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Subglacial deformation: evidence from microfabric studies of particles and voids in till from the upper Ürümqi river valley, Tien Shan, China

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ABSTRACT. Microfabrics formed by flat particles and voids in till samples from the upper Ürümqi river valley, Tien Shan, northwestern China, were analyzed using three mutually perpendicular thin sections. Chi-squared tests were used to determine significance levels of the orientations of both particles and voids. The basal tills in an end moraine, on the stoss sides of two roche moutonnées, on the stoss sides of a drumlin with a rock core, and on the lee side of the same drumlin far from the rock core have strong particle and void microfabrics. Field evidence suggests that these tills were deformed in a subglacial setting. Thus, consistent with recent laboratory studies of till fabric development, deformation is believed to be responsible for the strong particle and void microfabrics. In the same end moraine, particle microfabrics in an overlying till were strong, but void microfabrics were weak. This till is believed to have been formed by dumping and rolling of debris from hill slopes and of ablation moraine from the glacier surface. The weak void microfabric is interpreted to indicate that the till was not consolidated and hence not sheared under the weight of the glacier, despite the strong particle microfabric. Basal tills on the lee sides of the roche moutonnées, and on the lee side of the drumlin but near its core, have weak microfabrics.

INTRODUCTION

Subglacial deformation of till is an important process (e.g. Hart, 1994; Benn, 1995; Hooke and Iverson, 1995; Truffer and others, 2000), and studies of till microfabric provide information about this process. Microfabrics defined by elongate clay and sand particles in tills have been studied by Harrison (1957), Gravenor and Meneley (1958), Ostry and Deane (1963), Evensen (1971), Kujansuu (1976), Johnson (1983) and Nyborg (1989), among others. In some studies, microfabrics have been used as indicators of subglacial deformation (Menzies and Maltman, 1992; Van der Meer, 1993; Menzies and others, 1997) or to differentiate till types (Van der Meer, 1990). Yi (1997) used microfabrics to demonstrate subglacial comminution.

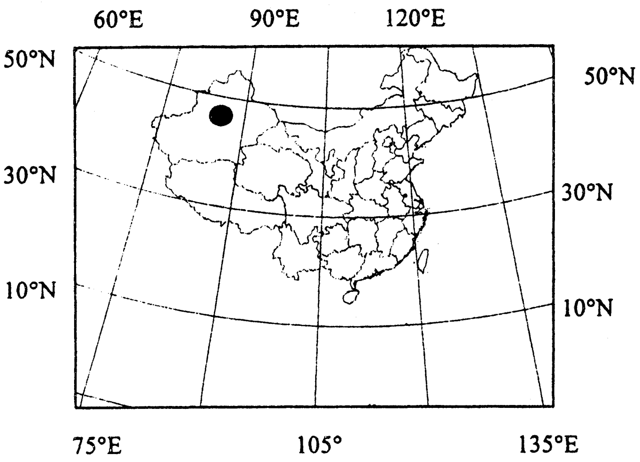

Fig. 1. Location of study area in northwestern China.

Many glacial geologists believe that deformation of till beneath ice leads to a weak fabric (e.g. Dowdeswell and Sharp, 1986; Hart, 1994, 1997). On the other hand, recent laboratory experiments by Hooyer and Iverson (2000) demonstrate that strong clast fabrics develop during shearing of till, and field observations by Benn (1995) support this conclusion.

The present paper deals with the microfabrics formed by flat particles, 0.25–5.0 mm in diameter, and for the first time considers the microfabric formed by elongate microscopic voids in till. The microfabrics are used to determine whether the till has been sheared subglacially.

REGIONAL SETTING AND SAMPLING LOCATION

The study area is in the upper part of the Ürümqi river valley on the north slope of Kalaucheng mountain, middle Tien Shan (43°7′ N, 86°9′ E), northwestern China (Figs 1 and 2). Cirque glaciers, small valley glaciers and hanging glaciers are present. Their termini are presently at elevations of 3650–3700 m, and the lower limit of Quaternary deposits is at 2900 m. The longest glacier was about 12 km long during the last (Wangfeng) glaciation. Most particles in the local tills are derived from schist. The ratio of the lengths of the shortest to the two longer axes is normally 1 : 2 to 1 : 4.

