deformation of underlying till (e.g. Hart, 1995a.). Andrews and King (1968) found an increase in divergence between the drumlin trend and the mean orientation of fabrics from the base upwards and pointed out that none of the fabric orientations were closer than ±20° to the drumlin trend. They suggested that this increasing divergence resulted from ice flow becoming increasingly deflected as the drumlin size increased. A similar explanation for divergent fabrics in drumlin flanks was noted by Wysota (1994). Furthermore, some studies have found fabrics in the opposite direction to the drumlin trend (e.g. Fisher and Spooner, 1994) and have suggested that they may reflect palaeo-water currents, rather than shear strain within the sediment. Other workers have found that fabric strengths differ greatly between drumlins within the same field (e.g. Zelčs and Dreimanis, 1997). Krüger and Thomsen (1984) analysed four drumlins in Iceland and found that fabric direction is more diverse on drumlins than in the inter-drumlins areas.

In addition to systematic studies of fabrics at different depths, some studies have examined fabrics longitudinally. Yi and Cui (2001) measured micro-fabrics of sediment obtained from the stoss and lee of a drumlin with a bedrock core, as well as in the immediate lee of the bedrock core. They measured both the particle (0.25-5 mm) and void fabric and found a strong fabric in the stoss- and lee-side of the drumlin but a much weaker fabric in the immediate lee of the bedrock core. They suggested this might reflect incipient separation of the ice and bed (cavitation), which protected the sediments in the immediate 'shadow' of the bedrock core from the high normal and shear stresses experienced elsewhere in the drumlin.

Finally, it has also been recognised that clast fabrics in drumlins may actually reflect earlier ice flow phases (e.g. Stea and Brown, 1989; Haavisto-Hyvärinen, 1997). Haavisto-Hyvärinen (1997), for example, reported fabrics from various depths and found that those in the upper till unit were aligned with most recent ice flow direction but that those in the lower unit were more likely to be related to an older ice flow direction. Similarly, Stea and Pe-Piper (1999) reported fabric orientations in a lower till unit that matched the long axis of the drumlin but that those in an upper till unit did not. They attributed this to two different flow directions, each of which may have helped shaped the drumlin into its final form (Figure 13).

In summary, although clusters of studies appear to suggest discernible trends, our review indicates that there are no universal trends across a broad range of studies, other than most fabrics being approximately parallel to the drumlin long axis, especially in surficial units. Indeed, there is some debate in the literature over the more fundamental issue of whether subglacial till deformation leads to a weak (e.g. Dowdeswell and Sharp, 1986; Hart, 1994; 1997) or a strong clast fabric (Hooyer and Iverson, 2000; Benn, 1995) or whether it can lead to either, depending on the thickness of the deforming layer (Hart, 1994). Perhaps nowhere is this complexity better highlighted than in the literature on drumlin internal structure and, perhaps, clast fabrics themselves need to be questioned in terms of their validity and reliability.

10. Discussion:

10.1. How representative are observations of drumlim composition and internal structure?

Our review of the literature suggests to us that most drumlins can be categorised into five basic types:

- mainly bedrock

- part bedrock/part till,
- mainly till,
- part till/part sorted sediments,
- mainly sorted sediments

Simplified versions of these are shown in Figure 16. Clearly, ‘real’ drumlins are often far more complex than those shown in Figure 16 but they do encapsulate the five main types of drumlin and will hopefully act as a useful observational framework for theorists to visualise and attempt to explain. Moreover, there may be some hybrid cases that are more rare (or yet to be reported) but we find it a relatively straightforward task to categorise the overwhelming majority of observations of drumlin composition (if not all) in to one of these groups and this is shown in Table 1.

A crucial question that a drumlin theorist might ask is: which of these drumlin types are common and which are rarer; or are they found in equal numbers? According to Table 1, the most common type of drumlin reported in the literature (emphasis on ‘reported’) are those that are composed mainly of till (68 papers), which has been suggested in other papers (e.g. Menzies, 1979b, p. 374). The next most commonly reported are those composed of part till and part sorted sediments (47 papers) and part till and part bedrock (29 papers). A total of 16 papers report drumlins composed of mainly sorted sediments and 7 report bedrock drumlins. Note that Table 1 only includes papers that specifically refer to ‘bedrock drumlins’. These landforms are, obviously, far more prevalent than shown in Table 1 but they often referred to by another name (see section 3.1) and often excluded from papers that specifically address the issue of drumlin internal structure (see also section 10.2.1.1, below).

Whilst it might be tempting to draw conclusions from Table 1, there are several important issues which suggest that this dataset is unlikely to provide a valid answer to the question regarding the commonality of different types. This is because Table 1 simply reflects ‘reported’ drumlins, rather than a systematic sampling programme. Indeed, there are four key issues, which suggest that we are still some way from obtaining a representative dataset of drumlin composition and internal structure.

The first issue is the geographic distribution of drumlin observations, which are clearly not evenly distributed across the entire population of drumlins to available to study. Figure 17 simply plots the location of each of the studies in Table 1 in relation to the limits of the last major mid-latitude ice sheets and the Precambrian 'shield' areas of predominantly crystalline bedrock. It clearly reveals that observations of drumlin composition are, generally, tightly clustered towards centres of population and away from parts of the ice sheet bed underlain by crystalline bedrock. It is apparent that several regions (e.g. southern Ontario, Northern Ireland), have attracted the interest of several workers, such that some drumlin fields are 'over-sampled', compared to others. Indeed, observations reported in the literature may even be taken from the same drumlins, resulting in some drumlins (and therefore drumlin-types) being duplicated in different papers. Furthermore, the clustering of observations in specific regions is likely to result in the over-sampling of certain types of drumlins at the expense of others. The death of observations from shield areas, for example, is likely to result in a general under-reporting of bedrock and part bedrock/part till drumlins and an over-reporting of drumlins composed of mainly till. Likewise, many observations are clustered towards the margins of palaeo-ice sheets, which is where glacio-fluvial sediments are more likely to accumulate for subsequent overriding and incorporation into drumlin sediments.

The second issue relates to the sample size within each study. As noted in section 2, observations of drumlin composition and internal structure are generally taken from very low sample sizes within drumlin fields and in almost half of the papers the sample size is not mentioned (see Fig. 2). Related to this, some observations are based on limited exposures of sediments inside a drumlin and these may have been erroneously extrapolated to the entire drumlin (and sometimes the entire drumlin field).

A third issue is that observations reported in the literature may be biased by particular paradigms at particular times. The composition and internal structure of drumlins is often linked to particular ideas/theories about how the drumlins form and, although unlikely, it may be that some investigators are less likely to publish observations that might conflict with previously published evidence. Table 1 is organised chronologically to show whether certain types of drumlin were reported at certain times over the last hundred years or so, revealing any temporal trends that might be related to technological or conceptual advances in understanding. It would appear that there are no obvious time periods when certain drumlins were more commonly reported than others, although it is clear that the literature on drumlins saw a period of huge growth in the 1950s, which appears to have accelerated in the latter half of the 20th century. Pre 1950, there are far fewer papers and these tend to be dominated by mainly till and part till/part bedrock types, possibly reflecting early ideas about deposition and accretion of drumlins around bedrock obstacles or till cores (e.g. Fairchild, 1907). Post 1950, there is a greater tendency to report drumlins with some component of sorted sediments and this may be linked to ideas about drumlin formation and the role of subglacial meltwater (e.g. Shaw and Freschauf, 1973; Shaw, 1983) and the large clutch of papers on lee-side stratified sequences from Ireland (e.g. Dardis and McCabe, 1983; Dardis et al., 1984; etc). Interestingly, there are very few papers that report part till/part sorted sediments between 1950 and 1975, but this increases substantially in between 1976-2000. This may be linked to ideas of drumlin formation in a deforming subglacial layer (e.g. Boulton, 1987) because many of the papers in this category also invoke erosion and deformation of pre-existing sorted sediments by ice as well as meltwater activity.

A fourth issue is that there may also be cases where drumlins with less sedimentologically interesting constituents (e.g. a fairly homogeneous single unit of till with few structures) might be reported less frequently than drumlins with more interesting constituents (e.g. several till units and/or sorted deposits with impressively formed contacts and/or deformation structures). Indeed, there may be a tendency for more interesting but more exceptional drumlins to attract greater attention in the literature. It might be more difficult, for example, to publish a paper reporting an apparently straightforward case of a drumlin consisting simply of a single homogenous till - there is not too much interesting detail to report. It might also be possible that commonly reported types of drumlins become so common that scientists become less interested in publishing papers about them, although this would not appear to be the case because drumlins with ‘mainly till’ are by far the most commonly reported drumlin.

We also note that there are several citations that appear in more than one column in Table 1, which provides clear evidence that drumlin composition is highly variable and that different types of sediments and structures are found even within the same drumlin field (cf. section 7). On occasions, we also note that some authors will cite a paper to provide evidence of one type of drumlin, but that other authors may take the same paper to draw a different conclusion about the contents of the drumlin. This further complicates Table 1, where we are sometimes reliant on 'cited in' references.

In summary, the drumlin literature has thus far been excellent at ascertaining the range of internal structures, but because of various potential biases and small sample sizes, we are left with only a limited understanding of what is usual for drumlins and what are the more exotic and tangential situations. We would argue that the identification of the five basic types is an important first step for theorists to tackle but whilst Table 1 might offer some useful clues as to the commonality of each type, a set of "statistically valid observations" (cf. Clark et al., 2009) of drumlin composition is not yet available.

10.2. What does the variability of drumlin internal structure tell us about drumlin formation?

One of the most intriguing aspects of drumlin formation is the way in which ice flow creates a pattern of upstanding mounds (drumlins); especially where their distribution is clearly not related to any pre-existing or underlying topography. This is the essence of the 'drumlin problem' and one which has prompted numerous attempts to solve it. Although it is not the intention of this paper to review specific hypotheses of drumlin formation (see section 1.1), it is important to discuss how the observations of drumlin internal structure might be linked to an explanation of their formation, at least conceptually. One starting point is to ask whether the five different types of drumlins identified in this paper are formed by different mechanisms, or whether they are formed by a single process that acts across broad areas to create drumlinised terrain. We term these two possible scenarios 'site-specific' and 'process specific' drumlin formation and discuss their implications below.

