Journal of Glaciology, Vol. 43, No. 145, 1997

Subglacial comminution in till — evidence from microfabric studies and grain-size distributions

YI CHAOLU

Laboratory of Environmental Sciences, Institute of Geodesy and Geophysics, Academica Sinica, Wuhan 430077, China

ABSTRACT. Quartz, feldspar and chlorite, the principal minerals in a basal till from the Halasi River catchment in the Altay Mountains, northwestern China, are present in approximately equal concentrations in the coarse fraction of the till, 1.0–0.125 mm. Quartz concentrations are significantly higher than those of the other two minerals in the 0.125–0.016 mm size range. Feldspar and chlorite concentrations are higher than those of quartz in the finest fraction. Quartz has a strong preferred mode at 0.063–0.032 mm. Feldspar and chlorite have two weak modes in the silt-size range, one between 0.063 and 0.032 mm and the other between 0.016 and 0.004 mm.

Thin sections of oriented impregnated samples were used to study crushing and abrasion. Over 2700 daughter particles were identified as products of comminution of 925 parent grains. Quartz and feldspar are most likely to be broken into two particles of roughly equal size, as are fine chlorite grains. However, owing to their weakness and cleavage, larger grains of chlorite tend to be split into more than two daughter particles.

Sizes of the daughter grains were measured and sizes of the original parent grains were estimated. Mean parent grain-sizes for quartz, feldspar and chlorite are 0.129, 0.078 and 0.059 mm, respectively, whereas mean daughter grain-sizes are 0.068, 0.041 and 0.024 mm, respectively. The greater percentage reduction in the size of chlorite reflects its tendency to break into more than two daughter particles.

Most grains tend to be crushed. Only a few large particles seem to have suffered from abrasion.

INTRODUCTION

Comminution of sediment grains is an important subglacial process. Many authors (Dreimanis and Vagners, 1971, 1972; Boulton, 1978; Haldorsen, 1981) have attributed a mode in the silt-size range in till to such comminution, and Drake (1972) inferred that a change in roundness of pebbles with increasing distance from their source in east-central New Hampshire was a result of it.

In studies of the size distributions of various mineral species in till, Dreimanis and Vagners (1971) suggested that quartz and feldspar can be reduced to a terminal grain-size of 0.062–0.031 mm, while other minerals might have smaller terminal sizes. Dilabio (1981) found that chalcopyrite in till in the Lac Mistassini–Lac Waconichi area of Quebec has a clast mode between 16 and 1 mm and a matrix mode from 0.063 to 0.016 mm. Other researchers have studied comminution of quartz in till with the use of a scanning electron microscope (e.g. Krinsley and Doornkamp, 1973; Mahaney and others, 1988), and have observed what they infer to be abraded surfaces and conchoidal fracture resulting from subglacial comminution.

In discussing comminution, a distinction between crushing and abrasion is sometimes made. The word "crush" implies a process in which forces are predominantly normal to a grain surface, whereas abrasion suggests forces parallel to the surface. Clearly, there must be a continuum between these end members. However, shear forces are likely to dislodge small particles from the surface of a larger one, whereas normal forces break grains into daughter particles of roughly equal size. Herein, mineralogical analyses of different grain-size fractions from a basal till and microfabric studies of impregnated samples of the till are used to clarify the role of crushing and abrasion in controlling the grain-size distribution of the till matrix.

REGIONAL SETTING

The area from which the samples were obtained is in the Halasi River catchment on the south slope of the Altay Mountains in China (48°30′–49°20′ N, 86°50′–87°55′ E). Elevations range from ~1000 m in the river valley to 4374 m at the top of the highest peak, Youyifong. The modern snow line is 3000–3100 m, so valley glaciers are present. Halasi Glacier, the largest and longest in the region, is over 10 km long. The snouts of modern glaciers are at elevations of 2300–2400 m, while the lower limit of known Quaternary glacial deposits is at 1300 m.

Lateral moraines are present along the banks of Halasi Lake and three sets of end moraines are distributed over a distance of 3.5 km down-valley from the lake (Fig. 1). Each set of end moraines consists of several minor moraines. The till is 20–30 m thick in these moraines. Near the outlet of Halasi Lake, there are two small patches of basal till (or ground moraine) about 10 m thick, with little relief.

^{14}C dating of a secondary carbonate coating on till gravels on the valley floor near site B (Fig. 1) yielded an age of 4040 ± 80 years BP. This is considered to be a minimum age for the deposits. Accordingly, consistent with data on moraine ages in the other Chinese mountains, this deposit