Samples W1–W6 (W = Wangfeng) were taken from an end moraine dated at 19–21 kyr (Yi and others, 1998) (Figs

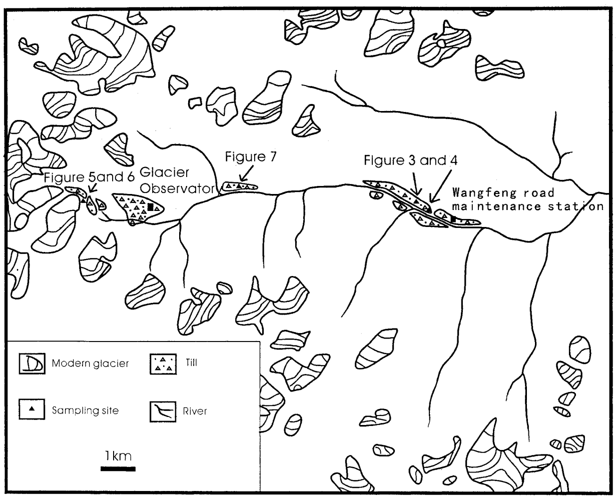

Fig. 2. Sampling sites in the upper Ürümqi river valley, Xinjiang.

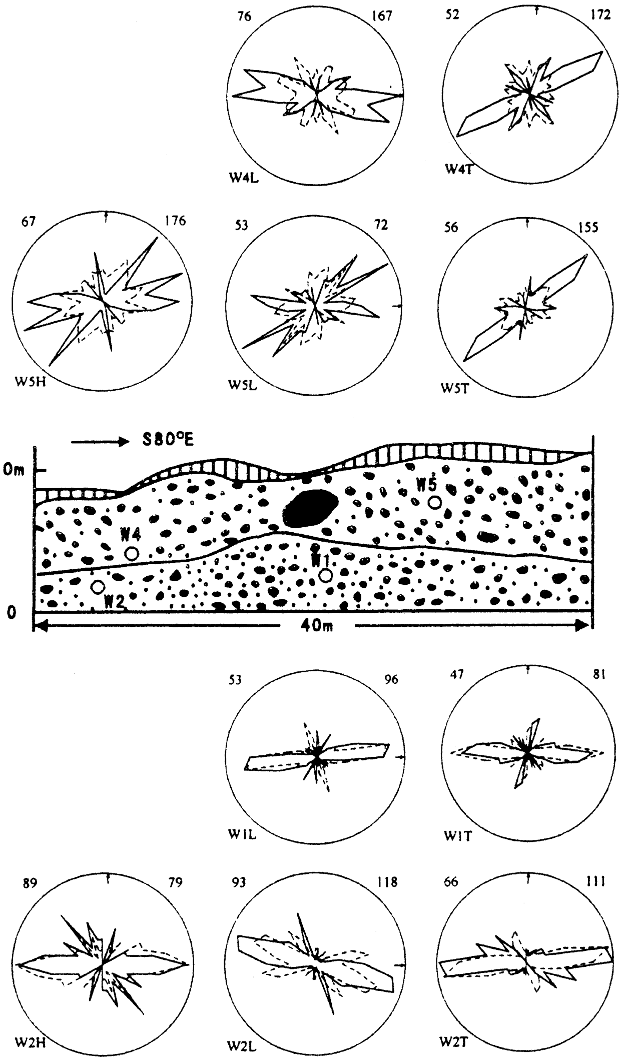

Fig. 3. Cross-section of Wangfeng moraine showing sampling sites W1, W2, W4 and W5, and rose diagrams of microfabrics. Patterns show two tills and overlying loess. In rose diagrams, solid lines indicate particles, and dashed lines indicate voids. Arrows on edges of the rose diagram point in direction of valley trend in horizontal and longitudinal thin sections, and upward in transverse thin sections. The number at the upper left is the number of particles measured, that at the upper right is the number of voids, and that at the lower left is the serial number of the samples. H, L and T represent horizontal, longitudinal and transverse thin sections, respectively.

