

Glacigenic clast fabrics: genetic fingerprint or wishful thinking?

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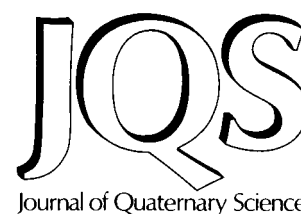
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ABSTRACT: The interpretation of glacigenic diamictos is a subjective process, for which quantitative support is frequently sought from parameters such as clast shape and fabric. It has been widely suggested that different glacigenic diamicton facies possess distinct clast-fabric signatures. This paper examines this concept using a data set of 111 clast fabrics, and a synthesis of published results. Eigenvalues are calculated and compared for a variety of sedimentary facies. It is concluded that clast fabric alone is not able to discriminate between different glacigenic facies, and it is argued that clast fabric offers little quantitative support in the interpretation of glacigenic sediments. It is suggested, therefore, that although clast fabric may continue to have a role as an indicator of relative strain at specific sites, its use in the discrimination of glacigenic facies is limited. Consequently, we should be much more selective in undertaking such analyses in the future. Copyright © 1999 John Wiley & Sons, Ltd.

KEYWORDS: clast fabrics; glacigenic diamictos; eigenvalues.



Introduction

The measurement and analysis of the clast fabric of glacigenic diamictos is considered by many to be a fundamental quantitative tool in the analysis of glacial sediments and its collection a matter of course and good practice. The presence and importance of clast orientation within glacigenic diamictos was reported in the first part of the century (Richter, 1932; Holmes, 1941), following the initial observation of Miller (1884), and quickly became a standard tool with which to interpret ice-flow directions (e.g. West and Donner, 1956; Glen *et al.*, 1957; Andrews, 1965; Hirvas and Nenonen, 1990). Today they are also used to support the interpretation of glacigenic facies of unknown origin (e.g. Lawson, 1981; Dowdeswell *et al.*, 1985; Johnson *et al.*, 1995; Huddart and Hambrey, 1996) and in the analysis of

local strain patterns (e.g. Hart, 1994; Benn, 1995; Benn and Evans, 1996). This paper examines the role of clast fabric in the interpretation of glacial facies.

During the late 1960s and early 1970s, our understanding of the processes of glacigenic sedimentation developed rapidly, primarily through the modern analogue work of G. S. Boulton (Boulton, 1967, 1968, 1970a, b, 1971, 1972) and later by D. E. Lawson (1975, 1979, 1981, 1982). This work revolutionised our understanding of the complexity of glacigenic sedimentary environments, and the range of processes and products within them. Our understanding of glacigenic sediment continued to advance with work on glaciolacustrine, glaciomarine and deforming bed sediments (e.g. Eyles and Eyles, 1983; C. H. Eyles *et al.*, 1985; Boulton and Hindmarsh, 1987; Dowdeswell and Scourse, 1990; Hart, 1995a; Benn and Evans, 1996). With this increased range of sedimentary environments and products, the need for diagnostic criteria with which to interpret sedimentary facies becomes critical (Eyles *et al.*, 1983; Karrow *et al.*, 1984; Brodzikowski and van Loon, 1991).

The potential of clast-fabric analysis as a diagnostic tool in determining the origin of glacigenic diamictos was not widely appreciated until the introduction (Mark, 1973, 1974) and subsequent widespread use (e.g. Lawson, 1979; May *et al.*, 1980; Domack and Lawson, 1985; Dowdeswell *et al.*, 1985; Rappol, 1985) of eigenvectors and eigenvalues in the analysis and comparison of fabric data. Normalised

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eigenvalues (S_1 , S_2 , S_3) represent the distribution of linear elements, in this case the long axis of clasts around three eigenvectors which define the direction of maximum (V_1) and minimum (V_3) clustering of these elements (Woodcock, 1977). Effectively, therefore, eigenvalues provide information about fabric strength. Central to the understanding of eigenvalues is the concept of fabric shape (Woodcock, 1977). That is the shape of the three-dimensional envelope of points scattered around the mean; the more elongate this envelope, the stronger the fabric, and conversely the more spherical, the weaker the fabric. The importance of fabric shape has been re-emphasised recently by Benn (1994b), who devised a method for plotting fabric shape on triangular diagrams (Fig. 1A). This plot is superior to other types of eigenvalue plot, such as the triangular plot of Mark (1974), and the bivariate scatter plots of May *et al.* (1980), because it focuses attention on fabric shape, thereby facilitating interpretation.

Dowdeswell and Sharp (1986) were the first to systematically explore the potential of clast fabric as a diagnostic tool, and by synthesising both published and original data produced one of the first eigenvalue plots with defined process fields (Fig. 1B; see also Hart and Roberts, 1994; Menzies and Shilts, 1996). Today there is a broad consensus about the fabric signature associated with particular glaciogenic diamictos, as recently reviewed by Hicock *et al.* (1996) and as summarised in Table 1. The extent, however, to which clast fabric can be used as a genetic fingerprint to distinguish glaciogenic diamictos of unknown origin remains largely untested. The problem is one of data consistency. In order to establish process fields on an eigenvalue plot such as Fig. 1B, which can be used subsequently to classify unknown fabrics (see Dowdeswell *et al.*, 1985; Johnson *et al.*, 1995; Huddart and Hambrey, 1996), one requires a large number of observations. Most studies attempt to address this problem by using a synthesis of published data (e.g. Dowdeswell and Sharp, 1986; Hicock *et al.*, 1996), but this approach is limited by the presence of interpopulation variance due to differences in the method of data collection between studies. Although early experiments by Hill (1968) suggested that operator variance was relatively small, there is a considerable amount of variability in the basic methods followed between different studies. For example, some operators use only 25 clasts (e.g. Lawson, 1979), others 30 (e.g. Hart and Smith, 1997), although the norm is 50 clasts (e.g. Benn, 1995; Huddart and Hambrey, 1996). Similarly, the importance of clast shape (Krüger, 1970) and size (Kjør and Krüger, 1998) has been well established, but the selection of individual clasts for measurement remains in most investigations a subjective process. What is required to test the discriminative potential of clast fabrics, at least in the first instance, is an internally consistent data set.