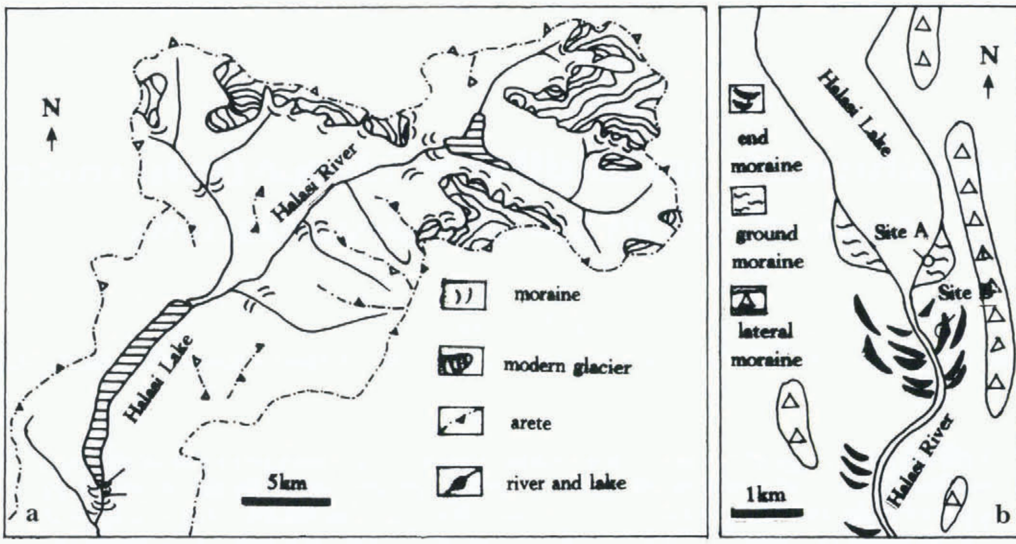

Fig. 1. Maps showing sampling sites. (a) Location map of the study area. (b) Geomorphological features of moraine in the vicinity of the outlet of Halasi Lake.

is believed to have been formed during the Last Glaciation in China (equivalent to the Wisconsinan or Weichselian) (Cui Zhijiu and others, 1992).

The bedrock in the glaciated area is predominantly granite and chlorite, chlorite-quartz and quartz-schists. Accordingly, over 90% of the mineral grains in the till are quartz, feldspar or chlorite (Table 1).

GENERAL PROPERTIES OF THE TILL

Tills near the outlet of Halasi River contain a large number of spherical clasts, believed to have come from ancient lacustrine sediments (Cui Zhijiu and others, 1992; Yi Chaolu and Cui Zhijiu, 1994). At site A (Fig. 1), the till is massive and compact, and the matrix has a high silt content. The till fabric is strong, with a preferred orientation of long axes parallel to the ice-flow direction and dipping up-glacier.

The till at site B is also massive but less compact and coarser. It contains lenticular layers of sand and silt, 0.18–0.50 m thick, with individual laminae that are 1–2 mm thick. The preferred orientation of gravel-sized clasts is perpendicular to the trend of the moraine.

METHODS

Grain-size and mineralogical analyses

Fourteen pairs of samples were collected, six from ground moraine near site A, and eight from an end moraine near site B (Fig. 1). One sample from each pair was loose and was used for grain-size analysis, whereas the second was an oriented, impregnated sample which was thin-sectioned and used for microfabric studies.

Size distributions of grains >0.039 mm were determined by sieving. Fractions >0.125 mm were separated at 1ϕ intervals ($\phi = \log_2 d$ where d is the grain-size in millimeters) and fractions between 0.125 and 0.039 mm were separated at $\frac{1}{4}\phi$ intervals.

The fine-sand (0.1–0.2 mm) fraction was divided into heavy- and light-mineral components with the use of tri-

Table 1. Mineral components in glacial till (grain-size: 0.1–0.2 mm)

Sample number	*7-1*	*7-2*	*7-3*	*7-4*	*7-5*	*7-6*	*3-1*	*3-2*	*3-3*	*3-4*	*3-5*	*3-2′*	*3-3′*	*3-4′*
Quartz	46.901	50.091	52.408	50.033	46.433	45.598	51.067	44.425	45.158	49.939	50.663	52.821	51.397	45.659
Feldspar	35.678	32.47	32.183	33.046	37.646	35.241	30.083	38.103	37.97	36.776	30.175	32.069	26.039	38.801
Chlorite	12.179	12.547	11.891	12.452	11.739	13.702	13.118	12.051	12.011	11.358	14.362	10.761	15.351	7.511
Muscovite	0.005	0.009	0.004	0.002	0.004	0.001	Trace	Trace	Trace	Trace	Trace	Trace	Trace	Trace
Biotite	0.756	0.734	0.789	0.752	0.716	0.642	0.732	0.525	0.61	0.369	0.575	2.037	0.973	5.811
Oisite	3.302	2.937	1.859	2.655	2.608	2.96	3.468	3.475	3.089	1.366	3.235	0.772	4.984	1.801
Epidote	0.006	0.004	0.006	0.007	0.005	0.008	0.003	0.006	0.004	0	0.008	0.005	0.018	0.002
Amphibole	0.208	0.212	0.182	0.179	0.18	0.201	0.163	0.165	0.099	0.02	0.227	1.129	0.253	0.008
Pyroxene	0.003	0.002	0.003	0.002	0.004	0.005	0.004	0.004	0.003	No	0.004	0.002	0.018	No
Garnet	0.008	0.016	0.011	0.01	0.007	0.146	0.01	0.013	0.005	0.004	0.011	Trace	Trace	Trace
Tourmaline	0.012	0.016	0.009	0.008	0.023	0.075	0.015	0.015	0.049	0.014	0.037	0.13	0.026	0.017
Zircon	0.034	0.052	0.072	0.065	0.03	0.07	0.107	0.167	0.08	0.066	0.044	0.055	0.175	0.203
Magnetite	0.712	0.63	0.398	0.554	0.43	1.041	1.005	0.862	0.527	0.043	0.488	0.094	0.588	0.151
Ilmenite	0.189	0.279	0.167	0.227	0.166	0.302	0.223	0.186	0.266	0.042	0.165	0.115	0.177	0.033
Limonite	0.001	0.002	0.001	0.001	0.003	0.005	0.001	0.001	Trace	0.001	0.001	0.002	0.001	0.001
Pyrite	0.002	0.001	0.001	0.001	0.002	0.001	0.001	0.002	0.001	No	0.002	0.001	No	No
Hematite	0.004	0.008	0.016	0.006	0.005	0.002	Trace	Trace	0.129	0.003	0.003	0.007	Trace	0.001
Gold	Trace	No	No	Trace	No	No	No	No	No	No	No	No	No	No