10.2.1 Site-specific drumlin formation

It is possible that the different types of drumlin (Figure 16) are formed by quite processes. Because they are often arranged next to each other, the implication is that different processes act at specific sites on the ice sheet bed and that these processes do not occur in the inter-drumlin terrain that exists between them. Here, we call this *'site* specific drumlin formation' Essentially, this scenario suggests that processes occur at a specific site on the ice sheet bed to create an individual drumlin. If this were the case, investigations of drumlins and non-drumlin sediments would be critical in providing information that could lead to a satisfactory explanation of the different types of site-specific drumlins. Indeed, there are three ways in which one might compare drumlins with non-drumlinised terrain and some of these have been attempted in previous studies:

(i) A comparison between the sediments and structures in different drumlins from within the same drumlin field and comparison to other drumlin fields

(ii) A 'lateral' comparison between individual drumlins and intervening non-drumlinised terrain within the same field (and potentially including comparisons between the drumlin field terrain and adjacent non-drumlinised terrain outside the drumlin field)

(iii) A 'vertical' comparison between drumlins and the substrate underneath (at depths greater than simple the break of slope at the base of the drumlin)

These comparisons might reveal different sediments and structures in drumlins compared to immediately adjacent non-drumlinised terrain (e.g. different lithologies, clast sizes, and/or degrees of sorting or deformation) and the observations presented in this paper can shed some light on such comparisons. For example, with respect to point (i), it is very clear (see section 7) that the sediments and structures found within drumlins can be highly variable, even within the same drumlin field, e.g. some might be composed of bedrock, some one till unit, some several till units, some sorted/stratified material, etc (see Figure 12).

With respect to point (ii), it is perhaps surprising that so few studies have attempted lateral comparisons between drumlins and inter-drumlin areas, but this is almost certainly due to the lack of suitable sediment exposures in the flatter, non-drumlinised terrain. However, of the few studies that have made this comparison, the results are inconclusive, some studies suggest there are differences and some studies suggest there are no differences.

With respect to point (iii), even fewer studies systematically investigate the nature of the boundary between the drumlin landform and the deeper underlying substrate, although there are some exceptions (e.g. Clapperton, 1989; Goldstein, 1989; Rattas and Piotrowski, 2003). Rattas and Piotrowski (2003), for example, noted that drumlin size appeared to be related to the permeability of underlying bedrock. A potential geological control on drumlin formation in Ireland was also investigated by Greenwood and Clark (2010). They suggest that underlying geology can modulate local drumlin form (cf. Phillips et al., 2010) but that it does not exert a more fundamental control on drumlin genesis. Indeed, it is clear from this review that drumlins occur over a wide range of substrates and incorporate such substrates into the drumlin form to varying degrees. In their review of the available data in the literature, Patterson and Hooke (1995) found unconsolidated sediments make up 34% of the substrates beneath drumlins, of which 18% were till and 16% were stratified deposits. The remaining 66% were rock. Their conclusion, like that of Greenwood and Clark (2010) is that drumlin development is not obviously linked to substrate.

Clearly, there is potential for future work to address the variability of drumlins sediments with respect to points (i) to (iii), above. Such investigations would be well suited to the use of geophysical and borehole investigations, which can cover larger areas and greater depths (cf. section 2.2 and 2.3). It would also be helpful for investigators to state: (a) approximately how many drumlins exist in the drumlin field; (b), the location and number of drumlins that are investigated; and (c), the precise location of the observations with respect to the entire drumlin surface. It might also be useful to describe all three aspects of drumlin composition and internal structure wherever possible, i.e. the composition, structure, and nature of deformation for each sampled landform. A further issue that is not often addressed but which may be very important is the temporal aspect of drumlin formation. It is still unclear how quickly and drumlin field may form, although it does appear that sediment can be eroded and deposited over very short (decadal) time-scales (e.g. years: Smith et al., 2007). Given that we know that some drumlin fields are composed of several populations of drumlins formed by different episodes of ice flow (Figure 13), it is likely that different sediments and structures are linked to different ice flow events and it might even be expected that neighbouring drumlins of different age would have different constituents. Thus, it would helpful for investigators to highlight any inferred chronology of drumlin formation within their studied drumlin field.

10.2.1.1. Bedrock drumlins as a 'site-specific' type

With the above discussion in mind, it is clear that bedrock drumlins (section 3.1) are likely to be site-specific in that some form of bedrock obstacle is required in a specific location from which a drumlin can be sculpted. Drumlin research has often leaned on form analogy and so it is clear to see why these features are labelled drumlins but it has been argued that such features should be seen as distinct from the other types of drumlin (e.g. Dionne, 1987). This is because the processes that streamline (and pluck) pre-existing bedrock outcrops into a variety of forms, including those that exhibit the classic drumlin shape, are relatively well known (cf. Benn and Evans, 1998). They result from glacial abrasion and meltwater erosion which smoothes and polishes bedrock protrusions and which also superimposes a variety of small-scale erosional landforms such as striae and friction cracks, etc. (cf. Linton, 1963; Bennett and Glasser, 1996; Benn and Evans, 1998). This is in contrast to the apparently counterintuitive way in which a glacier creates a pattern of upstanding mounds (drumlins) from unconsolidated sediments; especially where their distribution is clearly not related to any pre-existing or underlying topography.

Given that bedrock drumlins appear to be formed by subglacial processes that are relatively well described and which probably differ from processes that form the other main types of drumlins described in this paper, we suggest that it could safely be treated as a separate type of site-specific drumlin. Moreover, it might even be helpful to abandon the term ‘rock drumlin’ (cf. Dione, 1987) in favour of the previously employed term ‘whaleback’ (cf. Evans, 1996), with the prefix asymmetric for those features that are shaped with clear stoss and lee slope asymmetry. Following Dione (1987), the term ‘crag-and-tail’ should be restricted to landforms where the bedrock protuberance is clearly exposed at the stoss end of the landform and the unconsolidated material lies in its shadow (Figure 16e); and where the exposed bedrock occurs at the lee end (Figure 16f), the term ‘pre-crag’ be used (cf. Haaviston-Hyvärinen, 1997).

Site-specific drumlin formation, therefore, leaves room for different processes to produce different types of drumlin, even when they may appear very similar in terms of their morphology. This would imply that drumlins are a product of equifinality, i.e. different processes lead to different types of drumlins but which have similar morphology. Under these circumstances, however, we might want to call the different types of drumlin different names, as is suggested here for entirely bedrock forms, despite their similar morphology. Moreover, it might be that detailed morphological analysis of different types of site-specific drumlin may reveal subtle differences. We do not yet know, for example, whether the shape of bedrock drumlins is almost identical to drumlins composed of unconsolidated sediments, because it is unusual for studies of drumlin morphometry to include bedrock features (e.g. Clark et al., 2009).

10.2.2. Process-specific drumlin formation

The alternative to site-specific drumlin formation is that a single process acts to create drumlinised terrain. We use the term 'process-*specific'* to describe the development of drumlins that may result from a single process that occurs across a large area and leads to the development of the drumlinised 'surface'. A useful analogy here would be dunes formed by aeolian processes or ripples forming by fluvial processes: a process occurs over a large area and individual bedforms are not related to specific conditions at the site where they form and may even migrate. Under these circumstances, comparisons of drumlin and intervening non-drumlin sediments would not necessarily reveal any special processes occurring in drumlins, compared to non-drumlinised terrain; other than those that are inherited from pre-existing conditions, i.e. parts of the original pre-drumlinised surface were characterised by different sediments and structures. If this were the case, investigations of drumlin composition would not necessarily provide any critical information that could explain drumlin formation. Any observed differences between drumlins and the intervening non-drumlinised terrain may simply reflect pre-existing differences in pre-drumlinised terrain and may be largely unrelated to the processes that created the drumlin surface.

Whilst we suggest above that bedrock drumlins are site-specific, it is more difficult to ascertain whether the other four basic types are formed by different processes. There are some hints in the literature that certain site-specific processes may act to preserve or deform sediments to create individual drumlins, but there is no clear evidence to assume that they are formed by completely different mechanisms, especially as many are observed within the same drumlin field and may even be seen as a continuum in some settings (e.g. Boyce and Eyles, 1991). To the contrary, the unimodal distribution of drumlin shape parameters (cf. Clark et al., 2009) would appear to suggest that these landforms have much in common, despite their varied constituents. Indeed, if each of these types of drumlin are site specific landforms and if their internal sediments and structures are related to those processes; the great variability of drumlin internal structure within drumlin fields would imply that different subglacial processes occur at specific locations beneath the ice sheet and that neighbouring drumlins that might be just a few hundred metres apart are formed by quite different processes. This would seem to be introducing additional complexity where it is not required.

Putting aside bedrock drumlins, therefore, we consider it highly unlikely that the four remaining types of drumlins are formed by entirely different processes and suggest that they are formed by a single process that occurs across the ice sheet bed to create drumlinised terrain. Of course, this is not a new idea and previous authors have suggested spatially extensive processes that might create drumlins, such as catastrophic meltwater floods (e.g. Shaw, 1983; Shaw and Kvill, 1984) or an instability between the base of the ice and underlying sediments (e.g. Hindmarsh, 1998; Fowler, 2000). Similar processes act in aeolian and fluvial environments to create familiar patterned surfaces in a variety of sediment grain sizes (e.g. dunes, ripples, etc), yet it would be odd to question whether dunes with different grain sizes are formed by a fundamentally different mechanism. Indeed, such processes are not greatly sensitive to different sediments and structures (although this may still be important in more extreme situations) and, depending on the balance between erosion, transport and deposition, could erode and/or deform the landscape to leave drumlins with a range of constituents and structures. As Aronow suggested in 1959: “when the conditions within the ice are present for making drumlins and related features they are formed, seemingly, regardless of the materials available” (p. 202).

A key implication of the process-specific drumlin formation, which we favour for all but bedrock drumlins, is that the sediments and structures inside drumlins may not necessarily be related to the drumlin forming mechanism and simply reflect pre-existing sediments that have been subjected to the drumlin-forming mechanism (and to varying degrees).. This point has been made by previous authors (e.g. Menzies, 1979a; Smalley, 1981; Kerr and Eyles, 2007). Knight and McCabe (1997), for example, suggest that up to 95% of the sediment sequence in one drumlin they studied in NW Ireland probably pre-dates drumlin formation. An important issue with studies of drumlin internal structure is that some may uncritically assume that the sediments inside a drumlin are related to the drumlin forming mechanism. An attempt is then made to reconstruct the environment in which those sediments originated. The logical outcome of this line of thinking is that the large variability in drumlin internal structure leads to several different drumlin forming environments and radically different hypotheses regarding drumlin formation. Shaw (1983: p. 473) for example, states that "if the environment and processes of deposition for this stratified material [in the drumlin] can be determined then we might make some progress on the question of drumlin genesis". This may be true, but it is also possible that the environment and processes of deposition pre-date drumlin formation. If it is possible that some of the sediments and structures are inherited from previous sedimentary environments and not related to the drumlin forming mechanism, then the variability of drumlin internal sediments and structures need not be seen as a major obstacle to a universal drumlin forming theory that acts on various substrates.