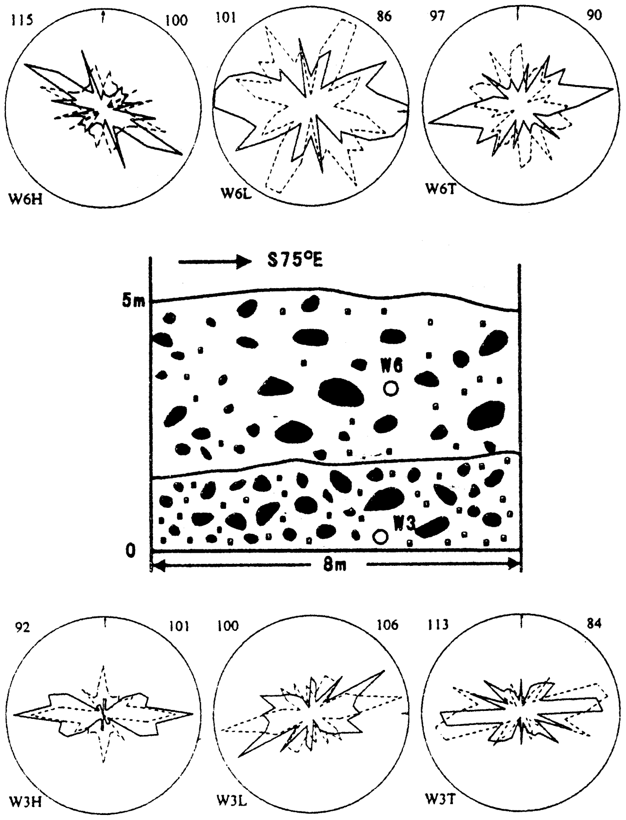

Fig. 4. Cross-section of Wangfeng moraine showing sampling sites W3 and W6, and rose diagrams of microfabrics. See Figure 3 for explanation.

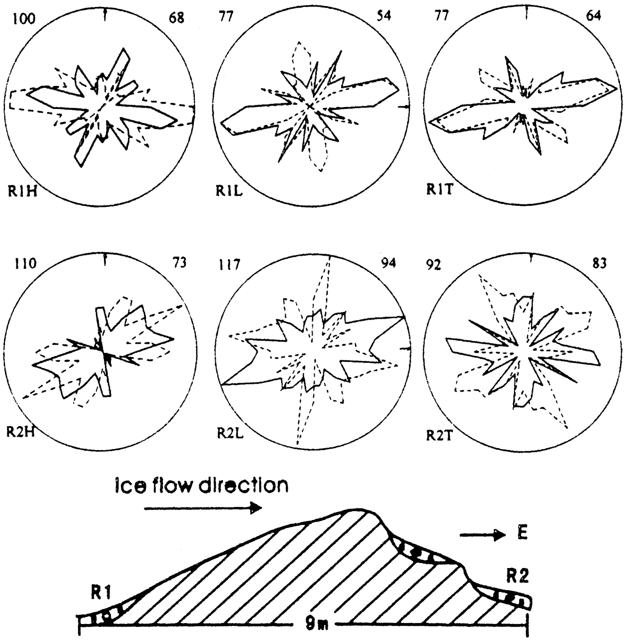

Fig. 5. Cross-section of roche moutonnée from which samples R1 and R2 were collected, and rose diagrams of microfabrics. See Figure 3 for explanation.

2–4). The end moraine is composed of two distinct tills and is covered by a loess cap (Figs 3 and 4). Samples W1–W3 were collected from the lower till, and samples W4–W6 from the upper till.

Samples R1–R4 were collected from tills on the stoss (R1 and R3) and lee (R2 and R4) sides of two roche moutonnées (Figs 5 and 6). The long axes of these roche moutonnées are parallel to the trend of the valley. The roche moutonnées were deglaciated in the 1960s.