https://doi.org/10.3189/S0022143000035073 Published online by Cambridge University Press

brothane (specific gravity: 2.89–2.93). Ferromagnetic minerals were further separated magnetically from the heavy fraction. The rest of the heavy fraction and the light fraction were sorted into three or four parts electromagnetically. The mineral constituents were then identified by using a binocular microscope, and occasionally with a polarizing microscope using oil immersion. The variation in mineralogy among the 14 samples collected is small (Table 1). Thus, four representative samples were selected for detailed mineralogical analysis of the respective grain-size separates.

Samples from grain-size fractions >0.039 mm were impregnated and thin-sectioned. Mineral species were identified using a polarizing microscope. Grain counts were made using more than 500 grains per sample.

The >0.039 mm grain-size fractions were further separated at 1ϕ intervals by pipette. The separate grain-size fractions were then ground into a fine powder and the mineral components were determined quantitatively by infrared spectrometer.

Microfabric studies

Sets of mutually perpendicular thin sections were prepared from the oriented impregnated samples. Microfabrics and characteristics of the comminuted mineral grains were studied by using a polarizing microscope. Sizes of over 900 primary grains and over 2700 daughter grains were measured (Table 2).

Table 2. Number of grains measured

	Parent grains	*Daughter grains*
Quartz	270	> 700
Feldspar	333	>1000
Chlorite	322	>1000

Some samples from the local bedrock, a schist, were also sectioned in order to determine mineral grain-sizes in the parent rock.

RESULTS

Size distribution of quartz, feldspar and chlorite grains

The variation in mineral content among the various size fractions is similar in the four samples (Fig. 2). Quartz dominates in the 0.125–0.031 mm size range. In contrast, feldspar and particularly chlorite concentrations increase relative to quartz in the smaller- and larger-size fractions.

Figure 3 shows the grain-size distribution in the bulk till samples and Figure 4 shows the grain-size distributions for quartz, feldspar and chlorite, individually, calculated from the data in Figures 2 and 3. Quartz has a preferred mode at 0.063–0.032 mm and in some samples a secondary mode at 0.25–0.125 mm. Feldspar and chlorite commonly have weak modes at 0.25–0.125, 0.063–0.032 and 0.016–0.004 mm.

Crushed and abraded minerals in thin sections from oriented samples

In thin sections prepared from the oriented impregnated samples, many grains of quartz, feldspar and chlorite appear to have been broken into two or more smaller fragments (Fig. 5a–g). In some cases, small quartz fragments are inferred to have been abraded from larger ones. The shapes of the edges of these grains mirror that of the larger presumed parent (Fig. 5c) and, in some places, they remain weakly connected to the parent (Fig. 5d).

Polymineralic fragments were sometimes found to be broken into monomineralic grains along mineral boundaries (Fig. 5h). Similar clasts, inferred to have resulted from crushing, were also observed in the field (Cui Zhijiu and

