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RELATIVE DIFFERENCES BETWEEN GLACIALLY CRUSHED QUARTZ TRANSPORTED BY MOUNTAIN AND CONTINENTAL ICE—SOME EXAMPLES FROM NORTH AMERICA AND EAST AFRICA

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ABSTRACT. Glacially-crushed quartz grains in the fine and very fine sand (250-63 μm) fractions from Quaternary tills on Mount Kenya, northern Ontario, and Wellsch Valley, Saskatchewan, were analyzed by scanning electron microscope (SEM) to determine if relative ice abrasion and thicknesses might influence the frequency and morphology of crushing planes on individual grains. In this study, clasts transported by mountain ice (Mount Kenya) were moved a distance of about 12 km in a glacier estimated to have a thickness of about 400 m; tills resulting from emplacement by continental ice were transported at least 200 km in systems about 1000 m thick (Superior Lobe) and about 1500 m (Laurentide Glacier). The relative differences in basal ice shear stresses appear to have influenced the frequency with which crushing surfaces (subparallel indentations) occur. Conchoidal fractures, resulting from ice abrasion, appear more numerous on the Wellsch Valley and Superior Lobe quartz sand samples than on the Mount Kenya grains. The overall grain relief (including edge sharpness and angularity) is greater on samples affected by continental ice. From this study it appears that quartz-grain surface features provide important information on the thickness and transport distance of Pleistocene ice sheets.

INTRODUCTION

Routine SEM analyses of glacially-crushed quartz from Quaternary tills on Mount Kenya (fig. 1), along with tills from the north shore of Lake Superior (Thunder Bay, Ontario) (fig. 2), and from Wellsch Valley, Saskatchewan (fig. 3) showed striking differences in the frequency with which subparallel crushing planes and conchoidal fractures occur, as well as with respect to grain relief (sharpness of edges and degree of angularity). We studied approx 250 samples with the objective of determining if relative differences in shear stress and distances of transport in mountain versus continental ice might account for the striking differences in quartz sand grain morphology.

FIELD AREAS

Mount Kenya.—Mount Kenya (fig. 1) has been glaciated at least five times during the Quaternary (Baker, 1967; Mahaney, 1979, 1982, 1984, 1985, 1987, 1988). Although quartz is largely a constituent in loesses

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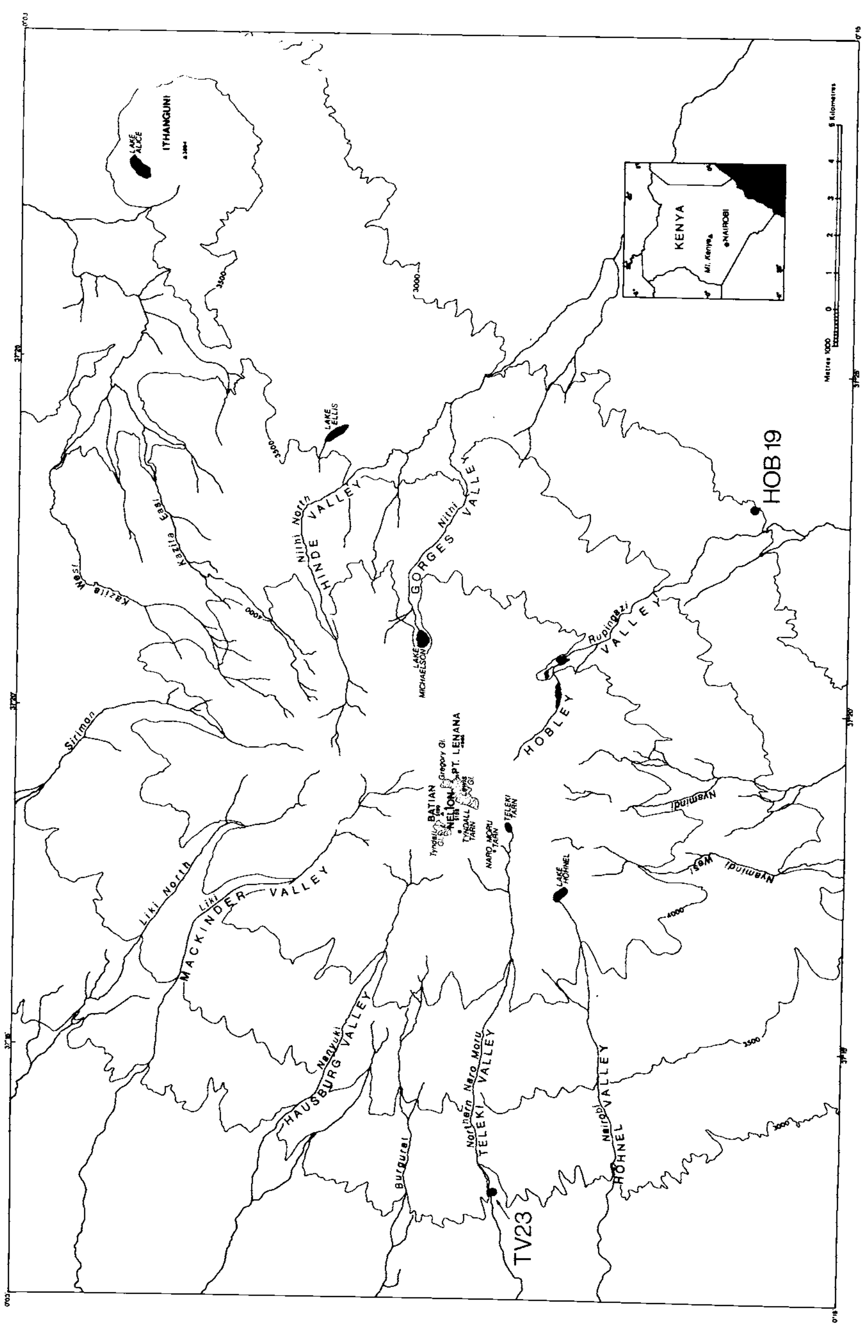