In this paper we set out to use a single data set of 111 fabrics, collected to a common standard method by a limited number of operators, to examine the level of sedimentary discrimination that can be obtained. These results are subsequently compared with a synthesis of published data.

The data set

As part of a wider project investigating modes of moraine formation and sedimentation at both surge-type and non-surge-type glaciers located in Kongsfjorden, Engelsbukta and Reindalen in Svalbard (Hambrey and Huddart, 1995; Bennett *et al.*, 1996a, b, in press; Huddart and Hambrey,

1996), over 150 fabric measurements from a range of different sedimentary environments were collected during five field seasons. All fabric data was taken from *in situ* deposits, either exposed in sections, or via shallow excavations (0.5–1 m deep) and are based on samples of 50 prolate clasts (ratio of a:b axis >3:2). Of these fabrics, 88 are included within this study; the remainder were excluded because their depositional history is not sufficiently well constrained. An additional 23 fabrics were taken from debris-rich basal ice as part of a wider study on the formation and tectonic evolution of basal ice (Waller, 1997). These fabrics were taken from two glaciers in Alaska (Matanuska, Worthington glaciers), from Skeiðarárjökull in Iceland, from the Ferpècle Glacier in Switzerland and from the Russell Glacier in Greenland. These fabrics are based on 25 clasts in keeping with the convention for basal ice (see Lawson, 1979; Ham and Mickelson, 1994). The complete data set contains the following depositional environments.

1. Debris-rich basal ice. All these fabrics were taken from stratified facies basal ice, as defined by Lawson (1979), located in ice-marginal environments and frequently altered by glaciotectionic deformation.
2. Meltout till. These deposits were formed by the meltout of debris-rich glacial structures, in particular the meltout of longitudinal debris pods associated with foliation-parallel folding (Bennett *et al.*, 1996a; Glasser *et al.*, 1998).
3. Terrestrial sediment-flows (flow tills). These fabrics were sampled from dissected sediment-flows, associated with the reworking of ice-cored moraines.
4. Deformed diamictos (deformation tills). These consist of matrix-supported diamictos that have been thrust either proglacially, or entrained along thrusts within the body of the glacier, before melting out as intact thrust blocks (Hambrey and Huddart, 1995; Bennett *et al.*, 1996b; Hambrey *et al.*, 1997). Most of these diamictos are derived from glaciomarine sediments that have been incorporated during subsequent glaciotectionic deformation. The tectonic history of these deformation tills involves in sequence (Hambrey *et al.*, 1997; Bennett *et al.*, in press): (i) initial loading; (ii) compression during thrusting as sediment-slabs either in front of or into the body of the glacier; and (iii) extension associated with settling of the thrust slabs as they melt out of the glacier. Only those examples exhibiting substantial mixing of the original sediment are included. Deformation occurs within a shear zone defined by the width of the thrust block (typically 0.3 to 1.0 m thick) and is considered analogous to the deforming layer beneath a glacier. In a deforming layer the shear zone is defined by the ice bed and the undeformed sediment below (Hart, 1994).
5. Lodgement till. Lodgement till fabrics were taken both from beneath the glacier bed and from the interior of small proglacial flutes.
6. Glaciomarine diamictos. These were associated with the rain-out of debris from icebergs and have been exposed by subsequent sea-level change.

The summary statistics for each of these facies are presented in Table 2A, and the eigenvalues are plotted on ternary diagrams in Fig. 2 following Benn (1994b). In addition, a synthesis of published results, for which raw eigenvalue data are available, is presented in Fig. 3. Fabric envelopes for all facies are superimposed and summarised in Fig. 4.