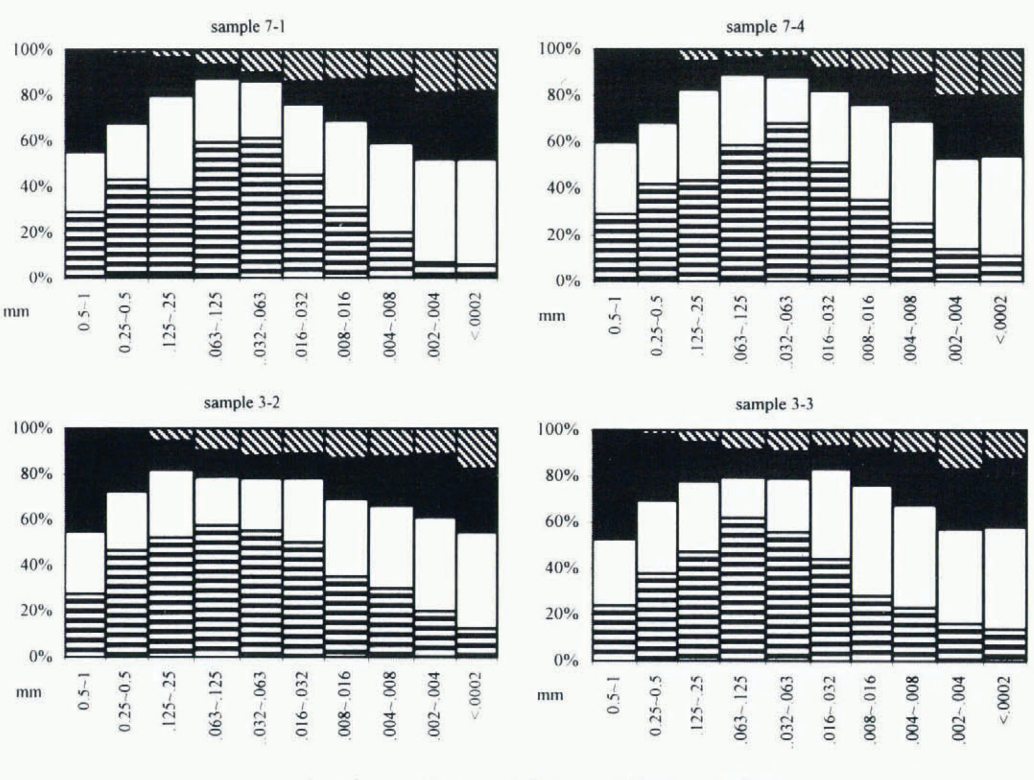

Fig. 2. Variation in mineral composition with grain-size for the four samples.

https://doi.org/10.3189/S0022143000035073 Published online by Cambridge University Press

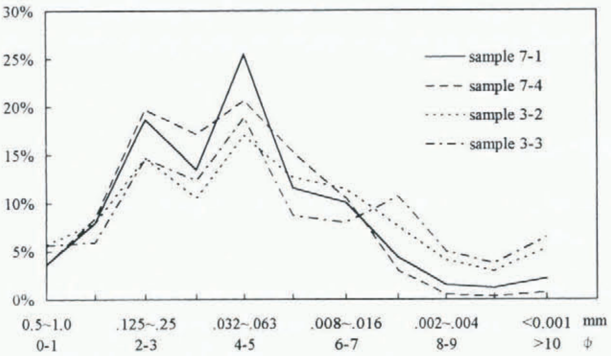

Fig. 3. Grain-size distributions of bulk samples.

others, 1992). The results that follow, however, come from analysis of monomineralic grains.

Modes in the distribution of parent grains are 0.063–0.125 mm for quartz and feldspar and 0.016–0.063 mm for chlorite (Fig. 6a). The mode for feldspar is skewed toward smaller grain-sizes compared with quartz. The average sizes of parent grains of quartz, feldspar and chlorite are 0.129, 0.078 and 0.059 mm, respectively, while the smallest parent grains observed were about 0.016, 0.006 and 0.002 mm, respectively. Although the shapes of the size distributions of daughter grains are similar to those of the respective parent grains, there is a clear shift of about a factor of 2 (1ϕ) toward finer grain-sizes (Fig. 6b). This reflects the fact that parent grains tend, most commonly, to split into two daughter fragments. The average grain-sizes thus decrease to 0.068, 0.041 and 0.024 mm, respectively. Observed daughter fragments can be as small as 0.005 mm for quartz, 0.003 mm for feldspar and 0.0014 mm for chlorite.

Figure 7 shows the changes in size distribution during comminution, expressed as the percentage of the total area of a thin section occupied by grains of different sizes. Transitions from net decrease to net increase occur at 0.125, 0.063 and 0.25 mm for quartz, feldspar and chlorite, respectively. The largest increases are 3.6% at 0.063–0.032 mm for quartz, 10.9% at 0.063–0.032 mm for feldspar and 10.0% at 0.032–0.016 mm for chlorite.

Let us define the *crushing factor*, C_f, as the number of daughter grains resulting from crushing a parent. A crushing factor of 2 was found for 65.6% of the quartz grains, 47.2% of the feldspar grains and 40.7% of the chlorite grains (Fig. 6c). Crushing factors greater than 5 are most common for crushing events involving chlorite. In addition, for chlorite crushing factors tend to be larger for larger grain-sizes, whereas this is not so clearly the case for quartz and feldspar. The correlation coefficient for the relation between C_f and grain-size is 0.392 ($n = 322$) for chlorite (significant at the 0.1% level), whereas those for quartz and feldspar are only 0.150 ($n = 270$) and 0.167 ($n = 333$), respectively.

A Student's t-test indicates that the average sizes of parent grains of feldspar and chlorite with $C_f = 2$ are significantly smaller than the average size of the total population of parent particles of these mineral species (Fig. 6d). This property is more obvious in chlorite (mean = 0.033 mm, $t = 4.89$, DF = 451, level = 0.1%, mean size of parent = 0.059 mm) than in feldspar (mean = 0.064 mm, $t = 2.87$, DF = 478, level = 5%, mean size of parent = 0.078 mm). In other words, smaller particles are more likely to split into only two daughter particles, whereas larger grains may split into three or more daughter particles. This is not true of quartz. On the other hand, the average sizes of daughter grains of the three minerals resulting from crushing events yielding exactly two particles are not significantly different from the average sizes of all daughter grains of these respective minerals.