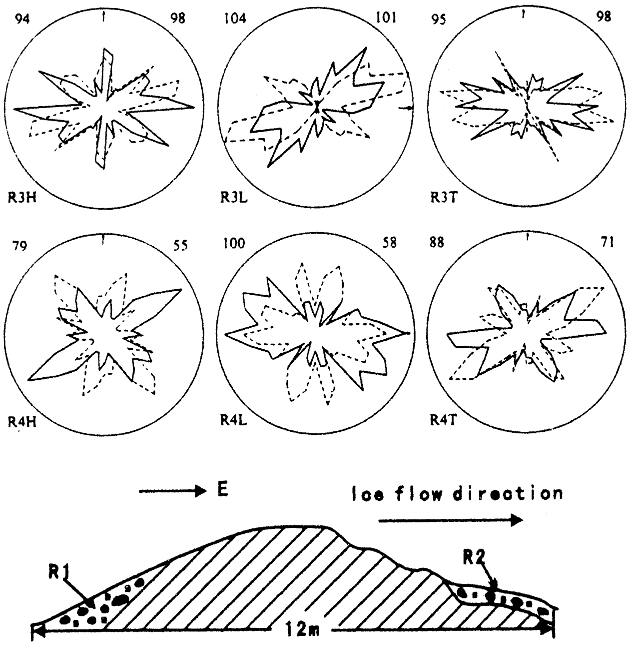

Fig. 6. Cross-section of roche moutonnée from which samples R3 and R4 were collected, and rose diagrams of microfabrics. See Figure 3 for explanation.

Sample Dl was collected on the stoss side of a drumlin, which is about 800 m long and 200–300 m wide (Fig. 7) and aligned with the valley trend. Samples D2 and D3 were collected from the lee side of this drumlin. The drumlin is believed to have formed during the Last Glacial Maximum. This is based on a 6.5 kyr accelerator mass spectrometry ^{14}C date from a moraine at Glacier Observatory (Fig. 2), which is near the stoss end of the drumlin, and dates of 19–23 kyr from a moraine at the Wangfeng road maintenance station (Wangfeng station), which is several kilometers down-valley from the lee end of the drumlin (Yi and others, 1998).

METHODS

1. Thin-section preparation

Oriented samples, which were roughly cubes, 60–80 mm on a side, were impregnated in the field with cyanoacrylate adhesive, a glue with low viscosity and quick adhesion. In general, the glue penetrated only the outer parts of the specimen. In the laboratory, the impregnated outer layers of the cubes were cut away, and the remainder impregnated with an unsaturated polyester resin in a vacuum chamber. Three mutually perpendicular thin sections were then prepared: a horizontal section, a longitudinal section parallel to the valley axis, and a transverse section (Fig. 8). Horizontal sections were not prepared from samples W1 and W4. Each thin section was 15–18 mm wide and 22–28 mm long.

2. Measurements of apparent orientation and plunge, and statistical studies

Elongate particles, both rods and disks, are quite common in the thin sections. However, because a thin section represents a plane through a three-dimensional grain, the true shapes and orientations of the grains are not known. Thus, all lengths, orientations and plunges discussed herein are “apparent”. The apparent lengths of particles considered in samples W4–W6 were 0.5–5.0 mm, and particles considered in the other samples were 0.25–2.0 mm long. These were the dominant sizes in these samples. The voids considered were 0.1–0.5 mm in apparent length.