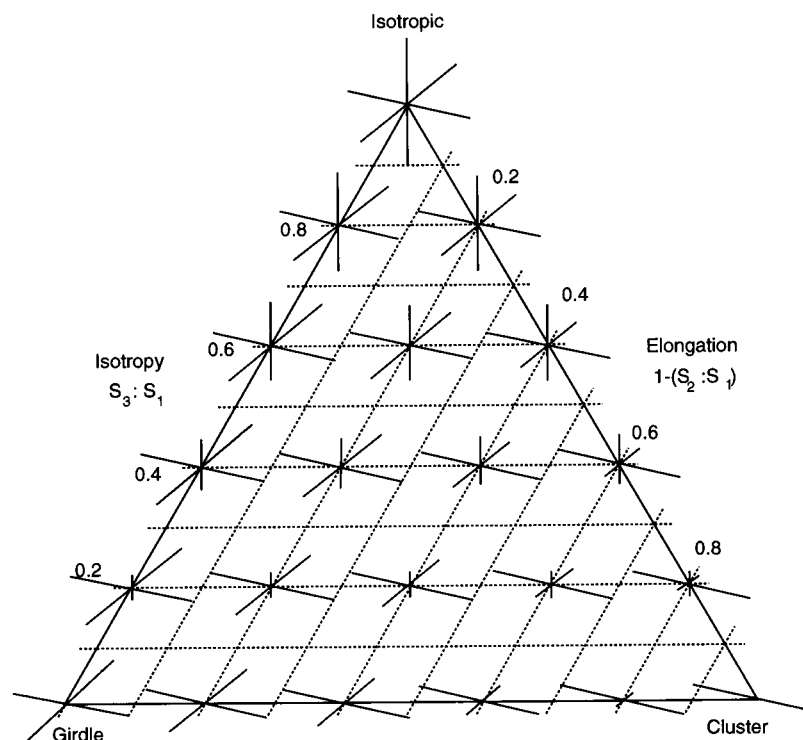
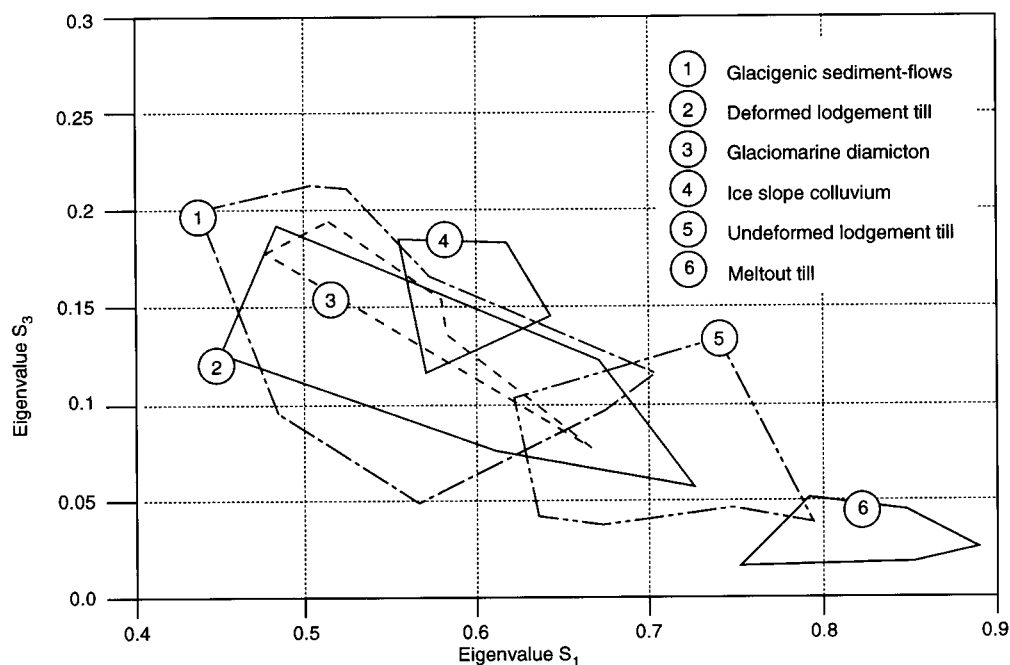
A**B**

Figure 1 (A) Triangular eigenvalue plot after Benn (1994b) emphasising the importance of clast-fabric shape. (B) Process fields as defined on a bivariate eigenvalue plot after Dowdeswell and Sharp (1986).

Results and discussion

Several points are apparent from the data and each facies sampled is discussed briefly below.

Debris-rich basal ice

Basal ice fabrics recorded in this study (Fig. 2A) tend to be strongly clustered, although some girdle-type fabrics are also

present. The data show a much greater degree of variability than that observed by Lawson (1979) and Ham and Mickelson (1994; Fig. 3A and B). This variability is not surprising in light of recent work which suggests that the character and clast fabric of the basal ice layer is determined by its tectonic history (Hart, 1995b; Waller, 1997). This tectonic history will vary from one glacier to the next, and may also vary from location to location at a single glacier. As a consequence a very wide range of possible clast fabrics may occur within the basal ice layer, and the results of Lawson (1979) do not reflect the true variability present, being taken from a single glacier.

Table 1 Summary of clast-fabric characteristics of the main types of terrestrial glacigenic diamicton based on information in Hicock *et al.* (1996)

Facies	Clast-fabric characteristics
Basal ice	Clasts are aligned parallel to the direction of cumulative strain within the ice, although transverse fabrics may develop due to compressive flow (Boulton, 1971) or as a consequence of interclast collisions (Glen <i>et al.</i> , 1957). Fabric strength may reflect the thickness of the basal ice layer and the rate of ice deformation within it (Hart, 1995b). In strongly tectonised ice the clast fabric will reflect the tectonic imprint
Meltout till	Meltout of debris from basal ice that is not sliding or deforming internally (Dreimanis, 1989). Fabric reflects that in the basal ice layer. Clast orientation should parallel the direction of local ice flow or pattern of strain within the basal ice layer. If this debris-rich basal ice melts out with the minimum of disturbance fabrics will show a strong tendency to cluster and be largely non-isotropic. Clast fabrics of meltout tills derived from highly tectonised, basal ice may retain the tectonic imprint. Fabric strength will decrease with the amount of disturbance during meltout
Lodgement till	Deposition is via the plastering of glacial debris from the base of a moving glacier (Dreimanis, 1989). Clast fabric should be strongly clustered and parallel to the direction of local ice flow, although some variability will be present reflecting local stress regimes. Stone collision and compressive ice flow may result in bimodal fabrics with a mode transverse to the direction of ice flow (Andrews and Shimizu, 1966; Lindsay, 1970). Deposition from the meltout of fallen blocks of basal ice and in subglacial cavities may not reflect ice flow direction and may be highly variable
Deformation till	Formed by the partial or complete deformation of rock or unconsolidated sediment beneath a moving glacier, some admixing of glacial debris may occur. The style of fabric will depend on the style of deformation. Clasts within sediment experiencing ductile flow will tend to rotate end-over-end in the direction of flow (Hicock <i>et al.</i> , 1996) and given time may stabilise to give a transverse and/or girdle fabric (Mark, 1974; Lawson, 1979). In contrast Benn (1995) has suggested that within deforming sediments clast fabric mimics the cumulative strain ellipsoid of the deforming matrix and does so through march rotation. Where this ellipsoid is closely constrained, such as in a flute, the fabric may be non-isotropic and strongly clustered. However, where it is less constrained fabrics may be more isotropic and less clustered. Alternatively, Hart (1994) suggests that fabric strength within deforming glacier beds is a function of the thickness of the deforming bed plus the amount of strain; a thin deforming layer gives a strong fabric in the direction of deformation, while fabric strength decreases as the thickness increases. During simple shear clasts will be oriented parallel to the shear surface giving strong clustered fabrics (Hicock <i>et al.</i> , 1996)
Flow till	Formed by the resedimentation, via mass movement, of debris released by meltout from debris-rich glacier ice. Fabric strength and character is largely a function of the fluidity of the depositional flow (Lawson, 1982); strong clustered fabrics may develop in fast, thin flows, whereas slow moving creep-type flows may have a random fabric. Rapid spatial variation in fabric both within and between flow packages is typical (Rose, 1974).