DISCUSSION

The process of comminution in till probably starts with breakdown of rocks along zones of weakness, eventually resulting in monomineralic grains (Fig. 5h). These grains

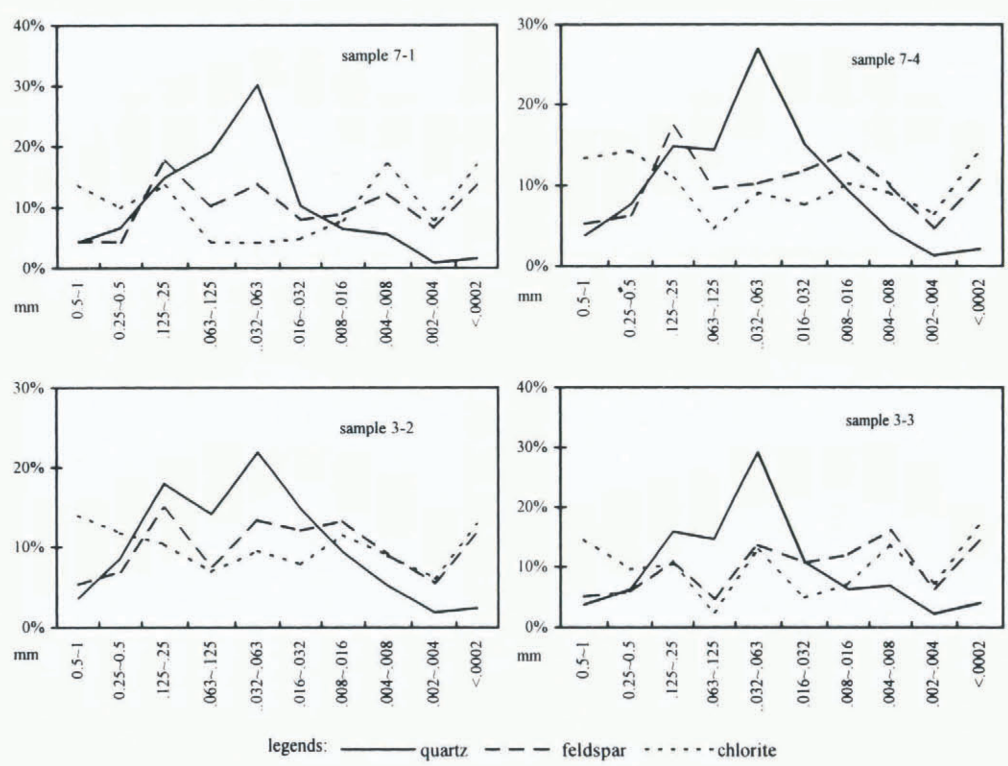

Fig. 4. Grain-size distributions of quartz, feldspar and chlorite.

https://doi.org/10.3189/S0022143000035073 Published online by Cambridge University Press