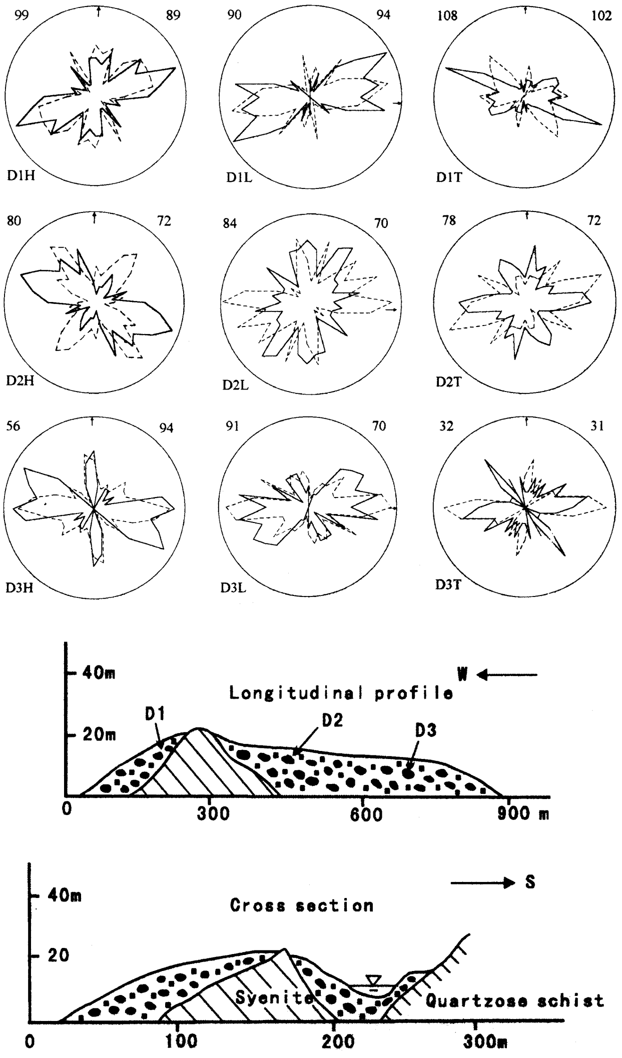

Fig. 7. Longitudinal and transverse cross-sections of drumlin from which samples D1–D3 were collected, and rose diagrams of microfabrics. See Figure 3 for explanation.

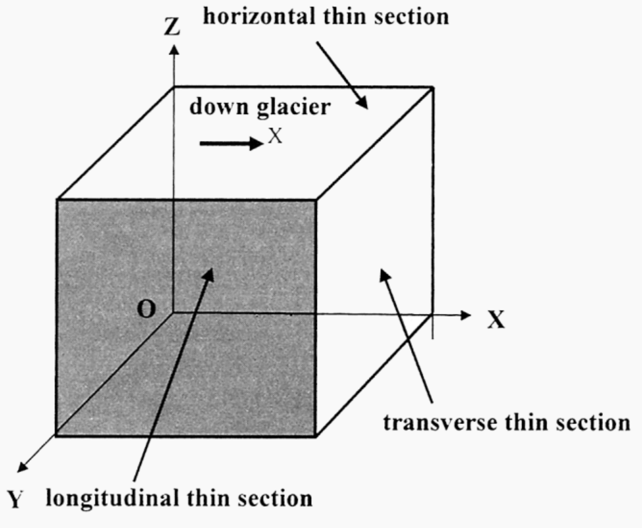

Fig. 8. Orientations of the three orthogonal thin sections with respect to the valley.

Particles and voids with apparent length/width ratios of >1.5 were measured with a rotating stage on a polarizing microscope. Orientations were recorded to the nearest degree.