11. Conclusions

The sheer diversity of drumlin internal composition and structure has often been seen as a major obstacle to a unifying theory of drumlin formation. Given the range of complexity reported (and interpreted formational hypotheses and hints) one might mischievously suggest that each drumlin formed by its own unique process. The key issue is to know which observations represent valid data with which to test hypotheses of drumlin formation. It would be dangerous to take sedimentary observations that record processes that occurred prior to or after drumlin formation (and just happen to be inside a drumlin or associated with it) and then use those to either construct or test hypotheses of drumlin formation. Our reading of the literature is that, to an extent, this issue has introduced some unwarranted complexity. Observations used inappropriately might overemphasise the exotic and the complex, such that we lose sight of the more fundamental issues and/or fail to recognise the commonality that may exist. With this in mind, we suggest that there are, essentially, five basic types that are commonly reported:

1. Mainly bedrock
2. Part bedrock/part till
3. Mainly till

4. Part till/part sorted sediments
5. Mainly sorted sediments

The most commonly reported drumlin ‘type’ (i.e. those that are cited most often in the literature, but irrespective of sample sizes) appear to be those composed of mainly till, followed by those composed of part till/part sorted sediments, part till/part bedrock, and, finally, mainly sorted sediments. However, ‘reports’ of drumlin internal structure are unlikely to be representative of the entire population of drumlins because they are not evenly distributed on former ice sheet beds; they are typically based on very low sample sizes; and they may be shaped/biased by particular paradigms or ideas.

In addition to the five main types of drumlin reported in the literature, distinct drumlin veneers/carapaces are often reported to be composed of either till or glaciofluvial sediments but most authors suggest that these thinner units draped over the drumlin surface are not related to the drumlin-forming mechanism and most likely reflect deposition during deglaciation. Specific stoss and lee features are also found in association with the five main types of drumlin, e.g. stoss-side features dipping up-ice, lee side features dipping down-ice (including lee-side stratified sediments) but, again, most authors suggest that such features require an obstacle (i.e. the drumlin) to form and that they may not necessarily be related to the drumlin-forming mechanism. Features associated with glaciotectonic deformation have attracted much attention in the drumlin literature and are found in all types of drumlins, excluding those formed of bedrock. Deformation features range from small and localised to several tens of metres and throughout the entire drumlin thickness, but some drumlin sediments show no evidence of ever having been deformed. Likewise, there are no obvious trends in the shape and size of clasts. The whole range of sediment clast sizes (clay to boulder) and shapes (angular to rounded) have been found inside drumlins and, whilst macrofabric analyses are commonly performed on clasts and usually show a preference for long-axes to be aligned with the drumlin orientation, there are no common trends across a broad range of studies, i.e. comparing vertical or horizontal profiles.

Drumlin theories are now being developed into models and, given the oft-cited complexity of drumlin composition, it is important for model-builders to know which aspects of drumlin phenomena actually need explaining (it would be impossible to attempt to explain every clast or sedimentological occurrence); and for those with working models, which aspects can be used as a test or falsification. It is hoped that the main types of drumlin identified in this paper provide a more realistic target for theorists to address. A key question, however, is whether each of the different types of drumlin identified in this paper are formed by a different process that are specific to conditions at a point on the ice sheet bed (termed here 'site-specific formation) or whether a single process can account for the formation of more than one drumlin type (termed here 'process-specific'). We conclude that bedrock drumlins are site-specific and, because they are formed by processes that are relatively well known (glacial abrasion and meltwater erosion), it might be helpful to cease to use the term drumlin to describe these features (cf. Dione, 1987).

The other four types might be produced by different subglacial processes and several different models might be required: drumlins would therefore represent an equifinal bedform, and with more knowledge we might be justified in developing process-specific drumlin names for the different types. However, we argue that they are more likely to be closely related because they often occur in close proximity within the same drumlin field and occasionally as a continuum (cf. Boyce and Eyles, 1991). We favour the alternative explanation that there is, essentially, a single drumlin-forming mechanism that acts in a wide range of sedimentary environments to create drumlinised terrain. The major implication of this view is that the composition and internal structure of drumlins largely reflects pre-existing sediments and sedimentary conditions that become drumlinised and are, therefore, unlikely to be diagnostic of the drumlin-forming mechanism. Rather, observations of the composition and internal structure will reveal the way in which the mechanism itself, is influenced by pre-existing sedimentary conditions.

Acknowledgements

This paper was funded by a Natural Environment Research Council (NERC) grant (NE/D013070/1), and has benefited from discussion with our colleagues Andrew Fowler and Richard Hindmarsh. We would like to thank the Editor, Jon Harbour, and the comments of Clas Hättestrand and two anonymous reviewers, whose comments improved the content and clarity of the manuscript. Chris Orton, Department of Geography, Durham University is thanked for drafting most of the figures.

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Table Captions:

Table 1: Reported evidence for each of the five main types of drumlin composition identified in this paper (see Section 3 and Figure 16). Papers that report each type of drumlin (listed in column headings) are presented in chronological order and split into different time periods (pre 1900; 1900-1925; 1926-1950; 1951-1975; 1975-2000; post 2000). Note that different papers report different sample sizes; some papers report more than one type of drumlin; and different papers may include data on the same drumlin(s). See section 10.1 for discussion of issues regarding representativeness.

Bedrock	Part Bedrock/Part Till	Mainly Till	Part Till/Part Sorted	Sorted
Fairchild (1907)	Chamberlin (1883)[1]	Upham (1892)[1]	Kupsch (1955)	Upham (1894)[3]
Linton (1963)	Tarr (1894)[1]	Lincoln (1892)	Chapman & Putman (1966)[5]	Alden (1905)[3]
Glückert (1973)	Högbom (1905)[1]	Crosby (1892)[2]	Hill (1971)	Gravenor (1953)[3]
Dionne (1987)	Hollingworth (1931)[1]	Fairchild (1907)	Miller (1972)	Lemke (1958)[3]
Raukas & Tavast (1994)	Crosby (1934)	Wright (1912)[1]	Shaw & Freschauf (1973)	Hoppe (1963)[3]
	Ebers (1937)[1]			
Evans (1996)	Armstrong (1949)[1]	Goldthwait (1924)[1]	Whittecar & Mickelson (1977)	Johansson (1972)[3]
Kerr & Eyles (2007)	Deane (1950)[1]	Fairchild (1929)[1]	Whittecar & Mickelson (1979)	Bayrock (1972)[3]
	Aronow (1959)	Wilson (1938)[1]	Aario (1977)	Muller (1974)[3]
	Aartolahti (1966)[1]	Sproule (1939)[1]		
	Savage (1968)[1]	Charlesworth (1939)[1]	De Jong et al. (1982)	Gillberg (1976)[3]
	Repo & Tynni (1971)[1]	Bergquist (1942)[5]	Dardis (1984)	De Jong et al. (1982)
	Hill (1971)	Bergquist (1943)[5]	Dardis & McCabe (1983)	Shaw (1983)
	Minell (1973)[1]	Putnam & Chapman (1943)[1]	Dardis et al. (1984)	Shaw & Kvill (1984)
	Gluckert (1973)	Goldthwait (1948)[1]	Sharpe (1985)	Sharpe (1987)
	Gillberg (1976)[5]	Gravenor (1953)[1]	Dardis (1985)	McCabe (1989)

	Dionne (1987)	Dean (1953)[5]	Dardis (1987)	Zelčs & Dreimanis (1997)
	Riley (1987)	Sharp (1953)	Dardis & McCabe (1987)	Menzies & Brand (2007)
	Gluckert (1987)	Wright (1957)	Hanvey (1987)	
	Boyce & Eyles (1991)	Hoppe (1959)[1]	Sharpe (1987)	
	Raukas & Tavast (1994)	Aronow (1959)	Krüger (1987)	
	Nenonen (1994)	Virkkala (1960)[4]	Hanvey (1989)	
	Newman & Mickelson (1994)	Wright (1962)	Goldstein (1989)	
	Fisher & Spooner (1994)	Muller (1963)[1]	McCabe (1989)	
	Hart (1997)	MacNeill (1965)[1]	Clapperton (1989)	
	Meehan et al. (1997)	Chapman & Putnam (1966)[5]	Boyce & Eyles (1991)	
	Zelčs & Dreimanis (1997)	Harris (1967)	Habbe (1992)	
	Haaviston-Hyvärinen (1997)	Hill (1968)[1]	Menzies & Maltman (1992)	
	Yi & Cui (2001)	Karrow (1968)[2]	Hanvey (1992)	
	Tavast (2001)	Lasca (1970)[1]	Ellwanger (1992)	
	Fuller & Murray (2002)	Lundqvist (1970)[1]	Wysota (1994)	
		Hill (1971)	McCabe & Dardis (1994)	
		Minell (1973)[1]	Newman & Mickelson (1994)	
		Gravenor (1974)	Fisher & Spooner (1994)	
		Hill (1973)[5]	Dardis & Hanvey (1994)	
		Jauhiainen (1975)[5]	Raukas & Tavast (1994)	
		Menzies (1976)[1]	Nenonen (1994)	
		Minell (1979)	Goldstein (1994)	
		Heikkinen & Tikkanen (1979)[5]	Hart (1995a)	
		De Jong et al. (1982)	Hart (1997)	
		Karrow (1981)	Zelčs & Dreimanis (1997)	
		Jones (1982)	Menzies et al. (1997)	
		Riley (1987)	Knight & McCabe (1997)	
		Piotrowski (1987)	Rattas & Kalm (2001)	
		Rabassa (1987)[5]	Raunholme et al. (2003)	
		Dardis (1987)	Rattas & Piotrowski (2003)	
		Dardis & McCabe (1987)	Jørgensen & Piotrowski (2003)	
		Piotrowski & Smalley (1987)	Kerr & Eyles (2007)	
		Piotrowski (1988)	Hiemstra et al. (2008)	
		Stea & Brown (1989)		

		Goldstein (1989)		
		Clapperton (1989)		
		Coudé (1989)[5]		
		Newman et al. (1990)		
		Habbe (1992)		
		Aario & Peuraniemi (1992)		
		Newman & Mickelson (1994)		
		Raukas & Tavast (1994)		
		Wysota (1994)		
		Hart (1995b)		
		Hart (1997)		
		Zelčs & Dreimanis (1997)		
		Haavisto-Hyvärinen (1997)		
		Menzies et al. (1997)		
		Stea & Pe-Piper (1999)		
		Jorgensen (2001)		
		Nenonen (2001) Williams & Thomas (2001)		
		Rattas & Piotrowski (2003)		