Fig. 1. Location of sites HOB19 and TV23 at the margin of glaciation on Mount Kenya (~3000 m).

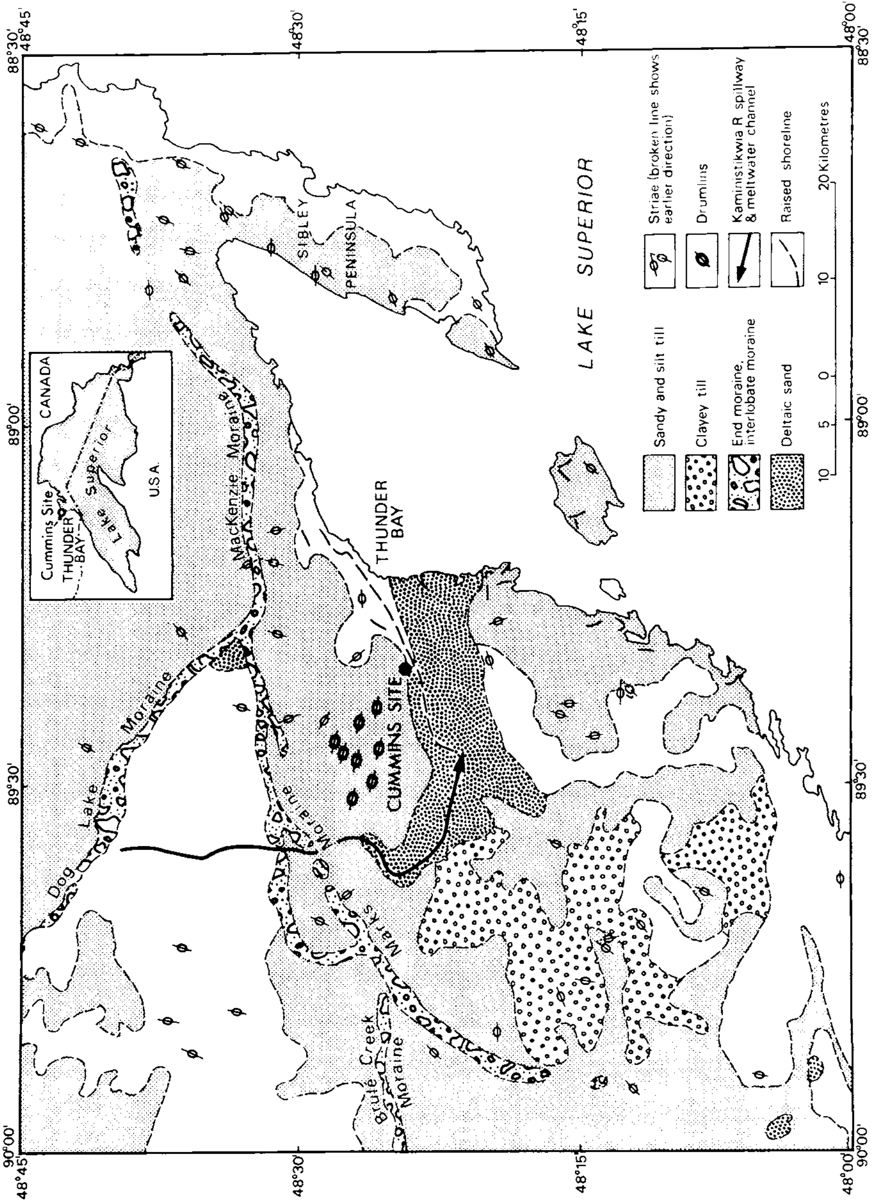


Fig. 2. Distribution of glacial deposits in the Thunder Bay, Ontario, area.

