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Clast-fabric strength in tills and debris flows compared for different environments

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Abstract

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Elongated-clast fabrics of Alpine till from western Allgäu (southern West Germany) and of lowland ice-sheet till from The Netherlands are compared with published results from other areas. A quantitative comparison is made through the use of an eigenvalue method which produces measures of fabric shape and strength for three-dimensional orientation data.

Clast fabrics of subglacial till in Western Allgäu tend to have lower strength than those from The Netherlands. Similar differences have been noted by comparing melt-out till fabrics of the Matanuska Glacier (Alaska) with Cordilleran ice-sheet and Alpine tills in North America. The possible reasons for these differences are discussed.

Clast fabrics of ice-marginal debris-flow deposits in western Allgäu are similar to fabrics from sediment-flow deposits reported from other areas. Eigenvalue plots of clast fabrics do not distinguish clearly between subglacial till and debris flows from western Allgäu.

Introduction

Clast-fabric analysis of glacial deposits has been applied to serve two main purposes, i.e. 1) to derive palaeo-flow directions of ice movement, and 2) to distinguish between sediments of different genesis.

Investigations at modern glaciers and comparative research in Pleistocene glacial environments demonstrate that elongated clasts in till generally align in the direction of ice movement; transverse and 'cross' fabrics seem to be rare.

Reconstructions of palaeo-flow directions in the areas of the large Pleistocene ice sheets of North America and Europe find strong support from the analyses of subglacial-till fabrics (e.g. Richter 1932; Holmes 1941; Virkkala 1960; Ehlers & Stephan 1983). On a smaller scale, clast-fabric analysis has been used to derive local ice-flow conditions associated with subglacial landforms as drumlins and fluted till surfaces (e.g. Muller 1974; Shaw 1977; Boulton 1976; De Jong et al. 1982). In Alpine environments the method has not been applied frequently; palaeo-flow directions of glaciers are generally more easily derived since they are strongly controlled by the local high-relief features.

Clast-fabric data have been used as additional evidence in genetic classification of sediments (e.g. Harrison 1957; Drake 1971; Marcussen 1975; May et al. 1980). Lawson (1979), in a detailed study of modern tills and sediment-flow deposits at the margin of the Matanuska Glacier in Alaska, found strong unimodal fabrics parallel with the direction of ice movement in melt-out tills; sediment flows produced polymodal dispersed fabrics with a mean orientation not related to ice movement. However, unimodal clast fabrics from mass-movement deposits have been reported occasionally by other workers (e.g. Lindsay 1968; Boulton 1971). Drake (1971) and Pessl (1971), comparing clast fabrics of subglacial and ablation tills, found the latter to be much more dispersed than the former.

Unfortunately, most authors reporting on clast orientation have only used qualitative methods of comparison, or very diverse measures of fabric strength and shape. A sophisticated eigenvalue method for fabric analysis was introduced in glacial sedimentology by Mark (1973, 1974), and is increasingly used in modern research (Mills 1977, 1984; Lawson 1979; May et al. 1980). It provides quantitative measures of mean orientation and fabric strength and shape for three-dimensional orientation data, and thence allows comparison of data from different workers.

The purpose of this paper is to compare clast-fabric data of Pleistocene, mainly Würmian, subglacial till and debris flows from the Allgäu Alps (southern West-Germany), and Saalian till of The Netherlands, as sampled by the present author, with those from other areas, and to discuss the possible influence of a number of variables on clast-fabric strength in these deposits.

Method

The orientation of 40 to 60 elongated clasts was measured in the field using an ordinary compass with clinometer. Clasts were selected with an a/b-axis ratio larger than 1.4 and a long axis between 2 and 10 cm. During part of the sampling program, clasts with dip-values over 60° were not recorded because of difficulties in accurately measuring azimuth in these instances. However, such high values are very rare, and this bias in procedure is not likely to influence the results significantly.

Sediment genesis was determined by field criteria (De Jong & Rappol 1983; Rappol 1983). Site descriptions and most fabrics in the form of rose diagrams and/or stereograms, were published previously in De Jong et al. (1982), De Jong & Rappol (1983), and Rappol (1983, in press).

The orientation data were analyzed using a three-dimensional eigenvector/-value method as described by Mark (1973, 1974) and Woodcock (1977); a flow chart of the calculations is given in Woodcock & Naylor (1983, fig. 10). In short, the method treats the individual orientations as unit vectors defined by their direction cosines. The eigenvectors (V_1, V_2, V_3) of the orientation matrix correspond to three mutually orthogonal axes, where V_1 represents the axis of maximal clustering while V_3 represents the pole to the preferred plane through the fabric. The normalised eigenvalues ($S_i=\lambda_i/N$) describe the shape of the fabric. When S_1-values are high, fabrics have a strong cluster (high strength). With $S_1 \approx S_2 > S_3$ the sample is best described by a girdle. Fig. 1 illustrates these relationships of the normalised eigenvalues with fabric shape in a two-axis logarithmic plot. Fabric strength increases away from the origin of the diagram.