Citation sources: [1]Menzies (1979a); [2]Karrow (1981); [3]Shaw (1983); [4]Karczewski (1987); [5]Patterson & Hooke (1995)

Figures:

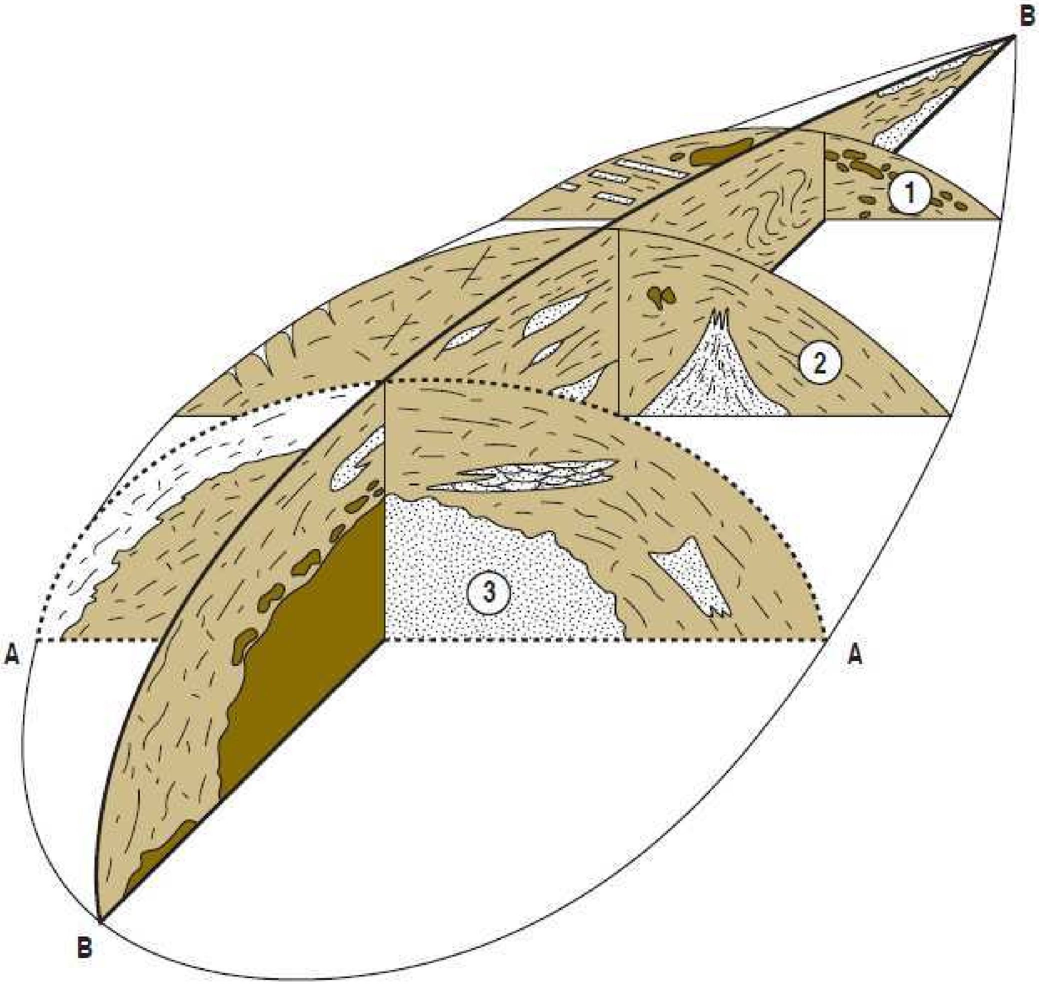

Figure 1: Cartoon of drumlin internal structure emphasising the potentially complex nature of their internal structure and how observations taken from limited natural exposures (e.g. areas labelled 1, 2 and 3) may not necessarily be representative of the internal properties of the entire drumlin. The ideal situation of having both a continuous transverse (A-A) and longitudinal section (B-B) is virtually impossible to observe using field traditional methods but is possible using geophysical techniques. This cartoon is used to simply illustrate the point about the internal variability of some drumlin sediments and is redrawn from the front cover of the 'Drumlin Symposium' book (Menzies and Rose, 1987).

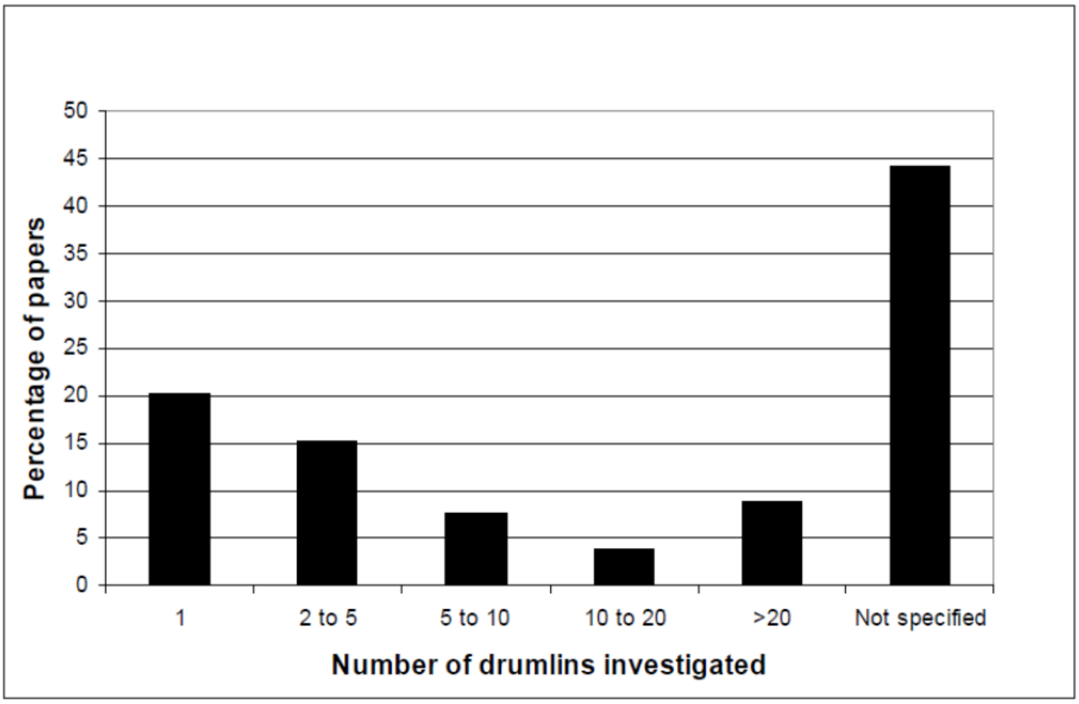

Figure 2: Samples sizes of drumlin composition and internal structure from 79 papers in the literature that we were able to consult and which specifically mention drumlin composition. Note that the majority of papers do not specify exactly how many drumlins were investigated and that for those papers which do state this explicitly, the dominant sample size is 1 drumlin (21%). Less than 10% of papers report from sample sizes greater than 20 drumlins.

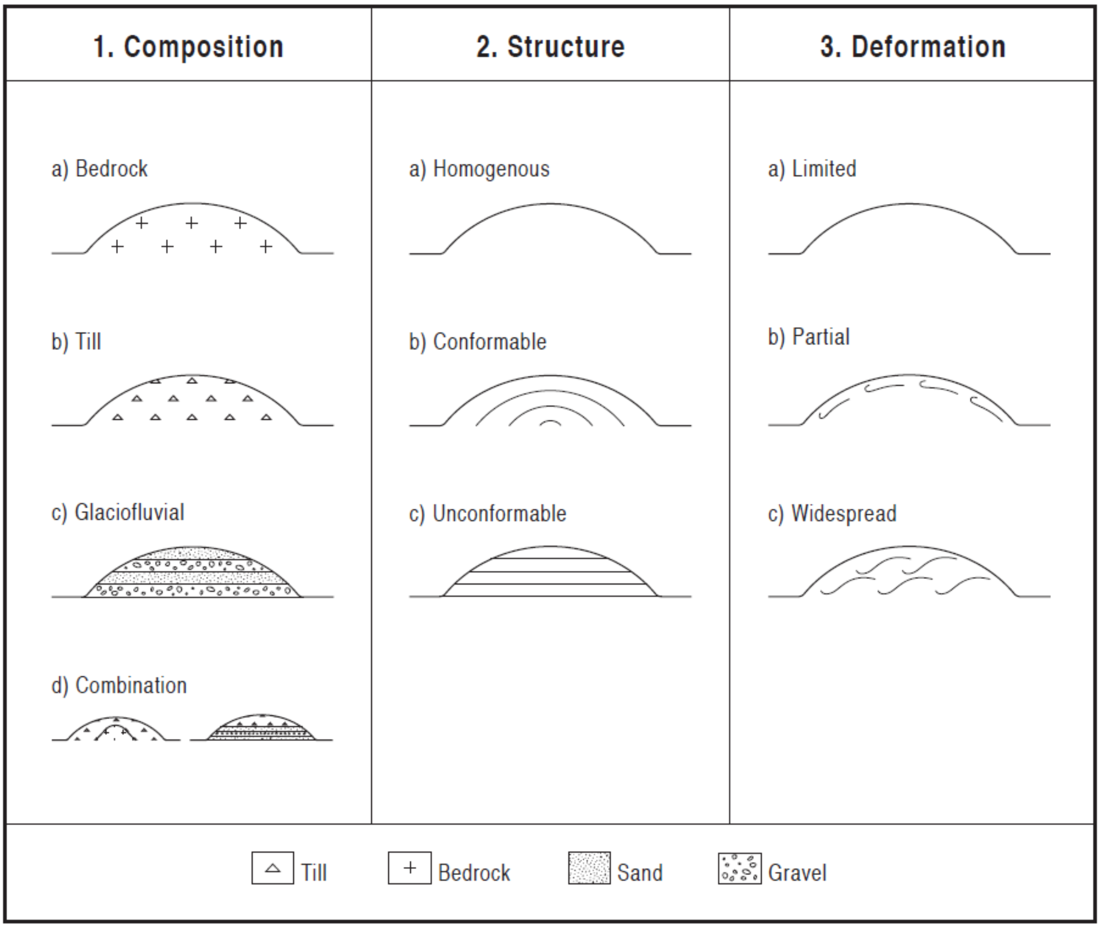

Figure 3: Three aspects of drumlin composition and structure that are of interest include their: (1) composition (i.e. bedrock, till, glaciofluvial, or a combination); (2) structure (homogenous, conformable, unconformable); and (3) deformation (limited, partial/non-pervasive, widespread/pervasive).