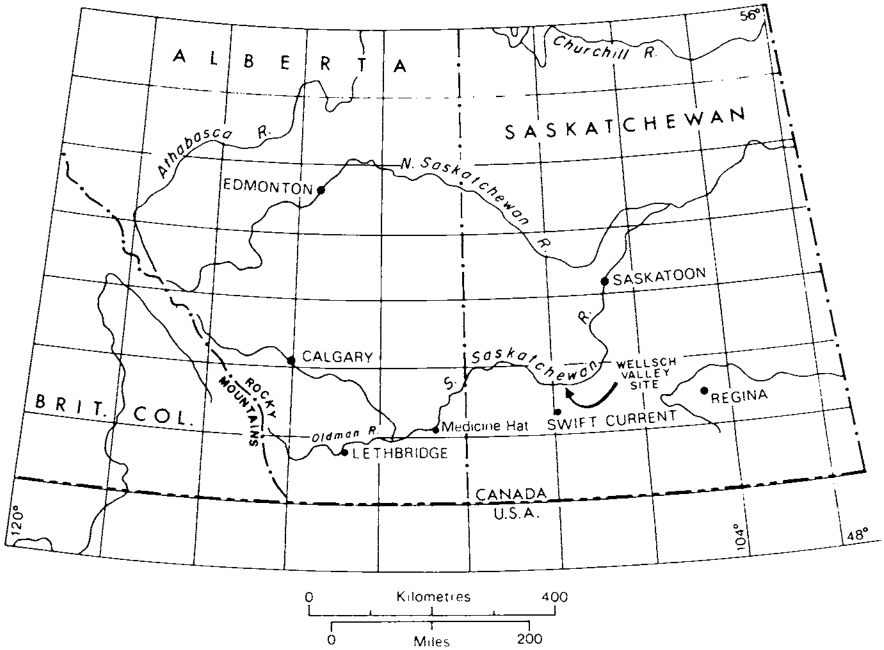


Fig. 3. Location of the WEV3 (North Cliff) section in Wellsch Valley, Saskatchewan.

and in deposits of mixed-tephra plus loess on Mount Kenya, some of it was reworked by Quaternary glaciers and emplaced in tills (Vortisch, Mahaney, and Fecher, 1987). While the total distance of transport is small (about 12 km) from the high cirques at about 4600 m to the lower limit of glaciation (about 3000 m), quartz in the very fine and fine sand fractions (250-63 μm) was analyzed along with other minerals to obtain information on environments of deposition and weathering histories (Mahaney, 1979, 1982; Vortisch, Mahaney, and Fecher, 1987). Sand-silt-clay ratios are variable, but in general these tills are sandy (for example sand = 35-55 percent, silt = 30-35 percent, and clay = 10-35 percent).

Thunder Bay.—The sequence of major events during the later stages of continental glaciation in the Thunder Bay (Ontario) area is readily discernable from till deposits considered to be of late Wisconsinan age. By about 12,300 yrs BP the main Patrician ice lobe had receded to the Thunder Bay region at a latitude of 48°26′N (Zoltai, 1963, 1965; Prest, 1970; Burwasser, 1977). Continental ice deposited relatively thin stoney sandy tills across much of northwestern Ontario, between many exposed Precambrian bedrock knobs. The thickness of the main ice sheet at about 18,000 yrs BP is estimated at 1600 to 2000 m

(Fisher, Reech, and Langley, 1985). The main ice mass fluctuated in the vicinity of Thunder Bay until about 11,000 yrs BP, when a brief advance formed the Dog Lake Moraine to the north of the study area (fig. 2) (Saarnisto, 1974, 1975). At around the same time part of the Hudson Bay Lobe passed across the Superior Basin (thus referred to as the Superior Lobe because of its relative freedom and independence of movement) and advanced across the study area from the east and south to the position of the Marks Moraine and the interlobate Mackenzie Moraine (fig. 2). This event resulted in the deposition of up to 7 m of gravelly silty clay till associated with the east-west oriented drumlin field near Murillo, Ontario.

In the immediate vicinity of the Cummins Archeological Site, the local facies of till was deposited by the Superior Lobe flowing approximately north, as inferred from striae and fabric (Burwasser, 1977), with an estimated thickness of approx 1000 m (Fisher, Reech, and Langley, 1985). Till samples collected from beneath archeological deposits at the Cummins Site consist of 37.5 percent sand, 36.5 percent silt, and 26.0 percent clay. The till is thin over much of the site, due to the erosive action of postglacial Lakes Duluth and Minong, which covered the site between about 11,000 and 9500 yrs BP.

Wellsch Valley.—Sections in Wellsch Valley, Saskatchewan, contain up to 8 tills estimated to span nearly the whole of the Quaternary (Stalker, 1976). The samples collected for this study were taken from the WEV3 section (Mahaney and Stalker, 1988) in units 2, 4, 5, 6, and 7; only till 7 is considered to be of Wisconsinan age. All till units were deposited by continental ice originating in source areas located several thousand kilometers away to the northeast (allowing for variations in ice direction from north to east depending on individual glaciations). Sand-silt-clay ratios vary as follows: (sand = 18-43 percent, silt = 55-39 percent, and clay = 14-28 percent) across the till sequence.