Meltout till

The three examples of meltout till reported here each have different fabric signatures (Fig. 2A). This reflects variations in the ice geometry at each site and the amount of gravity driven disturbance that occurred during formation. The meltout tills were formed by the ablation of debris-rich ice structures, particularly foliation-parallel debris pods (Glasser *et al.*, 1998). The amount of disturbance during meltout is determined by the local ice topography around each of these debris-rich structures; steep slopes lead to greater disturbance. This reinforces the idea that meltout tills will tend to have a very wide range of fabric types depending on type and location of debris-rich ice melting out and on local factors, such as the depositional slope and the availability of moisture to facilitate flow. The diverse range of meltout till forming environments probably explains the range of different fabric envelopes obtained for meltout tills in different studies (Fig. 3A and B). For example, the basal ice fabrics reported by Lawson (1979) show very little intersample variability when compared with those reported elsewhere, for example by Ham and Mickelson (1994). Given the variability in the basal ice fabrics already noted and the

importance of site-specific factors in the formation of meltout till such variability is not surprising, and Lawson's (1979) results should perhaps be regarded as the exception and not the norm.

Terrestrial sediment-flows

The sediment-flow (Fig. 2B; flow tills) fabric data presented here shows a high degree of fabric variability, both in orientation and strength. Clast fabrics generally display low isotropy indices and show a range of patterns from girdles to clusters. Of particular note is the spatial variability in clast fabric observed within a single sediment-flow, which is typical of glacigenic mass movement deposits (e.g. Rose, 1974; Eyles and Kocsis, 1988; Eyles *et al.*, 1988; Lawson, 1988). In comparison with the published clast-fabric data for sediment-flows of Lawson (1979; Fig. 3C) the data in Fig. 2B is generally less isotropic and shows a greater range of elongation values. These differences probably reflect the fluidity of the particular sediment-flows sampled and therefore the specific depositional processes involved, for example

Table 2 Summary statistics for clast-fabric data for specific facies: (A) this study, (B) published data

A	Basal ice		Meltout till		Deformation till		Lodgement till	
	Isotropy	Elongation	Isotropy	Elongation	Isotropy	Elongation	Isotropy	Elongation
χ	0.097	0.597	0.209	0.428	0.127	0.501	0.114	0.491
σ	0.058	0.179	0.156	0.1	0.09	0.19	0.063	0.086
Range	0.223	0.667	0.306	0.199	0.409	0.754	0.153	0.264
C of V (%)	59.8	29.9	74.6	23.4	70.9	37.9	55.3	17.5
N	24	24	3	3	47	47	6	6
A	Fluted till		Flow till		Glaciomarine diamicton			
	Isotropy	Elongation	Isotropy	Elongation	Isotropy	Elongation		
χ	0.091	0.633	0.122	0.436	0.309	0.254		
σ	0.031	0.037	0.075	0.169	–	–		
Range	0.062	0.079	0.277	0.8	–	–		
C of V (%)	34.1	5.8	61.5	38.8	–	–		
N	4	4	25	25	2	2		
B	Basal ice (Lawson, 1979)		Meltout till (Lawson, 1979)		Basal ice (Ham and Mickelson, 1994)		Meltout till (Ham and Mickelson, 1994)	
	Isotropy	Elongation	Isotropy	Elongation	Isotropy	Elongation	Isotropy	Elongation
χ	0.047	0.903	0.037	0.82	0.038	0.795	0.161	0.652
σ	0.033	0.058	0.018	0.072	0.04	0.096	0.079	0.16
Range	0.131	0.229	0.061	0.22	0.103	0.319	0.344	0.608
C of V (%)	70.2	6.4	48.6	8.7	105.5	12	49	24.5
N	38	38	8	8	9	9	27	27
B	(Lawson, 1979) Flow till		Glaciomarine diamicton (Domack and Lawson, 1985)		Fluted till (Hart and Smith, 1997)		Fluted till (Benn, 1994a)	
	Isotropy	Elongation	Isotropy	Elongation	Isotropy	Elongation	Isotropy	Elongation
χ	0.231	0.455	0.331	0.416	0.098	0.584	0.045	0.608
σ	0.086	0.116	0.08	0.086	0.054	0.181	0.019	0.079
Range	0.346	0.46	0.28	0.331	0.226	0.621	0.06	0.261
C of V (%)	37.2	25.5	24.2	20.8	55.1	30.9	42.2	12.9
N	6	6	11	11	26	26	8	8

χ = average; σ = standard deviation; C of V = coefficient of variance; N = sample size.

creep versus ductile deformation or fluid flow (see Lawson, 1982).

Deformed diamictons

Clast fabric within the deformed diamictons (Fig. 2C; deformation tills) sampled fall into two distinct populations, a group of closely spaced, non-isotropic fabrics, which show a tendency to be strongly orientated (clustered) and a second more variable group of fabrics which tend to be more isotropic and less well orientated. The simplest explanation for this contrast is that the more variable population is the product of a greater degree of post-depositional extension and modification (Bennett *et al.*, in press). The low isotropy of the main group of fabrics probably reflects the constrained nature of the cumulative strain ellipsoid during deformation,

as suggested by Benn (1995). In most cases deformation occurs within a thrust sediment-slab bounded by glacier ice which constrains deformation (Bennett *et al.*, 1996a, b; Hambrey *et al.*, 1997). This is analogous to the constrained deformation environment during flute formation (Benn, 1995). No relationship between the thickness of the thrust slab (i.e. the deformed layer) and the fabric strength was recorded (cf. Hart, 1994).