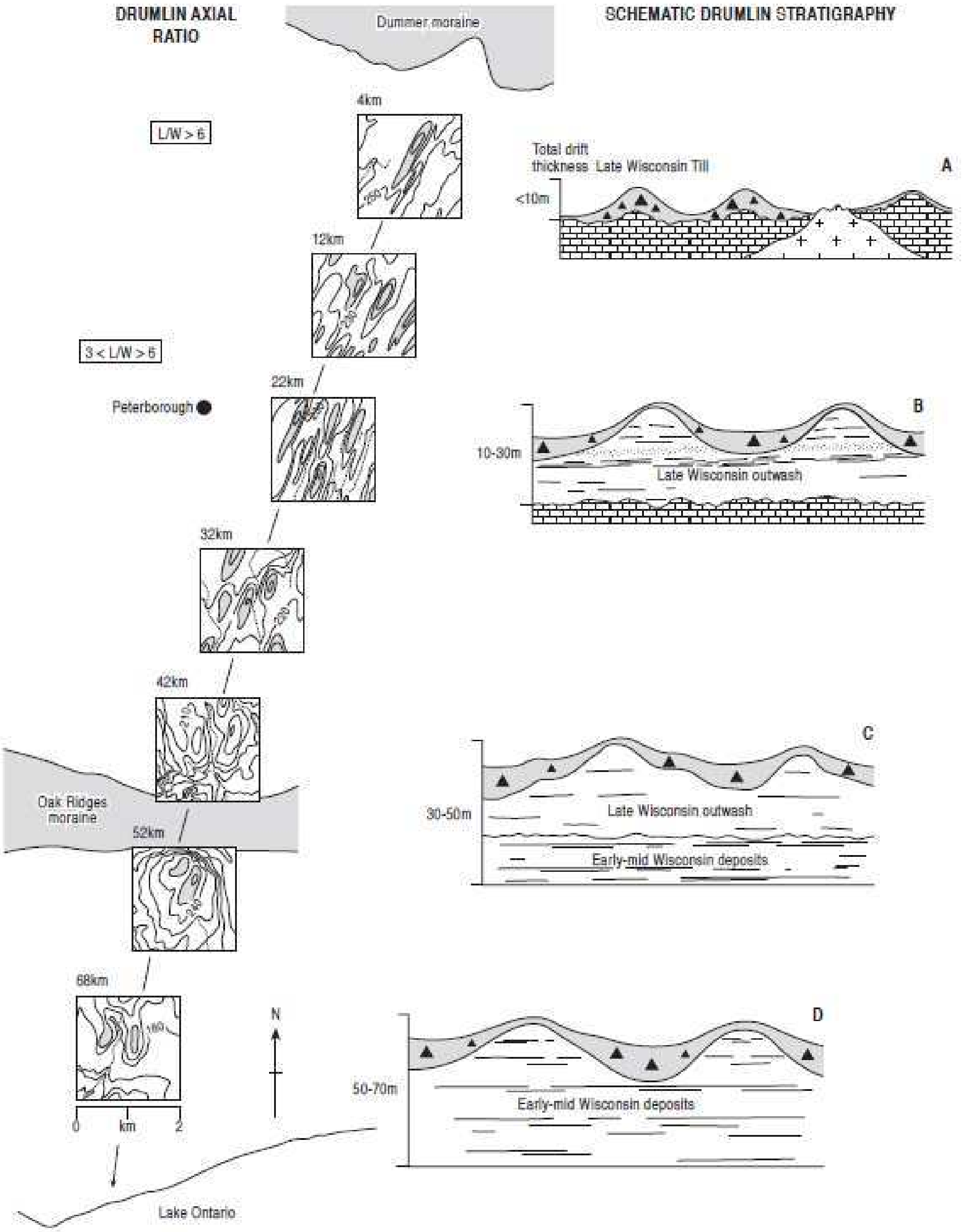

Figure 4: Variability in drumlin stratigraphy and external morphometry along a 70 km flow-line of the Peterborough drumlin field (redrawn from Boyce and Eyles, 1991). In the north, drumlins are composed of part bedrock and part till but, in the south, they are composed of overridden proglacial and glaciolacustrine sediments overlain erosively by deformation till.

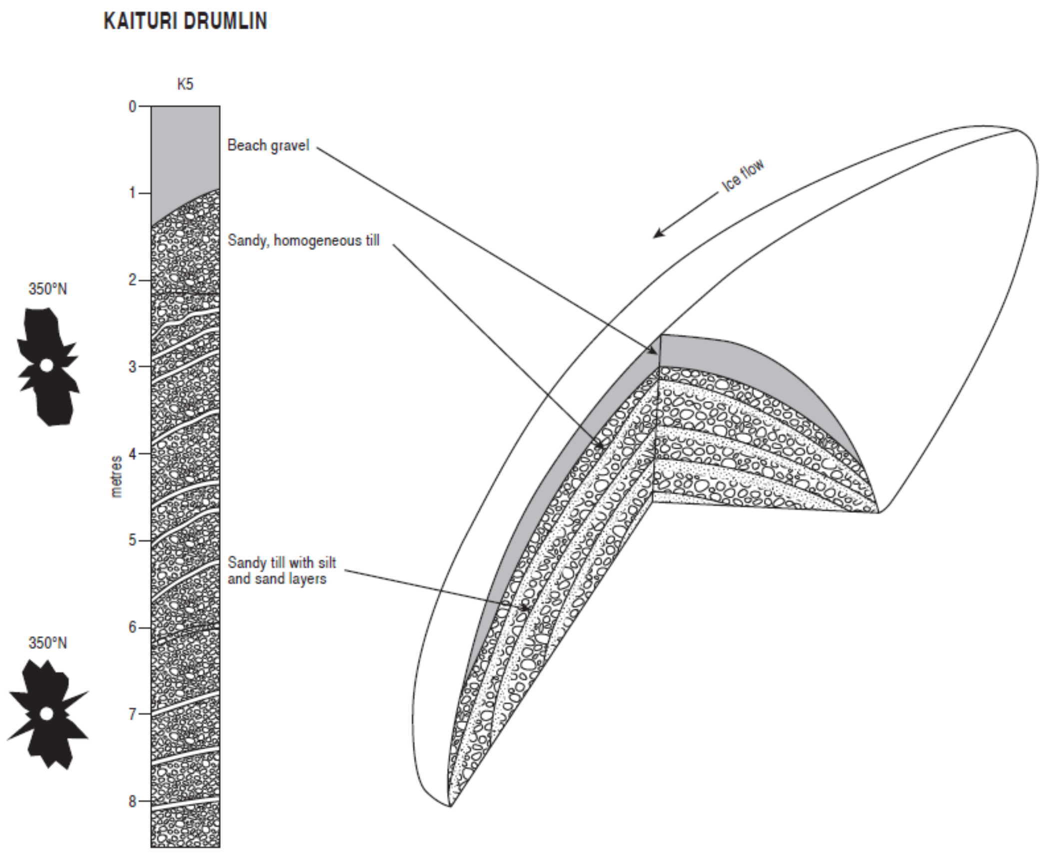

Figure 5: The stratigraphy of the Kaituri drumlin, central Finland, and an outline of its internal structure (redrawn from Nenonen, 1994). The drumlin is composed of mainly of a homogenous sandy till, but with stratified beds of silt and sand layers that conform with the drumlin surface (cf. Figure 3). Till macrofabrics from upper and lower units give a mean orientation of 350 °, which is parallel to the long axis of the drumlin (345°).

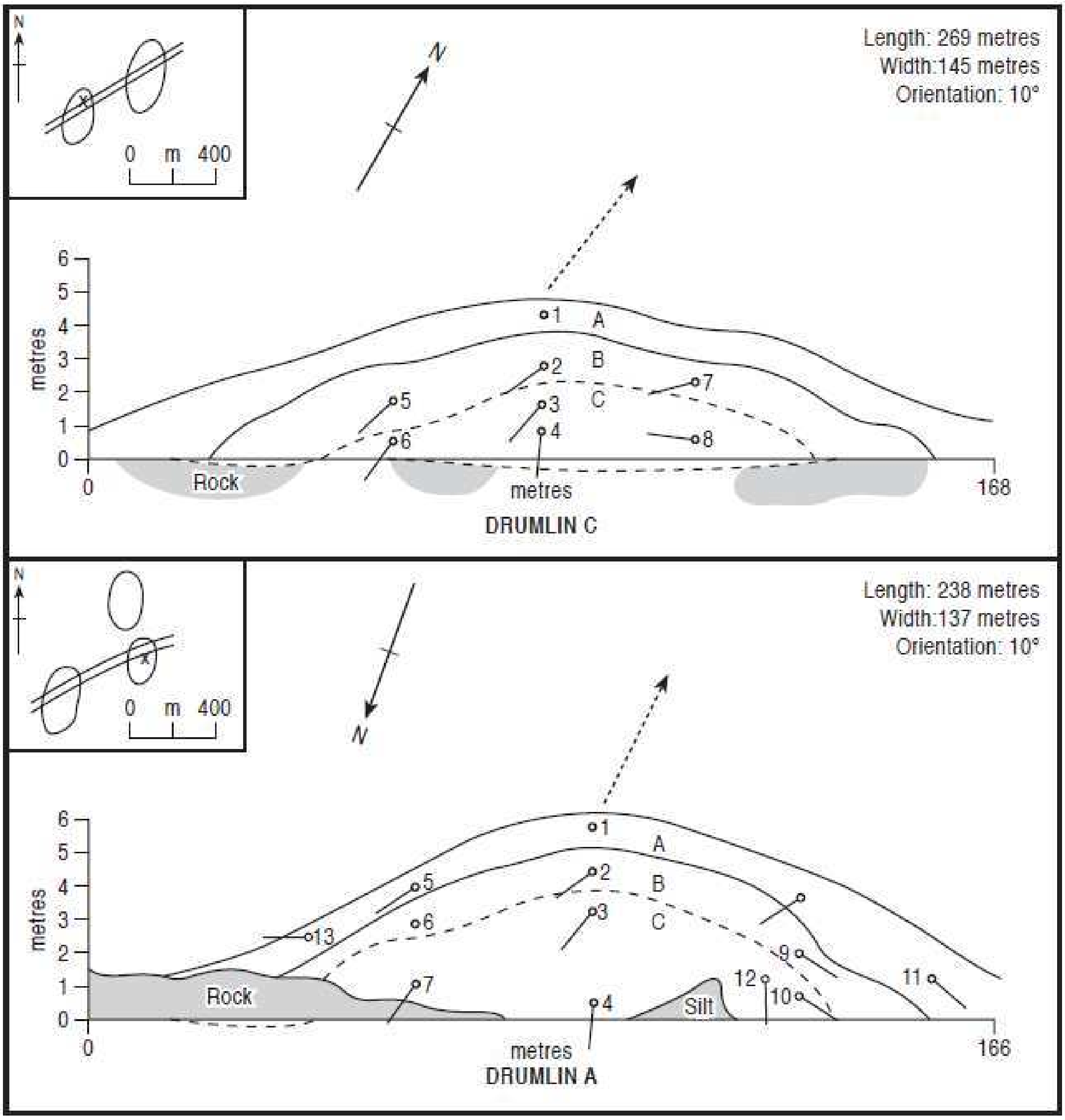

Figure 6: Internal composition and mean orientations of till fabrics in two drumlins from the Ards Peninsula, Northern Ireland (redrawn from Hill, 1971). The drumlins illustrated are composed of three units of till but those elsewhere are composed of only one or two units and some have cores of rock or are composed mainly of sand. Note the variations in till fabrics at different depths and within the different units (dashed arrow = ice flow direction).