METHODS

Over two hundred and fifty quartz sand samples were analyzed from Quaternary tills on Mount Kenya and from sites adjacent to Lake Superior (Ontario) and in Wellsch Valley (Saskatchewan). All quartz grains (between 20 and 30 grains per sample) were selected from the same fractions of very fine (63-125 μm) and fine (125-250 μm) sand, after pretreating the samples with H_2O_2 to remove organic matter and in some cases with sodium pyrophosphate to achieve deflocculation prior to particle size analysis (Bouyoucos, 1962; Day, 1965). All sand samples were sonified at low energy (to guard against fracturing preweathered grains) in distilled H_2O to remove clay particles. Standard particle size classes follow the Wentworth Scale of Folk (1968).

DISCUSSION

Quartz grains, often rich in inclusions, appear to have predominantly hydrothermal and/or volcanic origins. Abnormally high relative intensities of the 100 reflection in several quartz samples from Mount Kenya indicate an important proportion of secondary (chalcedonic) or low temperature quartz (Eslinger and others, 1973). This latter type of quartz, rarely observed under the polarizing microscope, occurs in devitrified volcanic glass along with quartz of hydrothermal origin in some of the Mount Kenya samples. Quartz grains from the Thunder Bay and Wellsch Valley areas are all of hydrothermal origin.

In Quaternary paleosols on Mount Kenya (fig. 1) quartz appears to be the main indicator of airfall influxes of finer silt and fine sand sediment (Vortisch, Mahaney, and Fecher, 1987; Mahaney, 1987). More than half the quartz grains are glacially crushed,[1] suggesting they have been reworked from glacial deposits by aeolian processes. While some of the sand[1] in the Thunder Bay and Wellsch Valley tills (figs. 2 and 3) may have been incorporated from previously exposed aeolian and/or fluviatile deposits, most of the samples are considered to have been entrained by ice directly from the nearby Laurentian Shield (Mahaney and Stalker, 1988). Samples collected at Thunder Bay from known aeolian and fluvial/lacustrine deposits showed striking differences in quartz sand grain morphology, particularly with respect to edge sharpness and angularity.

From the samples studied we selected a number of representative micrographs for analysis. The Mount Kenya samples (fig. 4A, B, C, D) show moderate relief characterized by sharp grain edges, subangular shapes, and only a few crushing planes. While grain shape and lower degrees of edge sharpness probably reflect short transport distances, the fewer parallel crushing planes (Krinsley and Takahashi, 1962; Hamilton and Krinsley, 1967; Krinsley and Donahue, 1968) are considered to reflect an overall low shear stress at the base of the mountain ice. Arc-shaped steps, although less common in the Mount Kenya sample suite, are considered to result from glacial abrasion (Krinsley and Takahashi, 1962).

The greater thickness of continental ice versus mountain ice might be expected to produce *at least* a twofold increase in shear stress at the base of the ice. While the increase in shear stress may not affect edge sharpness and clast relief on individual grains, it might affect the frequency with which crushing planes occur on quartz in the sand size fractions. Sand grains from the Thunder Bay area (fig. 5A, B, C, D) and Wellsch Valley (fig. 6A, B, C, D, E, F, G) show substantiall, greater angularity and extremely sharp-edged surfaces which tend to produce greater clast relief. Moreover, a threefold increase in parallel and conchoidal crushing planes indicates an increase in shear stress and mechanical abrasion, respectively.

[1] While it is not known exactly what the surface topography of the quartz grains was like after release from rocks at the localities studied, we assume some grains might contain fracture surfaces and relief features inherited from abrasion that occurred during weathering.