If one examines the data obtained by other studies (Fig. 3D and E) a wide range of results have been reported. This is hardly surprising given that clast fabric reflects the tectonic regime at a specific site, that is the type and rate of deformation as well as the degree to which that deformation is constrained (Hart, 1994; Benn, 1995). These factors are clearly all site-specific and will vary both between sites on a given glacier, as well as between glaciers, and through time. It is also interesting to note the similarity between the deformation till fabrics (Fig. 3D and E) and those reported

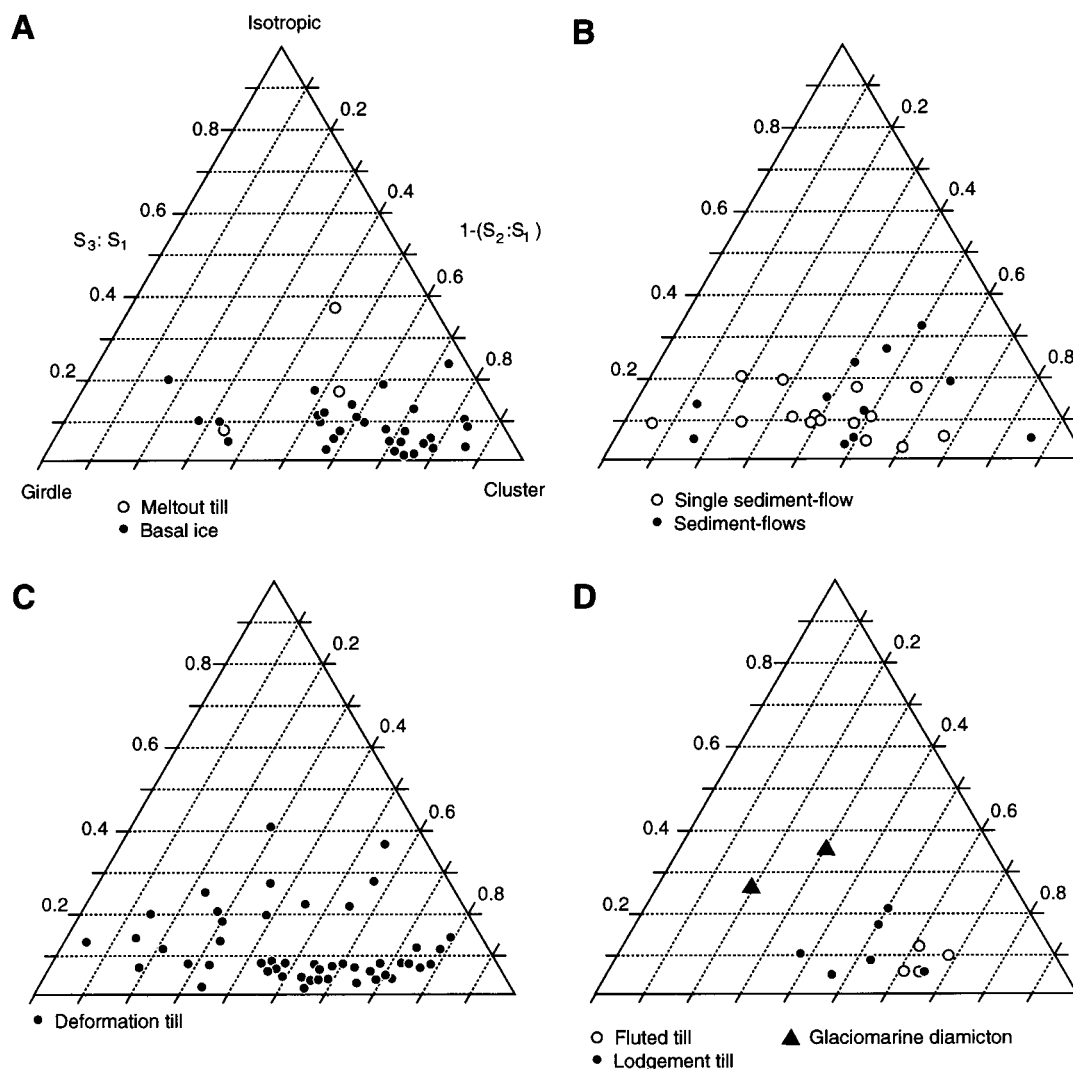


Figure 2 Eigenvalues for clast fabric data taken from a range of known facies by the authors.

here for sediment-flows (Fig. 2B), although Lawson's (1979) sediment-flow data tend to be slightly more isotropic (Fig. 3C). This similarity may simply reflect the common sedimentary process, that of flowage of a sediment-water mixture under an applied stress. In this context it is perhaps unrealistic to expect facies discrimination, the sedimentary processes are not unique to a given glacial environment.

Lodgement tills

The lodgement till (Fig. 2D) fabrics sampled here are typical of lodgement and deformation till fabrics as reported in the literature (Fig. 3D and E). A slight distinction between fluted and unfluted lodgement tills is perhaps apparent within our data, supporting the observations of Benn (1995) with regard to constrained and unconstrained nature of the cumulative strain ellipsoid. Given that within subglacial environments the real distinction between lodgement tills and deformation tills is subtle and that some form of continuum between the two may exist a clear distinction on the basis of clast fabric is again unlikely.

Glaciomarine diamictons

The two glaciomarine diamictons sampled (Fig. 2D) have clast fabrics which are strongly isotropic and broadly similar to the data of Domack and Lawson (1985; Fig. 3F). The glaciomarine data provides one of the more distinct fabric envelopes, although some overlap occurs with sediment-flow and deformation-till data. However, there is currently insufficient data on glaciomarine diamictons, with well constrained sedimentary histories, to present a clear picture of the fabric variability within this type of facies. Again the processes involved, free-fall and subsequent flow, are very similar to those that might occur in sediment-flows or even some meltout tills. This again emphasises the point that clast fabric may record sedimentary processes common to more than one facies.