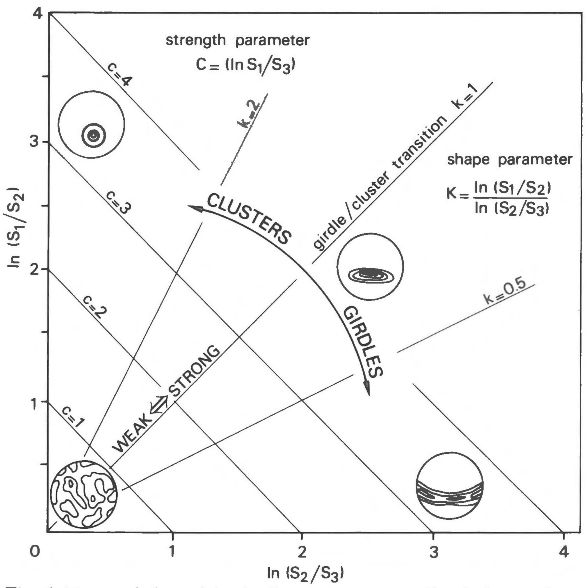

Fig. 1. Two-axis logarithmic diagram of normalised eigenvalues and its relationship to shape and strength of the fabric. After Woodcock (1977) and Woodcock and Naylor (1983).

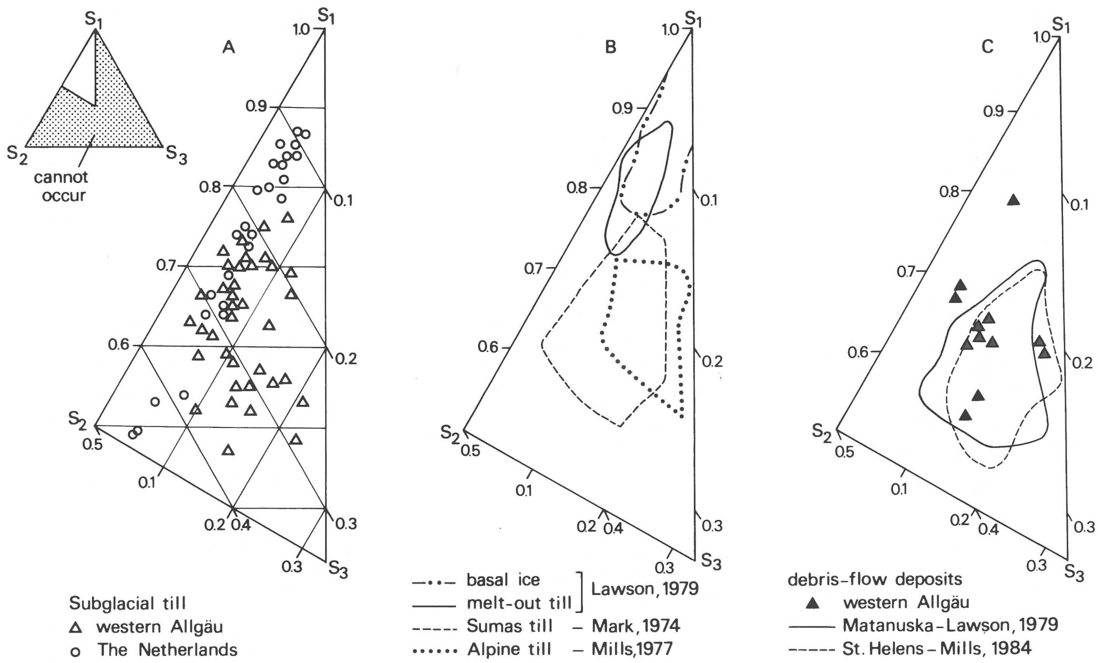

Fig. 2. Triangular plots of normalised eigenvalues.
A. Subglacial till from The Netherlands and western Allgäu.
B. Envelopes for debris-rich basal ice and tills from various regions.
C. Debris-flow deposits from western Allgäu and envelopes for sediments-flow deposits from two other areas.