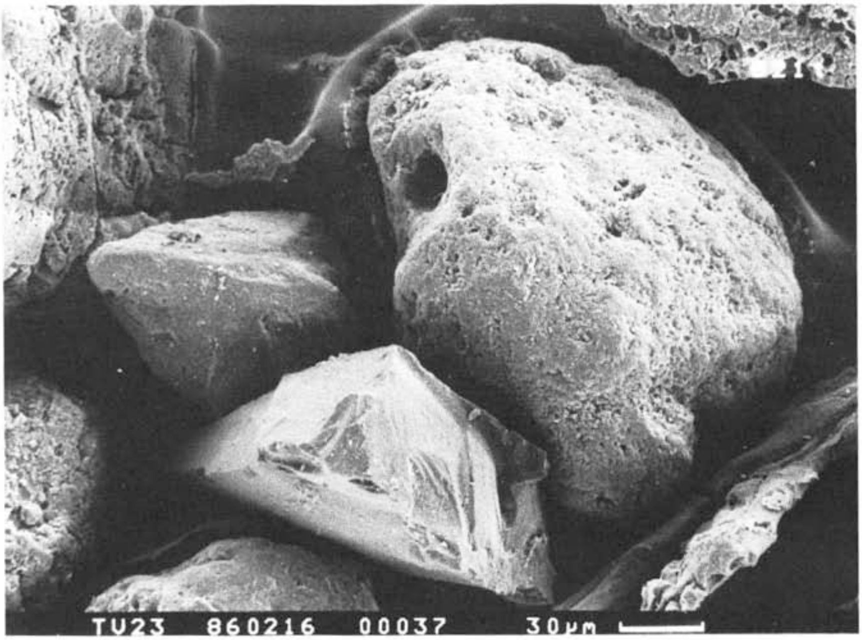
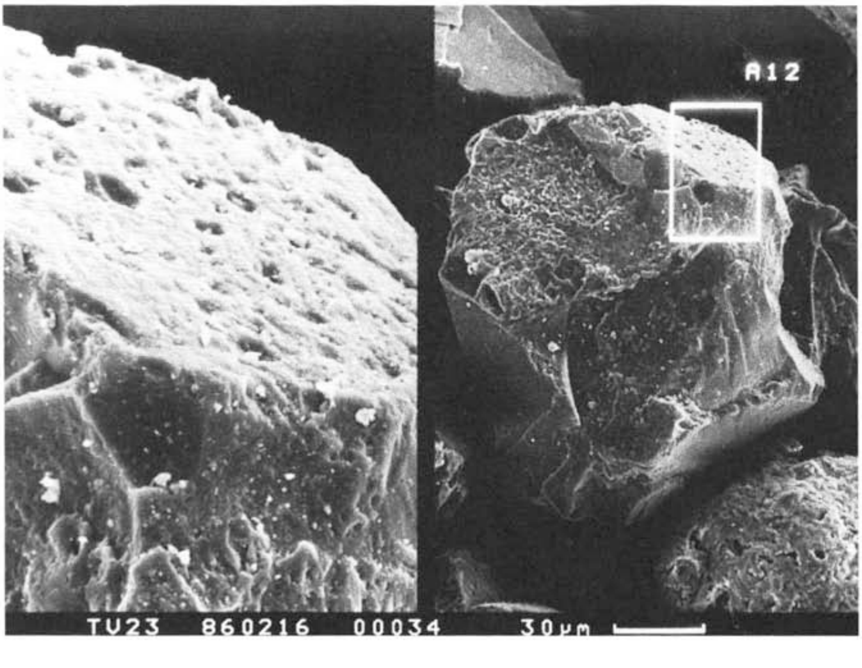


Fig. 4(A) Glacially-crushed quartz (lower center) in the B21t horizon of the post-Teleki (pre-Würm) loess at site TV23 (Vortisch, Mahaney, and Fecher, 1987) on Mount Kenya. The other grains consist mainly of weathered ash.



(B) Sub-angular grain of glacially crushed quartz with a remnant preweathered surface in the A12 horizon of the post-Teleki loess on Mount Kenya (site TV23) (Vortisch, Mahaney, and Fecher, 1987).

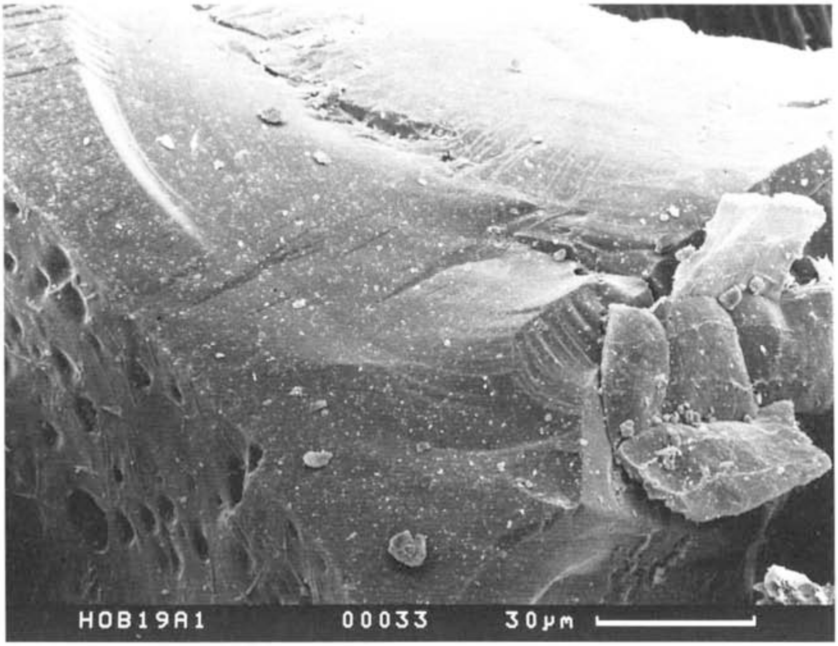
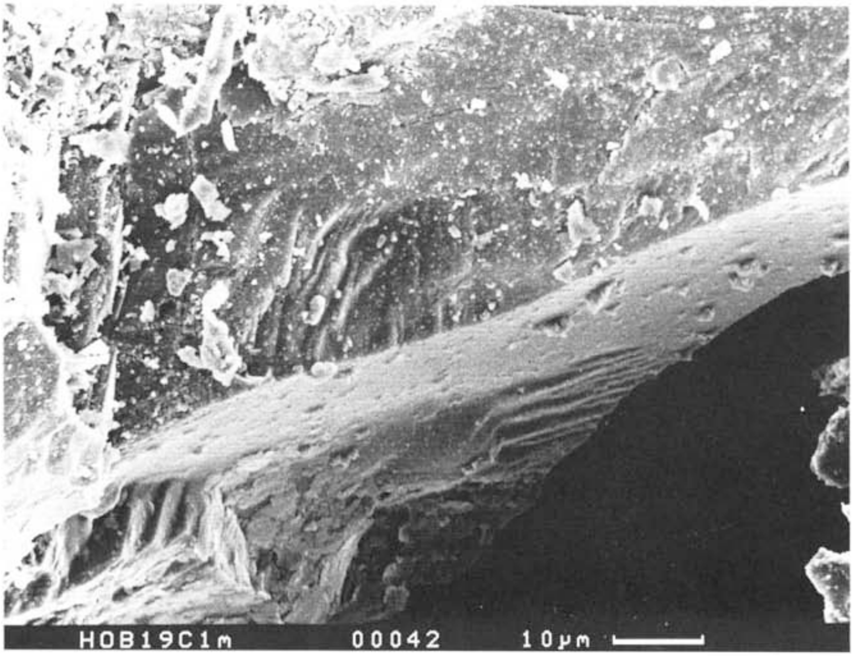