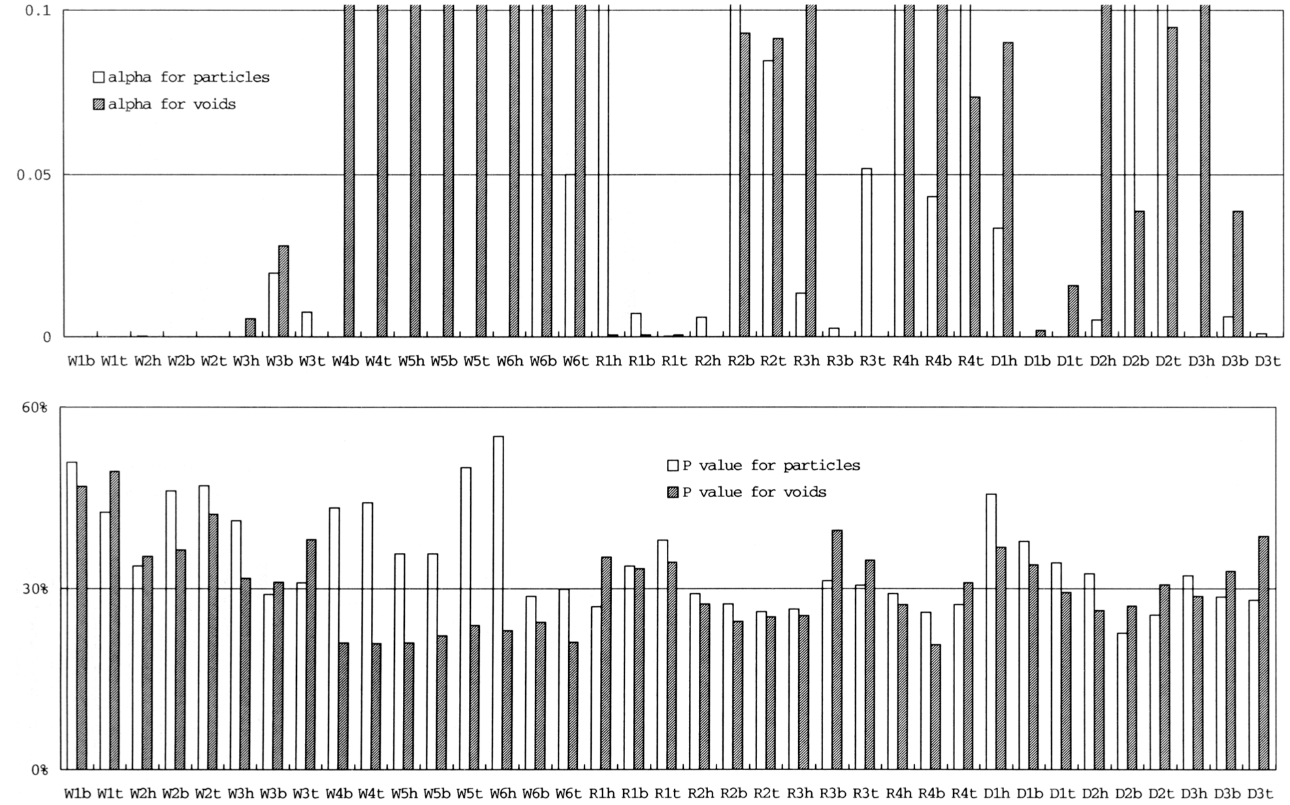

Fig. 9. Histograms of significance levels (α) of orientations and P values of particles and voids in thin sections. Letters h, b and t represent horizontal, longitudinal and transverse thin sections, respectively.

Between 32 and 117 particles and 31–155 voids were measured in each thin section. The data were grouped into 10° intervals and plotted in rose diagrams (Figs 3–7).

Since only one component of the orientation of a particle can be measured in a thin section, it is not possible to use the eigenvalue method (Mark, 1973) to characterize these microfabrics. Thus, χ^2 tests and the percentages of particles with orientations within respective 10° intervals in the rose diagrams were used to evaluate the level of significance of orientations (Fig. 9). The three highest neighboring values in each rose diagram (Figs 3–7) were summed and used as a measure of the strength of preferred orientations. For simplicity, these sums will be referred to as P values (Fig. 9). In any given thin section, the microfabric (of either particles or voids) is considered to be strong if it both passes the χ^2 test at the 0.05 significance level and $P > 30\%$. The relation between the significance levels and P values provides support for this criterion (Fig. 10). In a particular sample, the microfabric is considered to be strong if at least two of the thin sections from the sample have strong microfabrics.

RESULTS

In samples W1–W3, which are from the lower till in the Wangfeng end moraine, both particles and voids have strong preferred orientations in all three thin sections from each sample (Figs 3 and 4). Their P values are high, and they all passed the χ^2 test at a significance level <0.05 (Fig. 9). The apparent plunge in the longitudinal thin sections is small, with a direction either up- (W1 and W3) or down-valley (W2). Particles appear to be horizontal in transverse thin sections.