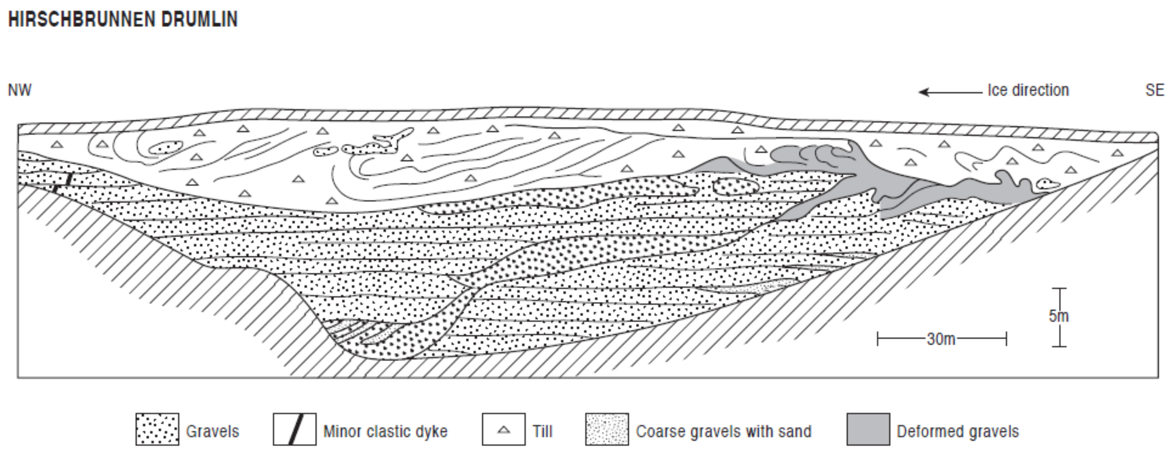

Figure 7: Schematic longitudinal section of the Hirschbrunnen drumlin (South German Alpine Foreland), which is composed of stratified sediments that have been deformed into an overlying till unit (redrawn from Ellwanger, 1992).

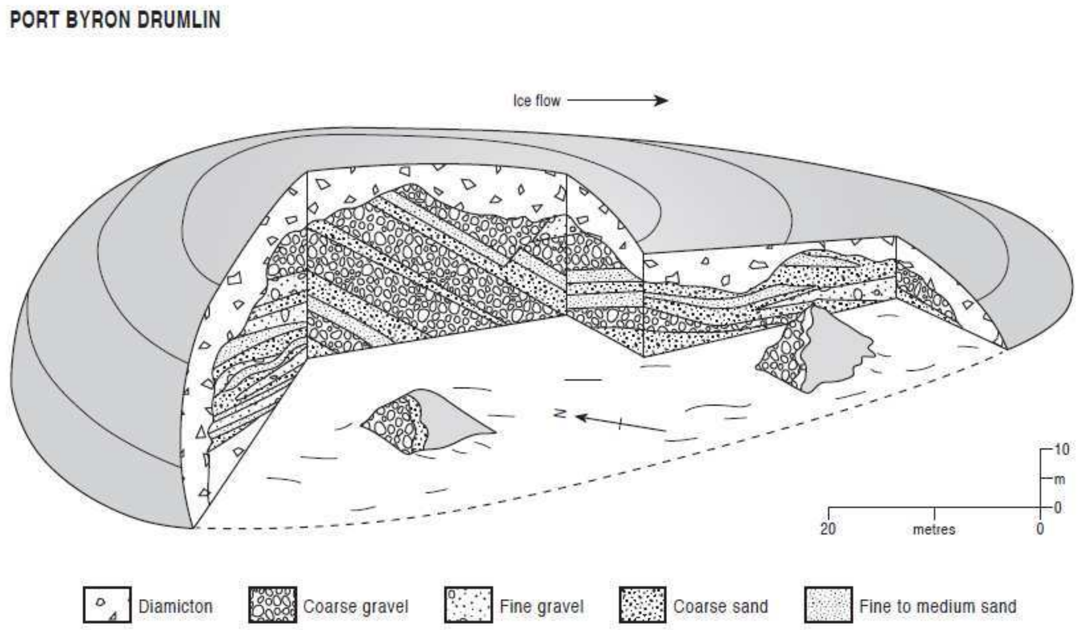

Figure 8: Cross section of the Port Byron drumlin, New York State, USA (redrawn from Menzies and Brand, 2007). This drumlin is composed of mainly stratified sediments overlain by a thin veneer of till which exhibits syndepostional deformation features.

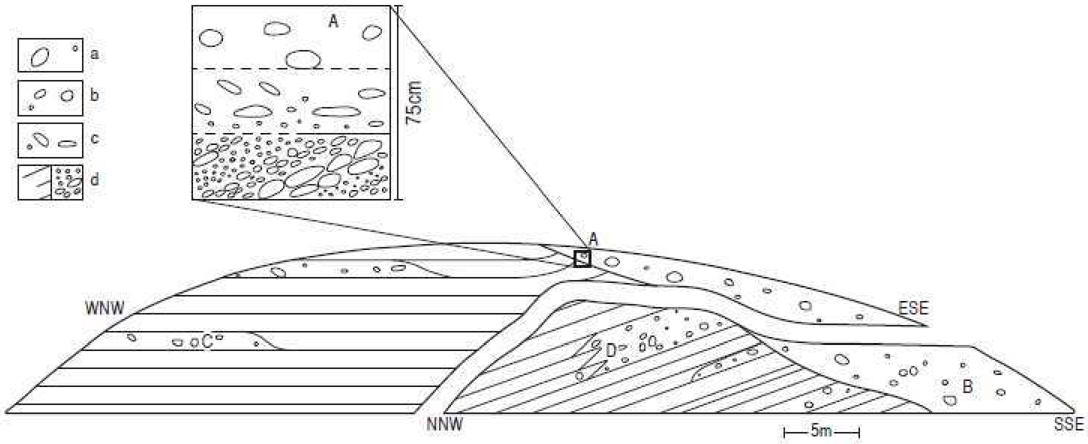

Figure 9: Internal structure of the Mehetsweiler drumlin, western Allgäu, southern Germany, which consists mainly of stratified sediments, overlain by a mantle of till (redrawn from de Jong et al., 1982) (a = subglacial till; b = flow till; c = contact zone between 'a' and 'd' (see inset); (d) = ice marginal meltwater deposits).

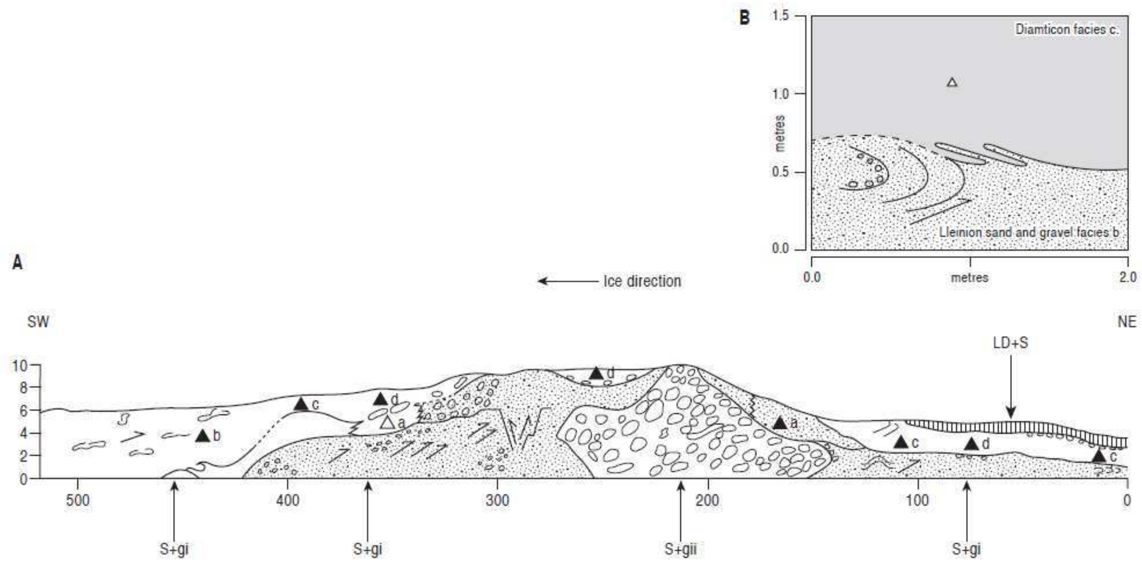

Figure 10: Coastal section of a drumlin at Lleiniog, North Wales showing a deglacial veneer comprising a stratified bed consisting of a laminated sand, silt and clay deposit (0.5 m thick) on the proximal side of a drumlin (redrawn from Hart, 1995a). Hart also noted prominent fold and thrust features that preferentially developed on the stoss side of the drumlin (inset). LD+S = Llandona Diamicton and Sands; Lleiniog Diamicton: a = very coarse gravel facies; b = more chaotic sand-rich facies; c = red homogeneous facies; d = homogeneous facies with gravel lag. Lleiniog Sand and Gravel: S+gi = grey-brown member/facies 'i'; S+gii = red-brown member/facies 'ii'.