Fig. 4. (continued)

(C) Glacially-crushed quartz in pre-Teleki loess at site HOB19 in Hobley Valley. This grain has four areas of subparallel crushing planes and one small area of crescentic gouges. A prominent preweathered surface was not affected by glacial crushing (left of center) indicating that some grains in ice probably have limited contacts with one another inhibiting abrasion.



(D) Glacially-crushed surfaces in till equivalent with the Lake Ellis Glaciation (>730,000 yr BP) on Mount Kenya (Mahaney, Barendregt, and Vortisch, 1988) in Hobley Valley at site HOB19. Some subparallel crushing planes were subsequently affected by solution etching.

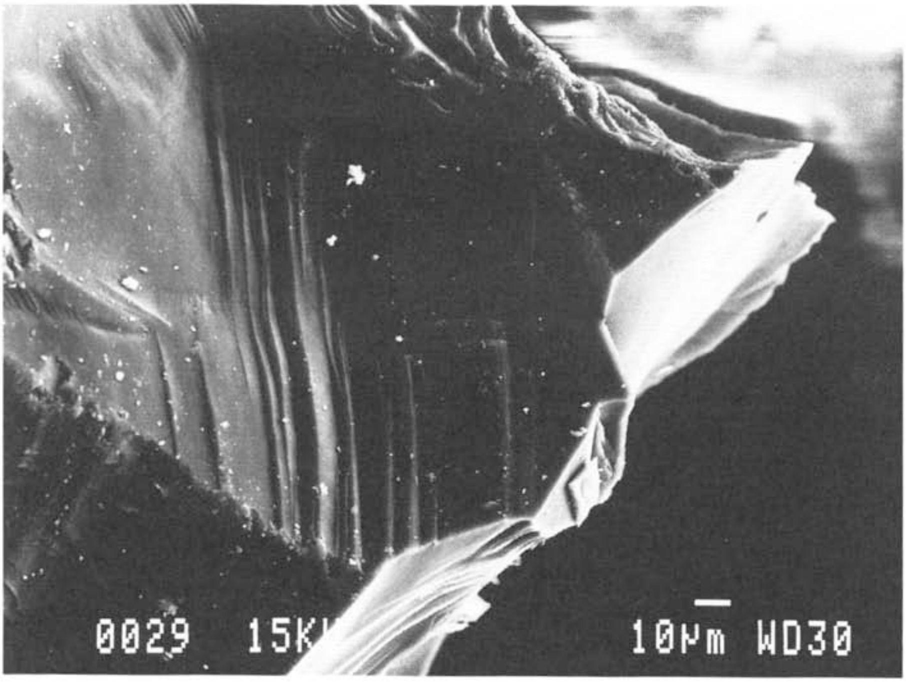
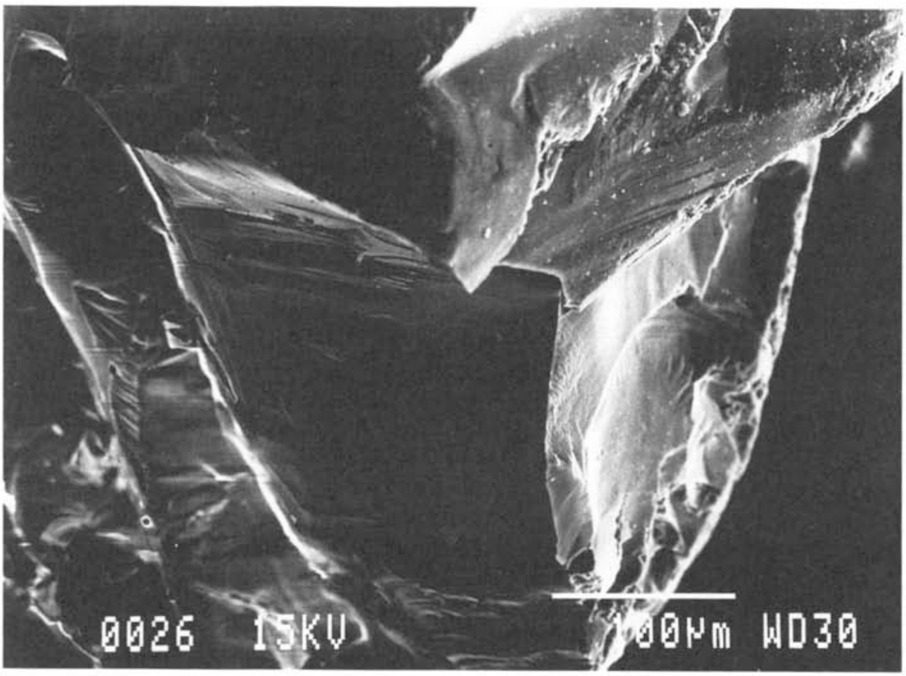