Microfabrics of voids in samples W4–W6 from the upper till are weak (Figs 3 and 4). Their P values are low and they all failed the χ^2 test (Fig. 9). In contrast, the particles from these samples have strong microfabrics. Their P values are high, and all but one passed the χ^2 test at a significance level <0.05. However, the preferred orientations of particles have different directions. The particles have one or more preferred orientations in horizontal thin sections. The apparent plunges of particles in longitudinal thin sections are both down- and up-valley (Figs 3, 4 and 9). In transverse thin sections, particles in samples W4 and W5 plunge steeply.

Samples R1 and R3, from the stoss sides of the roche moutonnées, have strong particle and void microfabrics (Figs 5 and 6). Their P values are high (Fig. 9), and all but two of them passed the χ^2 test with significance levels <0.05. The orientations of particles and voids are approximately the same. The particles in longitudinal thin sections plunge up-valley. In transverse thin sections, both particles and voids plunge slightly.

Particles and voids in samples R2 and R4, from the lee sides of the roche moutonnées, do not have strong microfabrics (Figs 5 and 6). Most of them failed the χ^2 test (Fig. 9). The P values are lower than those of samples W1–W3, R1 and R3. The microfabrics have multiple orientations. For the most part, preferred orientations of particles and voids are different from each other by as much as 13–48°.

Samples D1 and D3, from the stoss side of the drumlin with a rock core and the lee side of the same drumlin far from the core, respectively, have strong microfabrics and their P values are high (Fig. 9). Only the voids in the horizontal thin sections failed the χ^2 test (Fig. 9). The preferred orientations of particles and voids have the same trends in sample D3. The preferred plunge is small. The preferred orientations of particles in sample D1 differ from those of voids by 11–20°. The preferred orientations on horizontal thin sections are oblique to the valley trend, and the preferred plunges are small.

Most particles and voids in sample D2, taken immediately

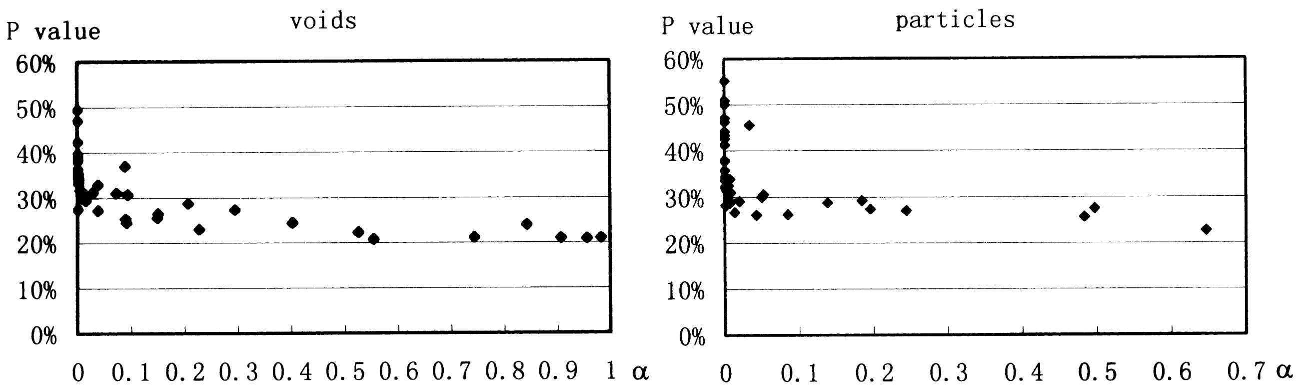

Fig. 10. Relation of significance level and P value for voids and particles.

in the lee of the core of the drumlin, do not have very strong microfabrics (Fig. 7). They failed the χ^2 test (Fig. 9), and their P values are low (Fig. 9). The microfabrics have multiple orientations that generally differ from each other by >10°.

DISCUSSION

Some researchers (e.g. Dowdeswell and Sharp, 1986; Hicock, 1992; Hicock and Dreimanis, 1992; Hart, 1994, 1997; Clark, 1997) have inferred that subglacial shearing of till results in weaker fabrics than the lodgment process. Similarly, Cui (1981) interpreted strong till fabrics in the upper Ürümqi river valley as resulting from lodgment and subglacial melt-out. Recently, however, the evolution of clast fabrics with shear strain has been investigated by Hooyer and Iverson (2000) using a ring-shear device to slowly shear a large till specimen to high strains. They found that strong fabrics develop parallel to the shearing direction.