Results

Subglacial-till fabrics from western Allgäu and The Netherlands are plotted in a triangular diagram of the normalised eigen-values in Fig. 2A. Because $S_1 \geqslant S_2 \geqslant S_3$, the data points can only plot in one-sixth portion of the regular triangular diagram. All fabrics are non-random at the 99% confidence level for the S_1/S_3-test of Woodcock & Naylor (1983) as wel as for Mardia's (1972) S_u-statistic.

An obvious difference is observable in the distribution between the two groups of samples, although some overlap exists in the central portion of the Fig. 2A diagram. The Dutch samples are characterised by low S_3-values, while a large sub-group of these shows extremely high S_1-values, which thereby is similar to Lawson's (1979) melt-out till from Alaska (Fig. 2B). Four samples from The Netherlands contain a strong girdle-type distribution. The Allgäu samples show a fabric-strength variability that is similar to that of Mark's (1974) Sumas till deposited by the Cordilleran ice sheet in a lowland environment, and to Mills' (1977) Alpine tills of modern Cordilleran glaciers, although Mills' samples tend to have higher S_3-values (see Fig. 2B, and Mills 1977).

Debris-flow clast fabrics from western Allgäu are plotted in Fig. 2C, together with envelopes for sediment-flow fabric data from other areas. They have rather similar fabric characteristics with a generally weak fabric strength (low S_1- and high S_3-values). However, the latter property is shared by a large number of subglacial-till fabrics from western Allgäu.

One of the debris-flow samples deviates strongly by a high S_1-value. This sample represents a transverse orientation of long-axes with b-axis imbrication, from the nose of a debris flow, similar to those reported by Boulton (1971; see also Van Loon 1983).

The debris-flow samples on Woodcock's (1977) two-axis plot of the ratios of normalised eigen-values (Fig. 3), show that about half of the Dutch samples are clusters, half are girdles. Slightly more

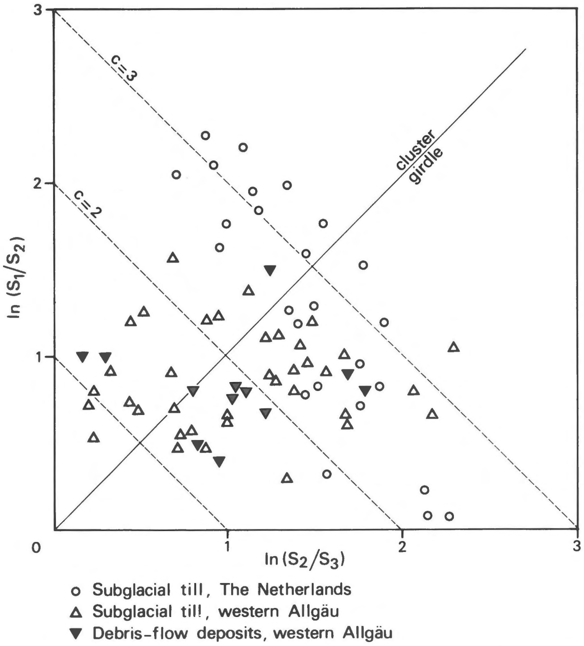

Fig. 3. Eigenvalue ratio plot for fabric samples of subglacial till and debris-flow deposits from The Netherlands and western Allgäu.

than one-third of the Allgäu samples are clusters. Debris-flow fabrics tend to show a higher preference for girdle-type distributions. Taking $C=\ln(S_1/S_3)$ as an estimate of fabric strength (see Fig. 1), the Dutch samples have greater strength than those from western Allgäu.

As noted by Mills (1984), little attention has been given to the dip-angles of the eigenvectors. In The Netherlands, 21 out of 25 fabrics have V_1 parallel to the supposed direction of ice movement, and of these, 19 dip up-glacier. In western Allgäu 26 out of 36 till-fabric samples with V_1 parallel to the direction of ice movement likewise have up-glacier dips for V_1. Mean dip-angles of V_1 and their standard deviations in The Netherlands and western Allgäu are 7.9 ± 6.1 and 8.9 ± 6.9 degrees respectively. For debris-flow deposits in western Allgäu these values are 9.4 ± 6.3. These values differ little but, as is shown in Fig. 4, the dip-angles of individual clasts tend to be higher in western Allgäu than in The Netherlands. Debris-flow fabrics tend to show higher dip-angles than subglacial till fabrics from western Allgäu, as was also observed by Mills (1984).