Fig. 5(A) Two areas of sub-parallel crushing planes on an angular quartz grain in Wisconsinan till deposited by the Superior Lobe.



(B) Angular quartz grain with glacially crushed features (subparallel planes) in till deposited by the Superior Lobe.

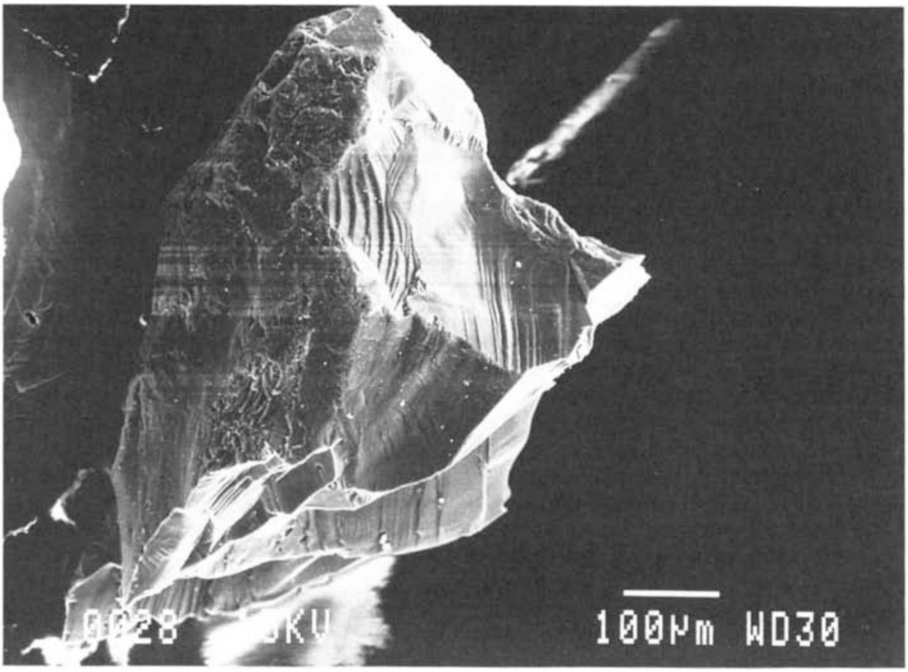
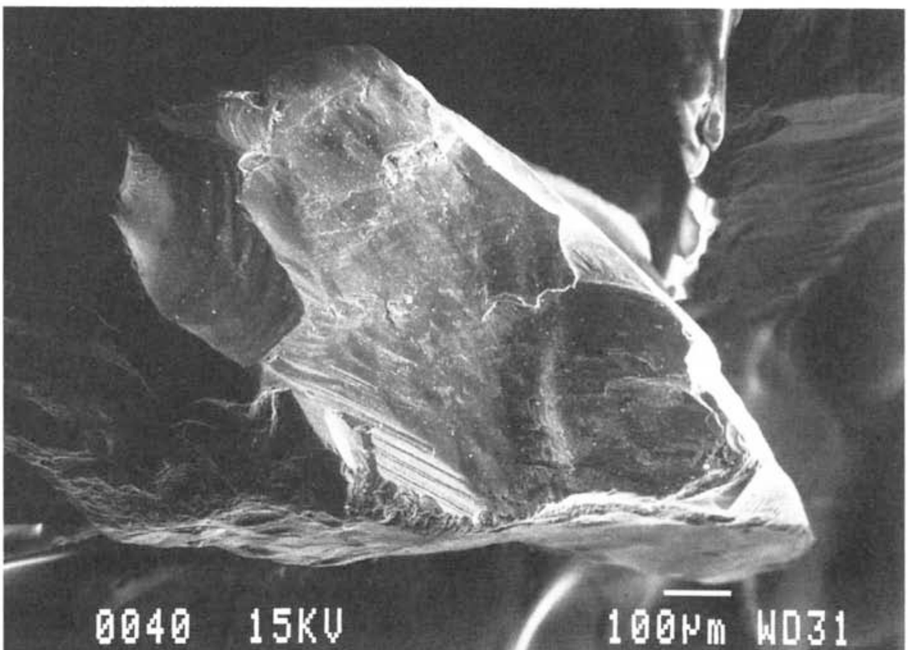