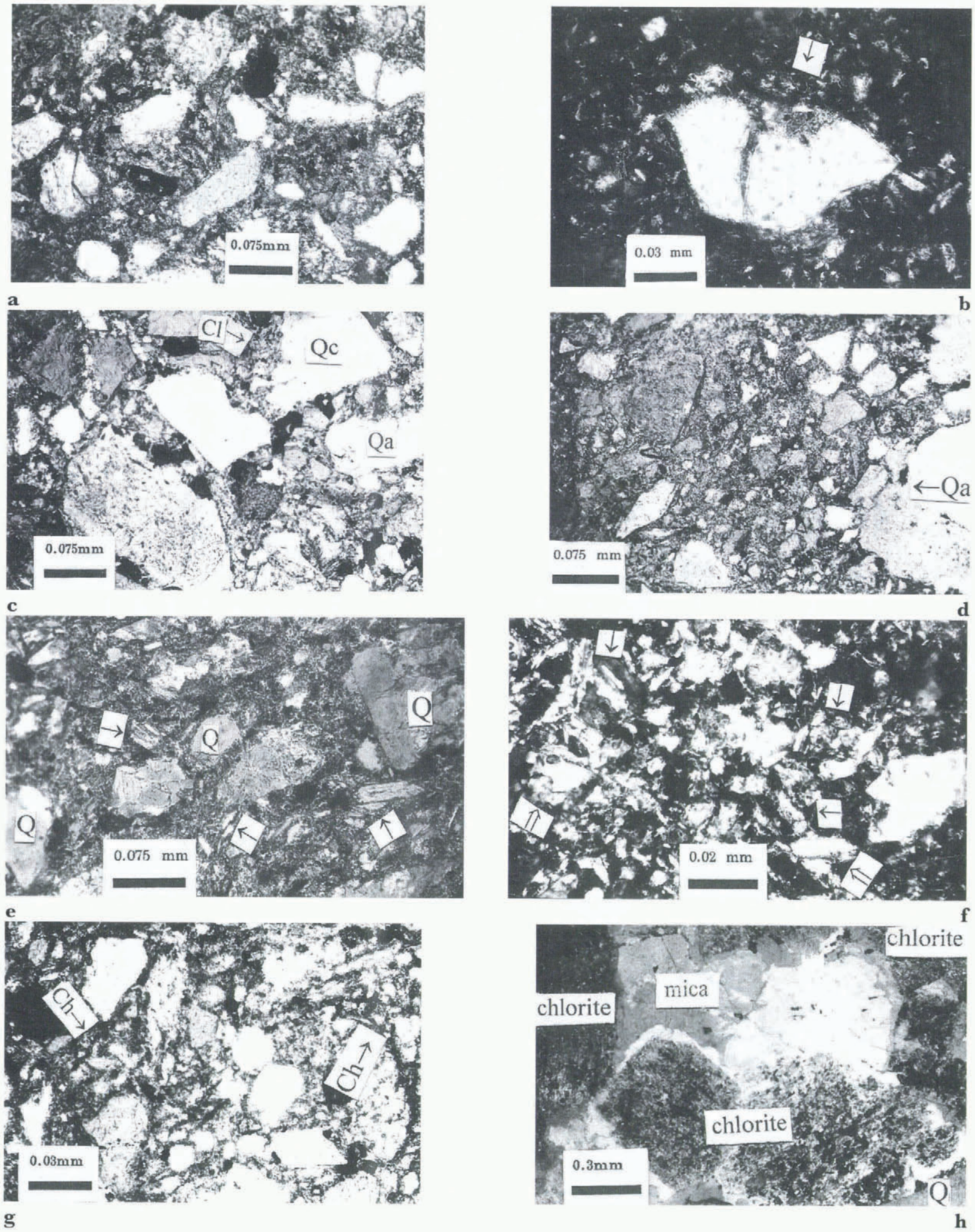

Fig. 5. (a) Quartz grains with clay rims, and two recently crushed 0.045–0.062 mm quartz grains (left side and upper right corner). Under crossed nicols. The clay was formed in situ. (b) Enlargement of the crushed quartz grain in upper right corner of (a). Arrow points to clay. (c) Crushed and abraded quartz grains. Under crossed nicols with gypsum plate. One quartz grain has been split into two smaller ones. On the right side, eight 0.04–0.05 mm quartz grains are inferred to have been abraded from a large one. One of the abraded grains is still weakly attached to its parent. Clay has formed on the rims of the grains. Qc, crushed quartz grain; Qa, abraded quartz grain; Cl, clay. (d) Small quartz grains, 0.03–0.05 mm in diameter, are inferred to have been abraded from a larger one. Note that in the lower right corner, the edges of two small grains mirror the shape of the corresponding edge of a larger one. Qa, abraded quartz grain. Arrow points to abraded daughters. Under crossed nicols with gypsum plate. (e) Except for several large quartz grains, most of the grains are feldspar. Large ones appear to have been crushed into finer grains 0.016–0.004 mm. Under crossed nicols with gypsum plate. Q, quartz. Arrows point to crushed feldspar grains. (f) Silt grains in fine matrix. Feldspar and chlorite were still being crushed into even smaller sizes. Single arrows point to chlorite grains and double arrows to feldspar grains. Under crossed nicols. (g) Crushed small chlorite grains (Ch). Under crossed nicols with gypsum plate. (h) Part of a mineral aggregate caught in the process of being crushed into individual minerals of chlorite, mica, quartz and so forth. Under crossed nicols with gypsum plate.