Discussion and conclusions

Several factors may contribute to the observed differences in fabric strength among glacial deposits from different region. These are:

1. *Sampling method*;

Variations in fabric strength may result from differences in clast selection among operators. For example, Mills (1977, 1984) and the present author use only clasts with an a/b-axis ratio higher than 1.4, while Lawson (1979) determines fabrics for composite clast shapes (prolate-, blade-, and plate-shaped clasts). The effect of clast shape on till fabric has been the subject of several studies (e.g. Krüger, 1970; Drake, 1974; Mills, 1977). From these studies it appears that clast shape may affect fabric, but there is little consensus about the nature of this relationship (Mills, 1977). Moreover, in conventional clast-fabric analysis, with measure-

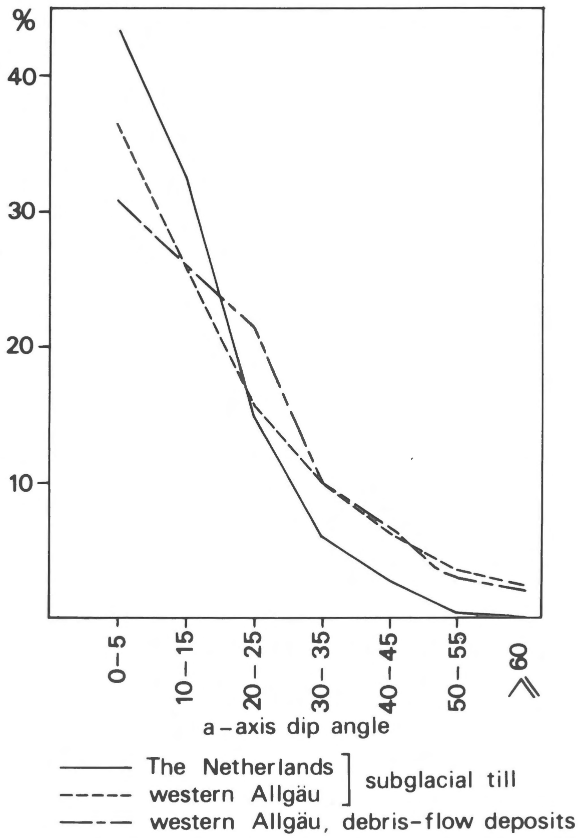

Fig. 4. Dip-angle frequencies of elongated clasts in subglacial till from The Netherlands and subglacial till and debris-flow deposits from western Allgäu.

ments of the a-axes of elongated clasts only, this factor will be of little importance; the samples from western Allgäu and The Netherlands were measured by the same method, that allowed only for limited between-sample variability in clast shape due to differences in rock-type lithologies.

2. *Textural variation*;

There is a large difference in the amount of coarse material that is found in till samples. The Dutch tills have a gravel fraction of less than 5%, whereas the Allgäu samples show 10-30% gravel (Rappol 1983). Moreover, the pebble and boulder fractions are much more abundant in the Alpine area than in the clast-poor till of The Netherlands.

Frequent clast interactions during shear may weaken the strength of the preferred orientation in the fabric (Derbyshire 1980; May et al. 1980), and thus the larger percentage of clasts might explain the weaker strength of till fabrics from western Allgäu.

3. *Depositional process*.

The possible effect of this third factor in the genesis of till fabric is strongly related to the effect of textural variation. Lawson (1979) observed very strong parallel fabrics in the basal debris-rich ice of the Matanuska Glacier, often even stronger than in the melt-out tills. Where clasts are dispersed within the basal ice, the frequency of clast interaction is consequently very low. Apparently, these strong fabrics are preserved during the melt-out process, as follows from the results obtained by Lawson (1979; see also Boulton 1971). A second mode of till formation is by lodgement accompanied by shear deformation of the subglacial till-bed. In this situation of concentrated water-soaked debris, clast interactions will be much more frequent. The latter process seems to be characteristic for temperate glaciers (Boulton 1979) and applies most likely to the Pleistocene Alpine environment (Rappol 1983). Till formation by melt-out may have been the dominant process during the Saalian ice cover of the northern Netherlands, where several features point to very cold conditions (Ter Wee 1983).

If frequency of clasts interaction is really one of the most important factors in clast-fabric strength development, then the variables grain size and depositional process may be responsible for the major part of the observed difference in fabric strength between tills from western Allgäu and The Netherlands. Mills (1984) added the possibility that many subglacial tills undergo modification by mass flow during or shortly after deposition. This could explain the large overlap of subglacial-till and debris-flow fabrics from western Allgäu. Moreover, gravitational flow can be expected to be a more common phenomenon in the high relief environment of western Allgäu than in the flat area of The Netherlands. The higher dip-angle values for the Alpine tills could also be related to the effect of higher clast interactions (compare with Rees, 1979). However, as the horizontal is taken as the reference plain, it could also be a function of subglacial slope.

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