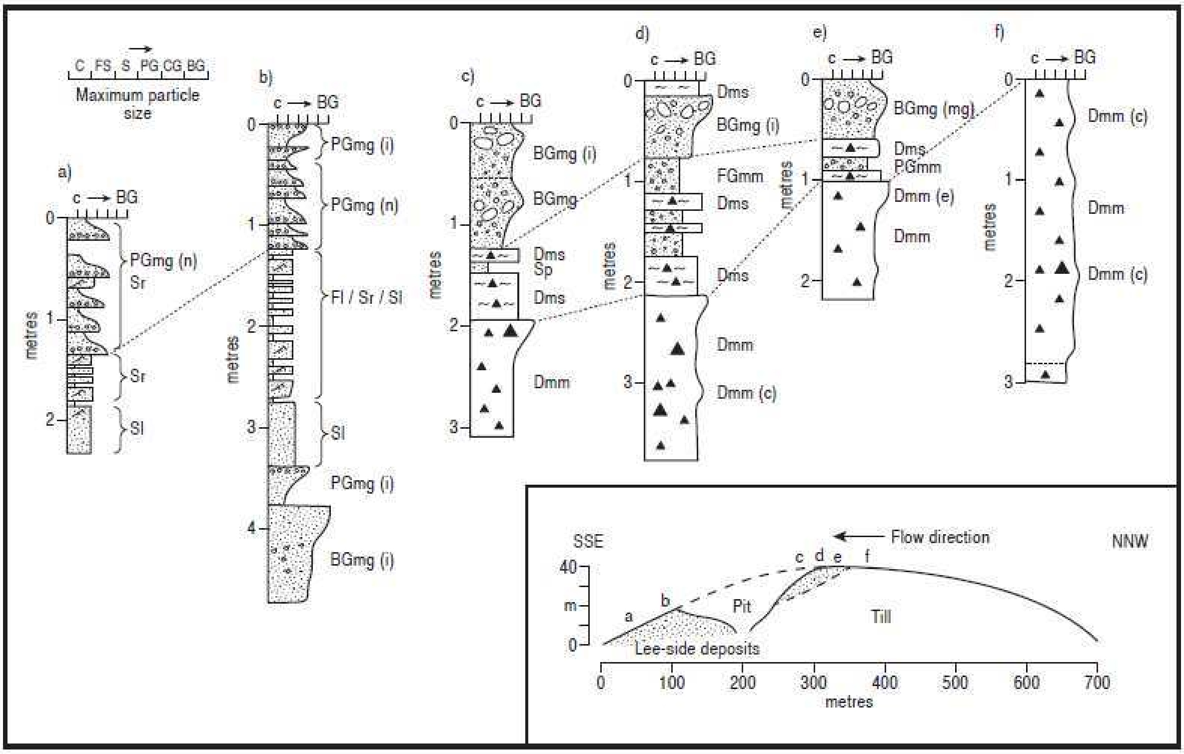

Figure 11: Proximal-distal lithofacies relationships in the Derrylard drumlin, Northern Ireland, illustrating lee-side stratified sediments (redrawn from Dardis et al., 1984).

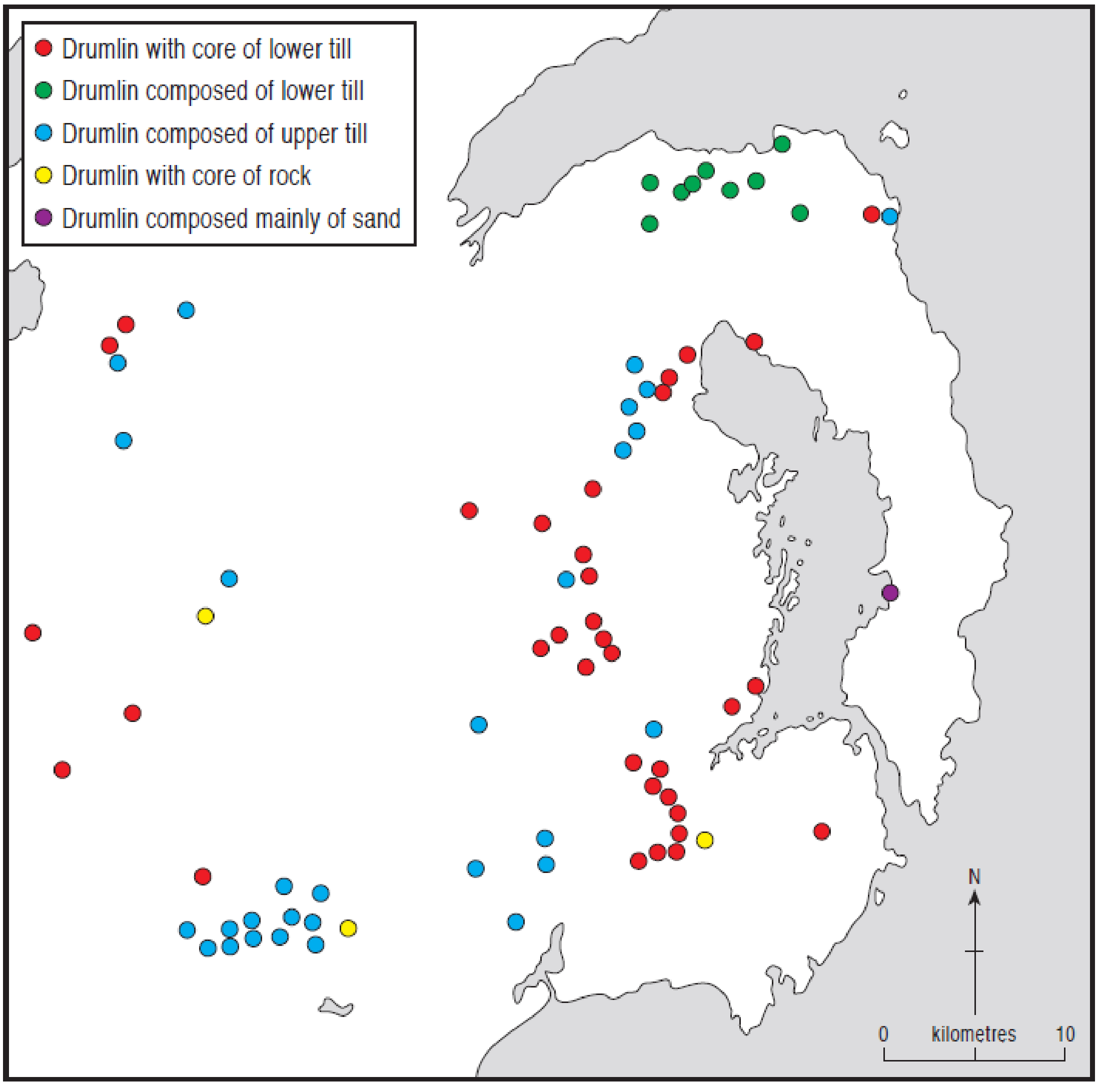

Figure 12: Internal composition of drumlins in north Down and south Antrim, Northern Ireland, redrawn from Hill (1971).

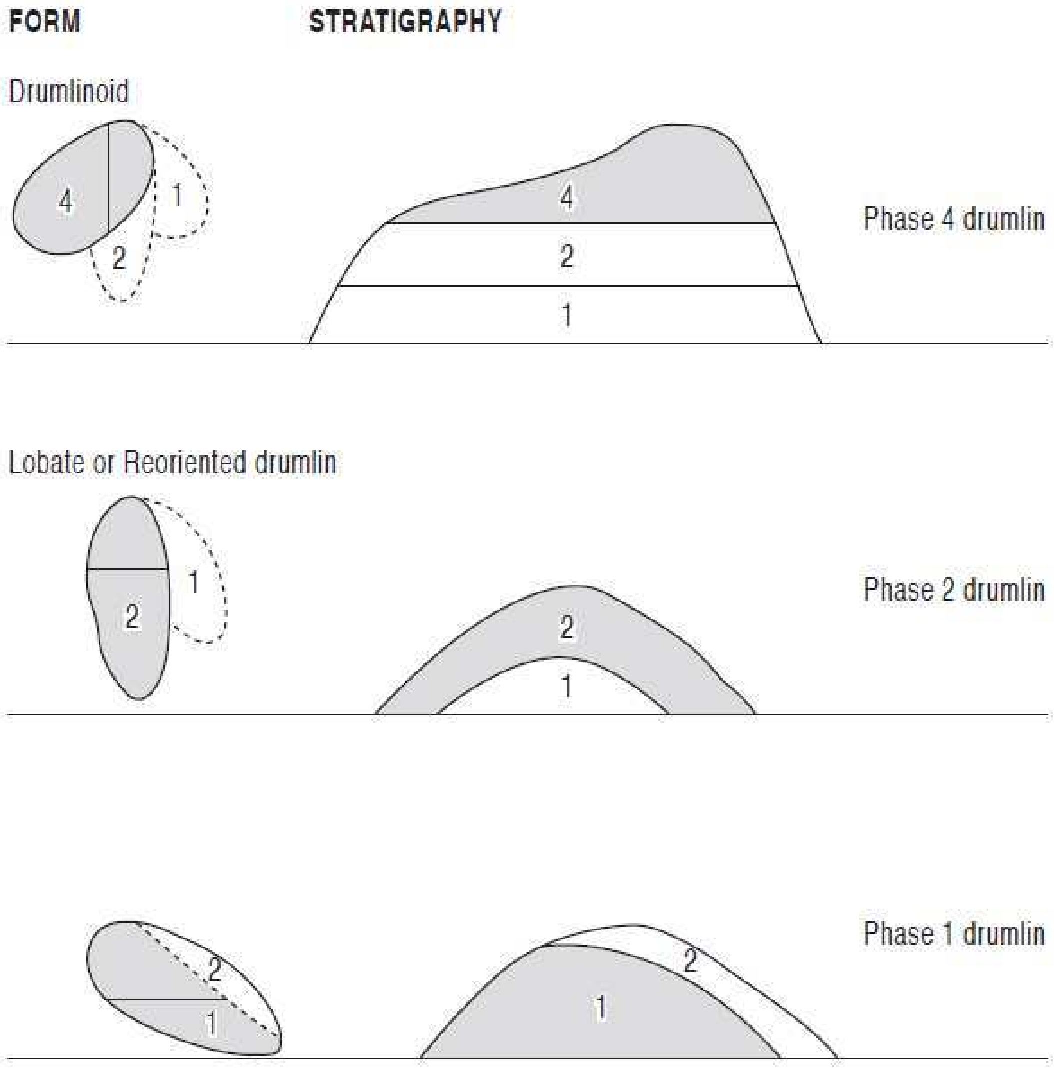

Figure 13: The development of drumlins in Nova Scotia through different ice flow phases (redrawn from Stea and Brown, 1989). Shaded areas under stratigraphy and form are thought to represent till units formed at the same time as the drumlin shaping process during specific ice flow phases. Unshaded areas under stratigraphy represent erosional remnants of earlier units. This figure illustrates the importance of appreciating the ice flow history of an area to understanding drumlin composition and internal structure.