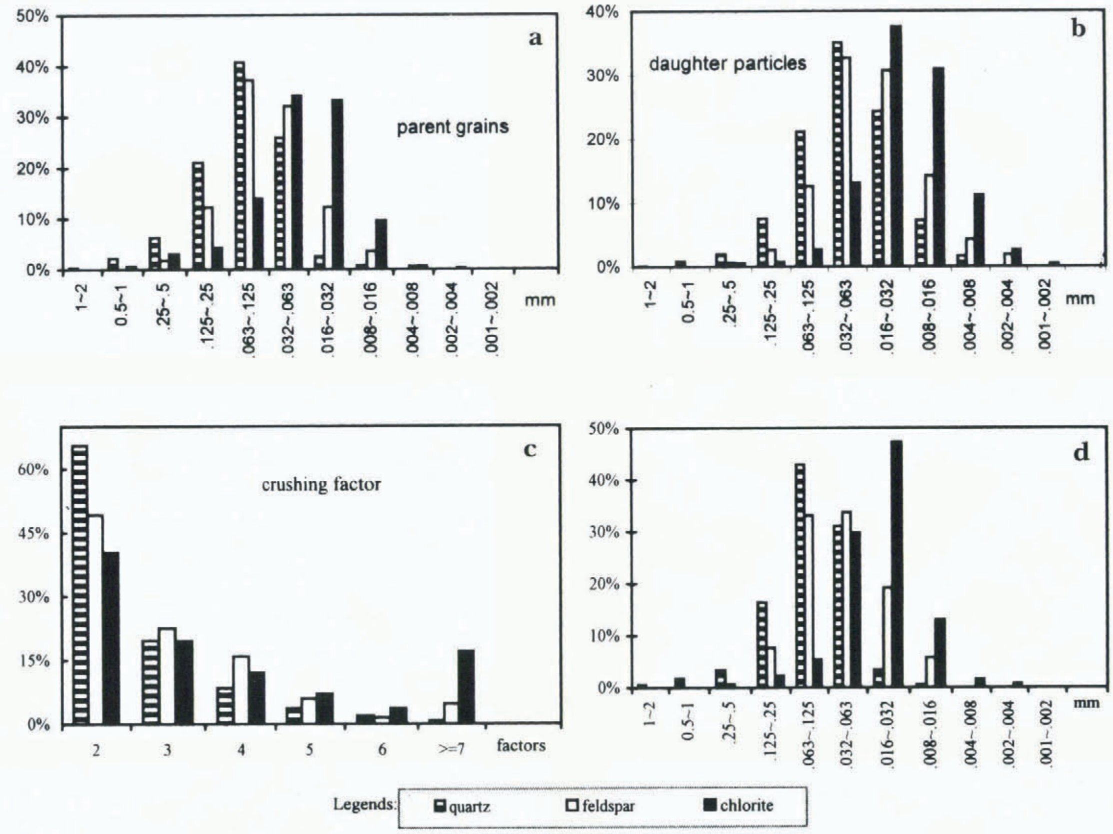

Fig. 6. (a) Grain-size distribution of parent particles. (b) Grain-size distribution of daughter particles. (c) Crushing factors, C_f. (d) Size distribution of parent particles that split into exactly two daughter particles (i.e. $C_f = 2$).

are then split into smaller ones (Fig. 5a–g), perhaps eventually reaching a terminal grade or crushing limit.

The common secondary modes at 0.25–0.125 mm in the grain-size distributions of quartz and feldspar (Fig. 4) come from the parent schists which have crystals of this size. Similarly, chlorite is relatively abundant in the 1.0–0.125 mm size range because chlorite crystals are large in the schists.

For quartz, the greatest increase in the number of grains, expressed in per cent by area, occurs in the size category 0.032–0.063 mm (Fig. 7). Consistent with the work of Dreimanis and Vagners (1971), this results in a mode in the grain-size distributions in this size range (Fig. 4). This mode, however, is not the lower limit of crushing or abrasion; rather it is a *preferred daughter grain-size*.

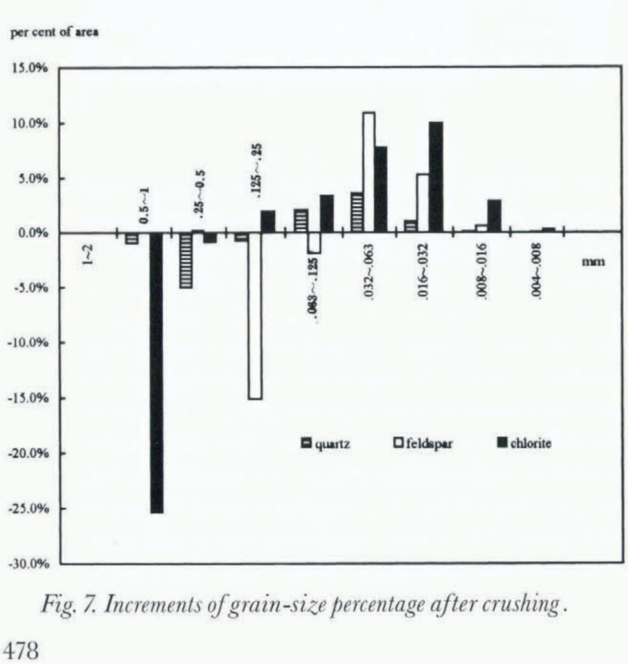

Fig. 7. Increments of grain-size percentage after crushing.

Feldspar is weaker than quartz, in part because it has three cleavage directions. Thus, it is crushed more readily, as shown by the larger changes in size distribution compared with quartz (Fig. 7). Furthermore, crushing of feldspar yields a wider range of grain-sizes with more fine material and no clearly dominant mode below 0.063 mm (Fig. 4).

Chlorite is quite weak and has a well-developed cleavage. Thus, it is readily crushed. The decrease in chlorite grains in the 0.5–1.0 mm size range is the largest observed (Fig. 7) and, consistent with grinding experiments summarized by Drewry (1986), the daughter grains vary widely in size (Figs 6b and 7). The strong positive relation between C_f and grain-size of chlorite, mentioned earlier, reflects the fact that larger chlorite grains are likely to be crushed into many small fragments rather than fewer large ones.

For feldspar and chlorite the maximum increases in Figure 7 appear to be in the 0.032–0.063 and 0.016–0.032 mm size categories, respectively. However, the lack of distinct modes at these sizes in Figure 4 suggests that these are not preferred daughter sizes. Rather, the preferred sizes may be as low as 0.016–0.004 or even 0.002 mm (Fig. 4), and thus not detectable given the limits of resolution of thin sections and the optical microscope.