Independent evidence for subglacial deformation

Field observations indicate that the tills described herein that have strong particle and void microfabrics have undergone deformation.

The tills from which samples W1–W3, R1–R4, D1 and D3 were collected are interpreted to be basal tills. They are compact, with a high silt content (Cui, 1981; Wang and Zhang, 1981) which is inferred to be a result of subglacial comminution (Dreimanis and Vagners, 1971; Boulton, 1978; Yi, 1997). Feng and Qin (1984) reported that the fabric formed by clasts larger than those considered in this study is strong, and concluded that these clasts were oriented subglacially by deformation of the till. Cui and Xiong (1989) and Xiong (1991) observed folding of thin layers of fine sand and silt, about 0.5 m thick and several meters long, in this same moraine. Cui and Xiong (1989) and Xiong (1991) inferred that the layers were deposited by subglacial water and later deformed subglacially.

In addition, we observed what are interpreted to be shear planes in the till where samples W1–W3 and D3 were collected, as did Derbyshire (1984) and Feng and Qin (1984). These planes occur within shear zones that are several to more than 10 m long and 0.8–2.0 m thick, dipping up-glacier at angles of 18–28°. Derbyshire (1984) and Feng and Qin (1984) reported that these shear zones contained finer sediment and more uniformly sized clasts than surrounding areas. Feng and Qin (1984), Ma (1984) and Cui and Xiong (1989) reported that the long axes of elongate clasts in the shear zones were parallel to the valley trend. Feng and Qin (1984) suggested that the moraines, from which samples W1–W3 were collected, were formed by thrusting. Furthermore, samples R1 and R3 were collected from the stratum in which Echelmeyer and Wang (1987) observed shear planes and deformation from an ice tunnel excavated in nearby Ürümqi Glacier No. 1.

Relation between deformation and microfabric

Samples W1–W3, R1, R3, D1 and D3 have strong particle and void microfabrics. As noted above, there is independent evidence suggesting that these samples are from tills that were deformed under the glacier. Samples R1, R3 and D1 may have been consolidated and sheared more intensely because they were on the stoss sides of the roche moutonnées and drumlin, respectively, where shear and normal stresses on the bed were likely higher than normal. The observations of Yi and Cui (1994), who reported that voids in these tills were isolated and that most of them displayed disk-like or elongate shapes, support this idea.

The upper till from which samples W4–W6 were collected has a strong particle microfabric but weak void microfabric. The rock fragments in this loose overlying till are the same lithology as the local valley sides (Li and others, 1981). This till, therefore, is believed to have formed by dumping and rolling of debris from surrounding slopes and from the glacier surface (Cui, 1981; Feng and Qin, 1984; Ma, 1984; Cui and Xiong, 1989; Xiong, 1991). Flat particles settled parallel to the land surface without being consolidated under the weight of the glacier. Yi and Cui (1994) reported that the voids in this till were not isolated but rather were interconnected. Most of these voids were large and irregular in shape.

Samples R2 and R4 were from the lee sides of roche moutonnées, and sample D2 was close to the lee side of the rock core of the drumlin. The particles and voids in these samples have weak fabrics. These samples might have been in an area of incipient separation of the ice from the bed, and thus shielded from normal and shear stresses that cause consolidation and shearing.

CONCLUSIONS

Strong particle and void microfabrics are associated with till that is inferred to have been deformed subglacially, a conclusion consistent with the recent experiments of Hooyer and Iverson (2000). If particles of a till have a strong microfabric but voids do not, as in the upper till of the end moraine described herein, then it is unlikely that the till was consolidated or sheared subglacially. Microfabric of till in the area studied illustrates that small subglacial landforms can influence subglacial till deformation. The particle and void microfabric of till on the stoss sides of two roche moutonnées and a drumlin is strong, indicating deformation. But microfabrics on the lee sides of the roche moutonnées and immediately in the lee of the rock core of the drumlin are weak, suggesting that the till in these locations was not sheared significantly.

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