Facies discrimination

If we first use the data presented here it is clear that there is little discrimination between the different sedimentary facies sampled, and that all the populations overlap to some extent. Greatest discrimination is provided by the elongation

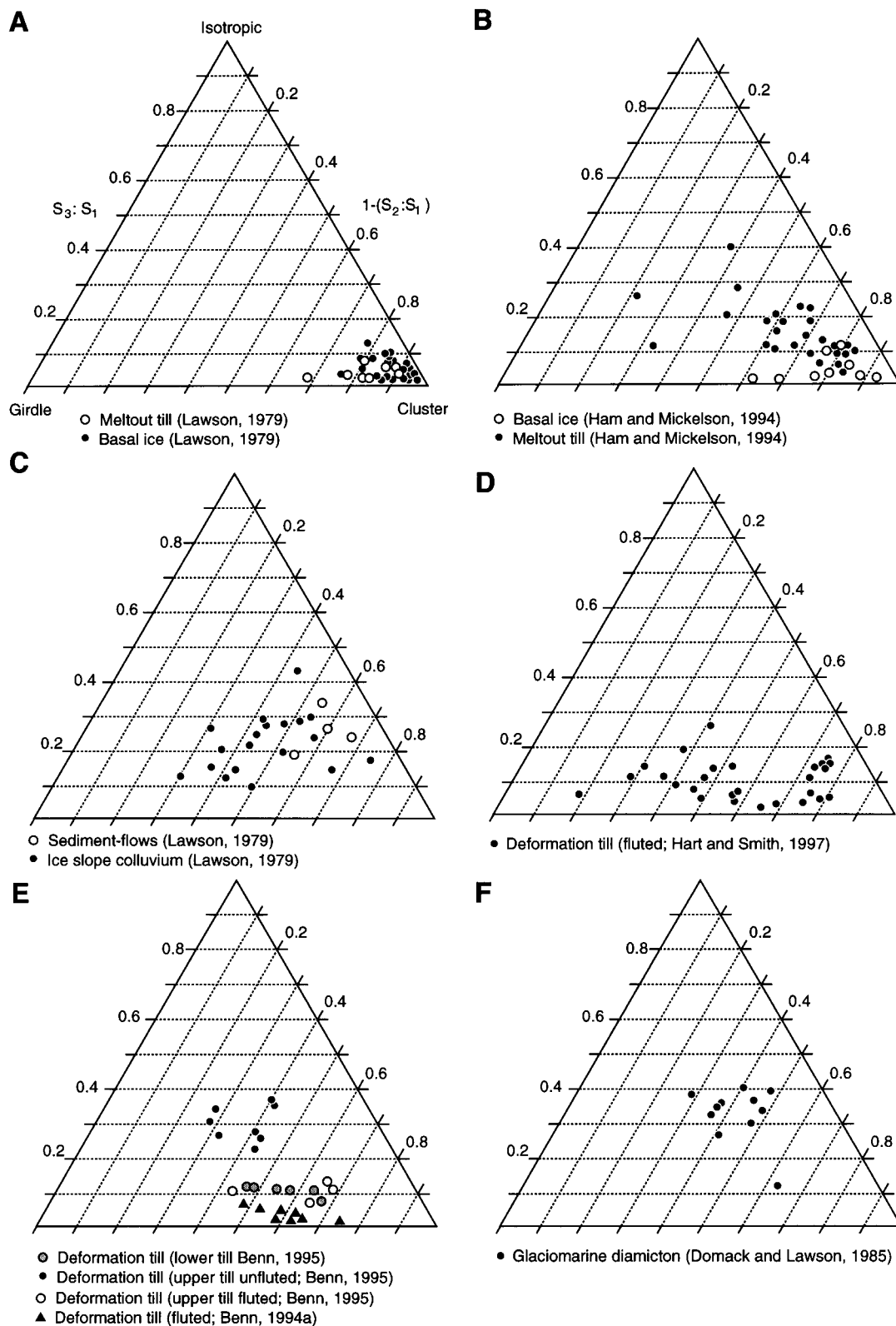


Figure 3 A synthesis of published data for which eigenvalues are available.

index, because all the fabrics have low isotropy values of < 0.4 and in most cases < 0.2 . This point is reinforced by the superimposed fabric envelopes in Fig. 4A and B. Discrimination between different sedimentary facies is not possible. The absence of discrimination is independent of the method of data plotting; more conventional bivariate plots (e.g. May *et al.*, 1980; Dowdeswell and Sharp, 1986) do not give better discrimination.

The lack of facies discrimination is also apparent from the

synthesis of published data (Fig. 4C and D). Two points are particularly apparent. Firstly, clast-fabric envelopes for a given facies rarely plot in the same position from one study to the next (Fig. 4C and D). This interstudy variability is not only the product of differences in the methods followed, but also, and perhaps more importantly, in the definitions used. For example, in the subglacial environment the distinctions between deformation tills, lodgement tills and meltout tills, although clear in theory are in practice often ambiguous