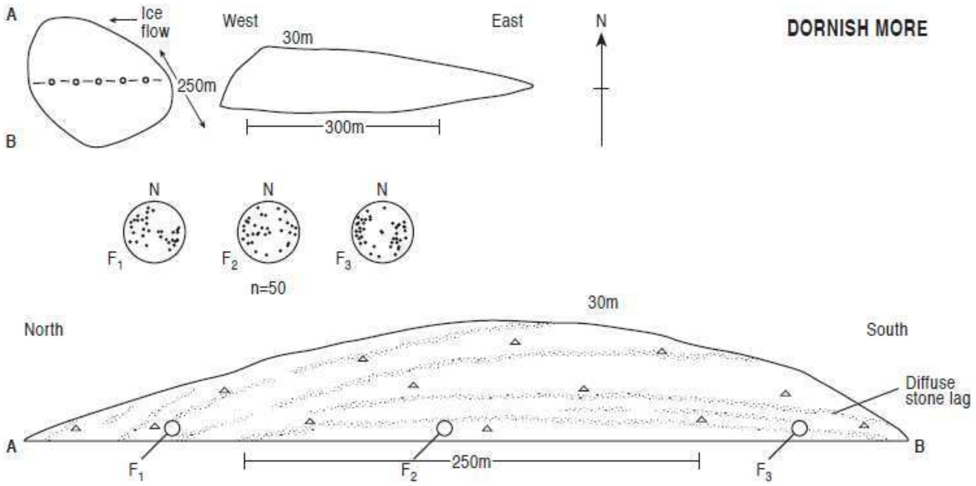

Figure 14: Morphology and stratigraphy of a drumlin in western Ireland showing boulder concentrations with a distinctive concentric arrangement that closely corresponds to drumlin morphology (redrawn from Hanvey, 1992).

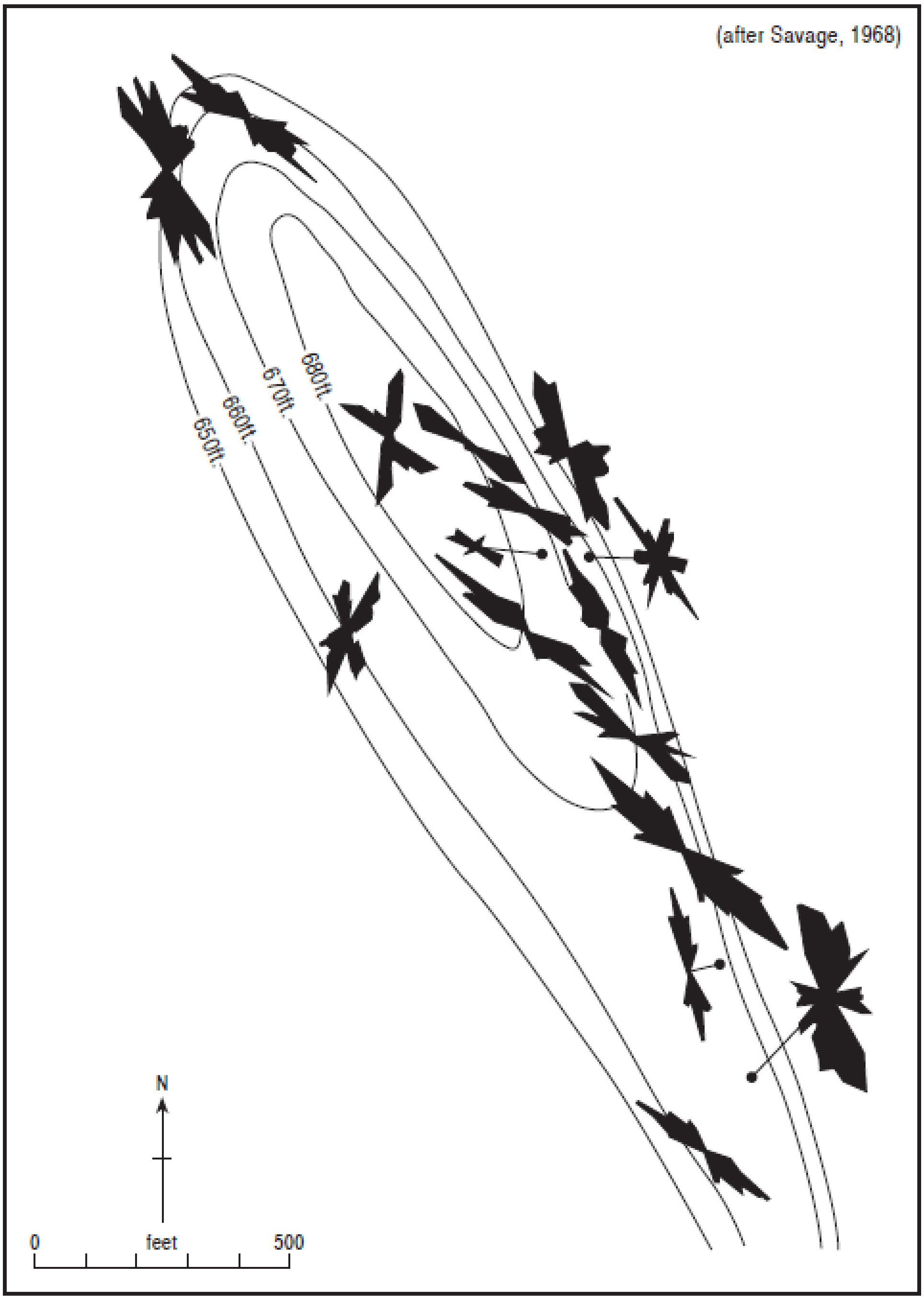

Figure 15: Till fabrics from a drumlin in SE Syracuse, New York showing a general aligment with drumlin orientation but with divergence around the stoss end and convergence around the lee end (redrawn from Muller, 1974, data from Savage,1968).

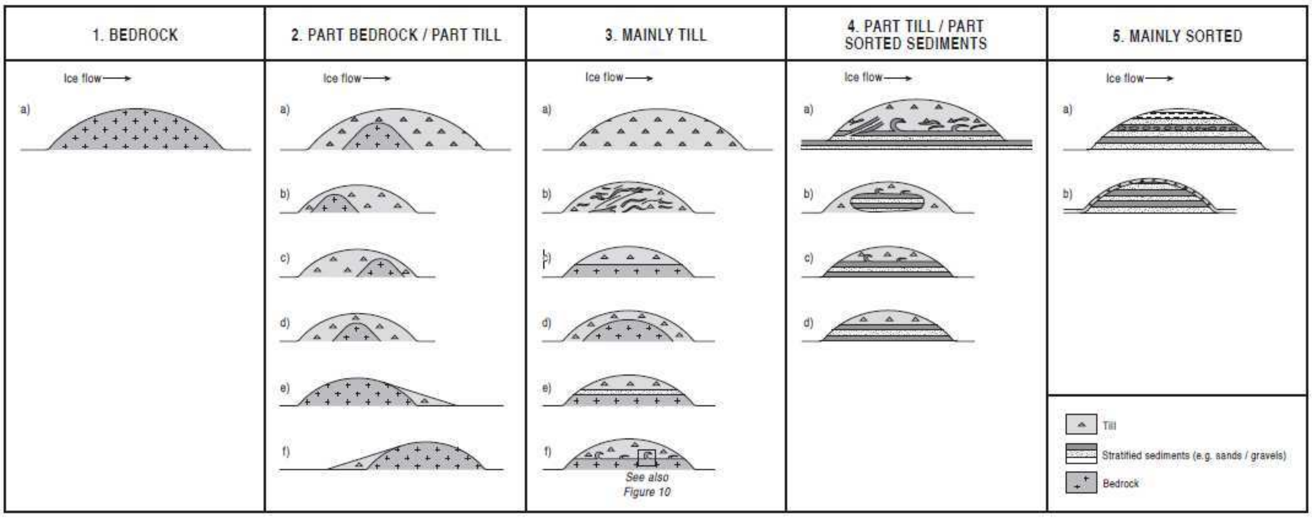

Figure 16: Schematic illustration of the five main types of drumlin reported in the literature, including various sub-types. It is argued that most reports of drumlin composition and internal structure can be classified according to each of these five main types, which we suggest are a useful observational template for theorists of drumlin formation to explain. See text for further discussion (section 10).

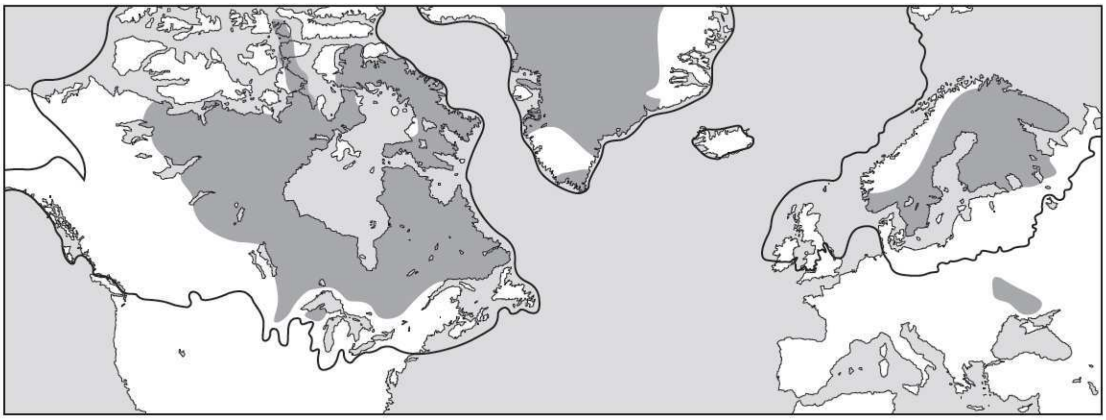

Figure 17: Location map of investigations of drumlin internal structure listed in Table 1 and the approximate extent of former mid-latitude ice sheets (black line). Several papers represent reviews or syntheses of data from different areas (e.g. Linton, 1963) and not every location from these papers is mapped. The key point is the general absence of studies from shield areas (grey shading), despite the fact that they underlie large areas of former ice sheets. Ice extent taken from Ehlers and Gibbard (2007) and shield areas from USGS Geological Province Map http://earthquake.usgs.gov/research/structure/crust/maps.php).