Some failures involve detachment of one or several quite small fragments from the rims of a parent (Fig. 5c and d). These surficial failures are most common on larger grains. It is inferred that they are due to particle–particle interactions that are dominated by shear forces rather than by normal forces. The term *abrasion* may be appropriate for this process, although any distinction between abrasion and crushing is likely to be arbitrary. Micro-shears that could result in such failures have been observed in till in scanning electron-microscope studies (Love and Derbyshire, 1985) and in optical microscope studies using thin sections (van der Meer, 1990; Yi Chaolu, 1992). Because such failures are most common on larger grains, they are most commonly observed on quartz.

CONCLUSIONS

Mineral properties determine grain-size distributions of individual minerals in till. During comminution, parent grains of quartz and feldspar tend to break into two daughter particles of roughly equal size, whereas chlorite grains, particularly the larger ones, break into more than two daughter particles. There appears to be a preferred daughter grain-size for quartz of about 0.05 mm. In contrast, for feldspar and chlorite the preferred daughter grain-size is less distinct, and may be quite small as these weaker minerals are more abundant than quartz in the fine-silt and clay fractions.

Failures resulting in a small number of daughter particles of roughly equal size are far more common than ones yielding several very small daughter particles and a large residual parent. To the extent that the former process is associated with normal stresses and the latter with shear stresses, crushing appears to be more common than abrasion. This has implications for understanding deformation mechanisms in till.

ACKNOWLEDGEMENTS

The author thanks Lady W. Zhu, senior laboratory technician at the Department of Geology of Peking University, for infrared spectrometer analysis, Zhijiu Cui, Professor at the Department of Geography of Peking University, for valuable suggestions, R. LeB. Hooke for revision of the manuscript, and R. LeB. Hooke, N. Iverson and M. Sharp for valuable suggestions in revising the paper. This paper has been supported by Natural Science Foundation of China grant No. 49501003 and Tianshan Glacier Observatory grant No. 9402.

REFERENCES

Boulton, G. S. 1978. Boulder shapes and grain-size distributions as indicators of transport paths through a glacier and till genesis. *Sedimentology*, **25**(6), 773–799.

Cui Zhijiu, Yi Chaolu and Yan Jinfu. 1992. [Quaternary glaciations in the Halasi river catchment and its surroundings in the Altai Mountains in Xingjiang.] *J. Glaciol. Geocryol.*, **14**(4), 342–351. [In Chinese with English summary.]

DiLabio, R. N. W. 1981. Glacial comminution of chalcopyrite. *Geol. Surv. Can. Bull.* 323.

Drake, L. D. 1972. Mechanisms of clast attrition in basal till. *Geol. Soc. Am. Bull.*, **83**, 2159–2165.

Dreimanis, A. and U. J. Vagners. 1971. Bimodal distribution of rock and mineral fragments in basal tills. *In* Goldthwait, R. P., *ed. Till: a symposium.* Columbus, OH, Ohio State University Press, 237–250.

Dreimanis, A. and U. J. Vagners. 1972. The effect of lithology upon texture of till. *In* Yatsu, E. and A. Falconer, *eds. Research Methods in Pleistocene Geomorphology. Proceedings: 2nd Guelph Symposium on Geomorphology, 1971.* Norwich, England, Geo Abstracts Ltd., 66–82.

Drewry, D. 1986. *Glacial geologic processes.* London, Edward Arnold.

Haldorsen, S. 1981. Grain-size distribution of subglacial till and its relation to glacial crushing and abrasion. *Boreas*, **10**(1), 91–105.

Krinsley, D. H. and J. C. Doornkamp. 1973. *Atlas of quartz sand surface textures.* Cambridge, Cambridge University Press.

Love, M. A. and E. Derbyshire. 1985. Microfabric of glacial soils and its quantitative measurement *In* Forde, M. C., *ed. Proceedings, International Conference on Construction in Glacial Tills and Boulder Clays, 12–14 March 1985, Edinburgh, Scotland.* English Technical Press.

Mahaney, W. C., W. Vortisch and P. Julig. 1988. Relative differences between glacially crushed quartz transported by mountain and continental ice — some examples from North America and East Africa. *Am. J. Sci.*, **288**(8), 810–826.

Van der Meer, J. J. M. 1990. Micromorphology of some North Sea till samples — a pilot study. *J. Quat. Sci.*, **5**(2), 95–101.

Yi Chaolu. 1992. [Physico-chemical processes of ice–bed interface and microfabric of till, the Halasi river catchment, the Altai Mountains and the source region of the Urumqi river, the Tianshan Mountains.] (Ph.D. thesis, Peking University.) [In Chinese.]

Yi Chaolu and Cui Zhijiu. 1994. [Classification and sedimentary types of glacial lakes in the Halasi river catchment, the Altai Mountains.] *Oceanologia et Limnologia Sinica*, **23**(5), 477–485. [In Chinese with English abstract.]

MS received 10 May 1995 and accepted in revised form 28 April 1997