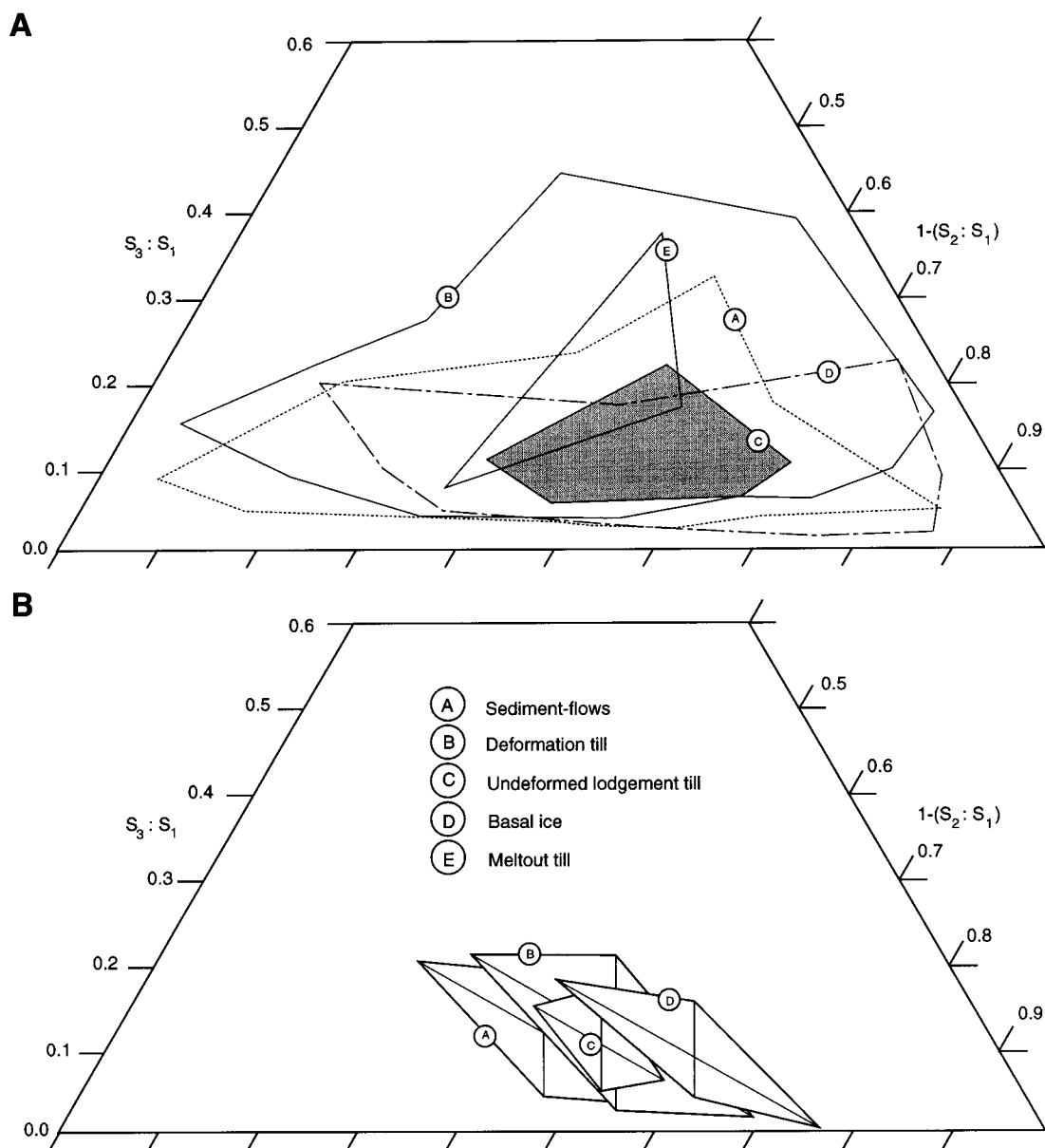


Figure 4 Summary statistics for clast-fabric data. (A) Fabric envelopes drawn to enclose all points for selected facies sampled in this study. (B) Fabric envelopes based on the mean and one standard deviation, for selected facies sampled in this study. Only those samples of sufficient size are included.

in the field and open to conflicting interpretations. As a consequence the comparisons being made in Fig. 4C and D may not be valid in all cases. Furthermore, subglacial sediments may possess a very complex and polygenetic history (Hicock *et al.*, 1996). For example, an ice-marginal block of debris melting out to form a meltout till may previously have undergone deformation before being frozen into the ice block. In most cases this history is not known and this again introduces variability and undermines the comparability between studies at different locations.

The second point to emerge from the synthesis of published results (Fig. 4C and D) is that most of the fabric envelopes for different facies overlap to some extent. Although individual studies such as those of Benn (1994a, 1995) and Lawson (1979) show facies discrimination, it is the exception rather than the norm (Fig. 4C and D). This is not necessarily surprising given that there are many similarities between the different till-forming environments. For example, clasts in both sediment-flows and ductile deformation tills are responding to the deformation of sediment-

water mixtures when a stress is applied. As a consequence clast fabric may show a similar range of characteristics. Similarly, brittle deformation occurs in some deformation tills located in constrained settings and is also a feature of lodgement tills (Benn 1995; Benn and Evans, 1996). In this context clast fabrics should be regarded as a tool with which to investigate depositional processes; processes which may be common to one or more till-forming environments. There is a need for much more process-orientated work in this field.

Although the process fields overlap it has been suggested previously that spatial variability in clast fabric may be of diagnostic value (e.g. Rose, 1974). For example, the data from a single sediment-flow (Fig. 2A) is highly variable and units with such variability may be indicative of such a depositional environment. However, rapid variations in fabric are well known from other types of till, such as lodgement tills (e.g. Andrews and Smith, 1969; Young, 1969; Andrews, 1971; Catto, 1990; Hicock, 1992; Kjær and Krüger, 1998), and the fabric in some deformation tills may reflect the tectonic geometry of the unit (e.g. Eyles *et al.*, 1994) and therefore may also vary over short distances.

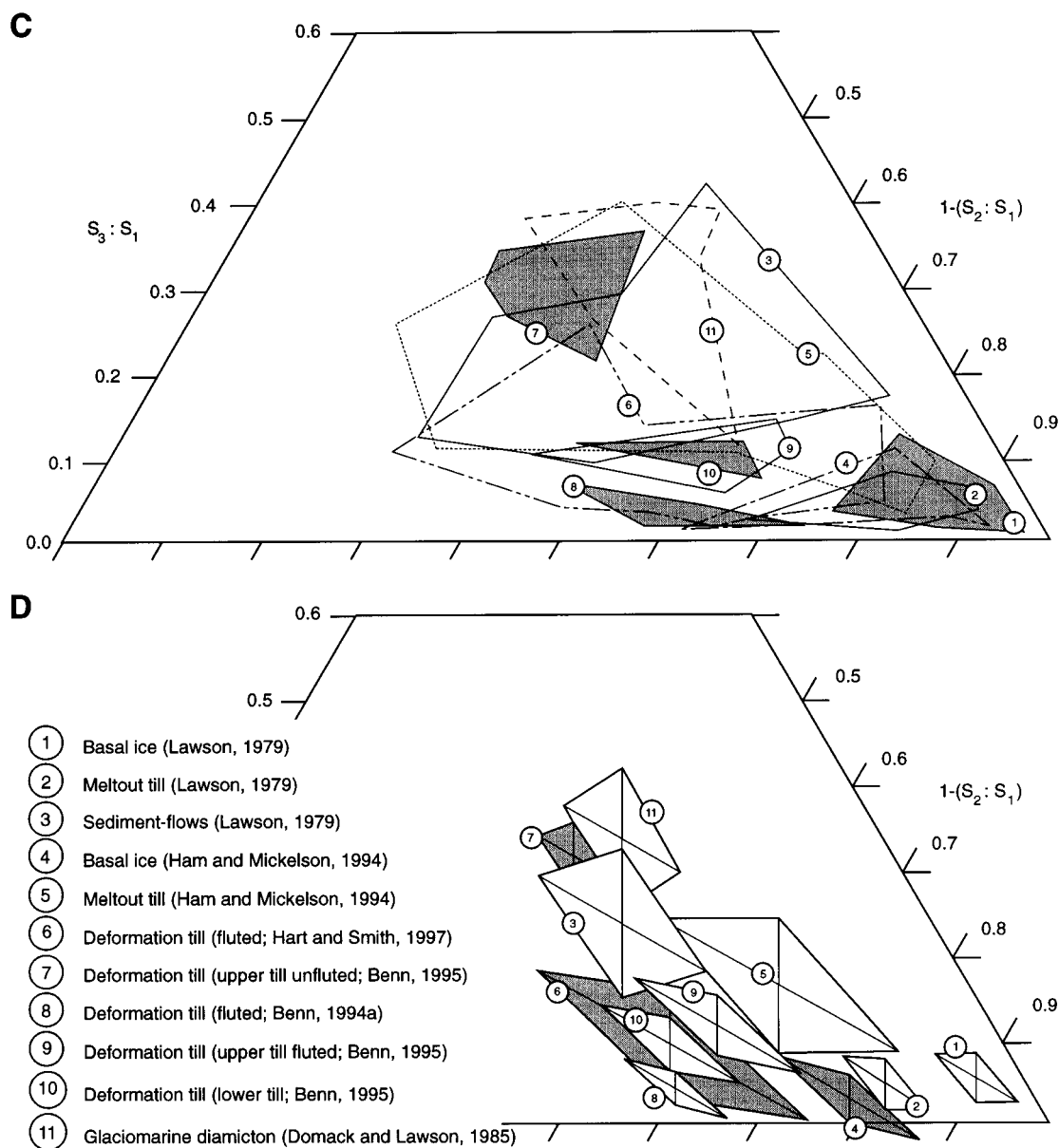


Figure 4 (C) Fabric envelopes drawn to enclose all points for selected facies based on published data. (D) Fabric envelopes based on the mean and one standard deviation, for selected facies based on published data.

Recently, Hicock *et al.* (1996) have suggested that greater discrimination can be achieved by examining fabric modality. They argue that multimodal fabrics are more likely to have a polygenetic origin, and that this can be used to distinguish lodgement tills from deformation tills, the latter having shear fabrics superimposed on lodgement-type fabrics and therefore are more likely to be multimodal. The analysis of fabric modality may, as argued by Hicock *et al.* (1996), assist in distinguishing deformation tills from lodgement tills, but is of little use in distinguishing other facies. Moreover, the process of subjectively classifying fabric modality simply adds to the lack of objectivity associated with clast-fabric analysis.

In summary, therefore, neither the facies presented here, nor those derived from published data display clast-fabric eigenvalue envelopes that allow unambiguous discrimination. In addition, those envelopes that have been presented in the past (e.g. Lawson, 1979; Dowdeswell and Sharp, 1986) are not reproducible between studies.

Conclusions

It is a well established premise that the interpretation of different glacial diamictos should be based on a range of different criteria, only one of which is clast-fabric analysis (e.g. Karrow *et al.*, 1984; Dowdeswell and Sharp, 1986; Hambrey, 1994; Bennett and Glasser, 1996; Benn and Evans, 1998). Clast fabric, however, like clast shape (e.g. Benn and Ballantyne, 1994; Bennett *et al.*, 1997), offers the potential to quantify these often subjective interpretations and as such is very attractive to the glacial geologist. Plots such as those of Dowdeswell and Sharp (1986) are highly seductive (Fig. 1B), and appear to offer a means of quantitative validation of facies interpretations. We argue, however, that on the basis of the data presented here, clast fabric determinations are of little value as a genetic fingerprint, or even as an unambiguous guide in the interpretation of glacial diamictos. In truth few people would disagree with this state-

ment, yet we continue to routinely collect and present clast fabric data. There is no doubt that clast-fabric analysis has an important role as an indicator of relative strain within deforming sediments, or in the basal ice layer (e.g. Benn, 1995; Hart 1994; Benn and Evans, 1996) and may also be indicative of other sedimentary processes. There is a need for further work to explore these applications. Unfortunately, however, these processes are not specific to a given environment and are unlikely on their own to allow facies discrimination. We question, therefore, the value of continuing to collect fabric data as part of routine sedimentary description and interpretation. The quantitative support provided for the interpretation of glacial facies by clast-fabric analysis may be more perceived than real.

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