Fig. 5. (continued)
(C) Angular quartz grain (from Superior Lobe till) with glacially-crushed features on parts of three faces.



(D) Angular quartz grain (from Superior Lobe till) with subparallel crushing planes on one facet.

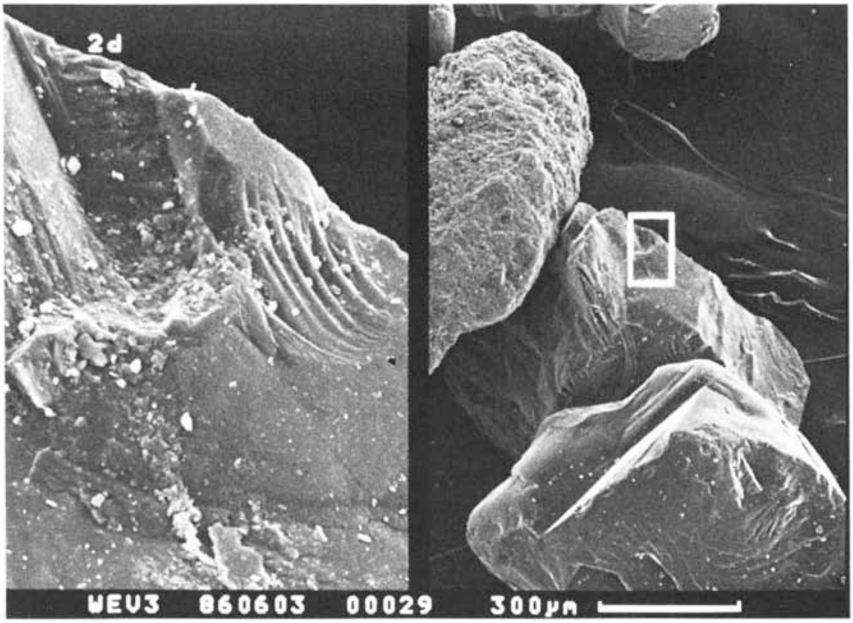
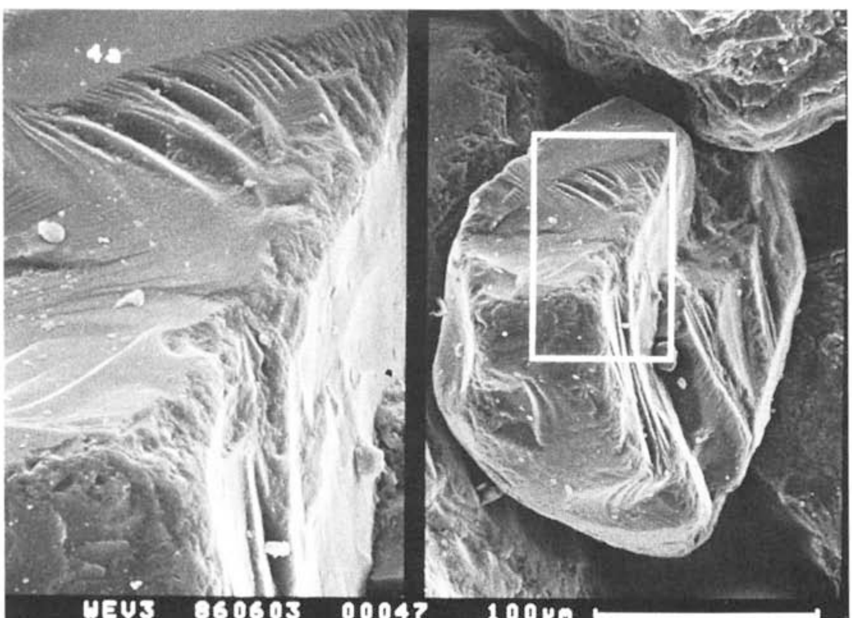


Fig. 6(A) Subrounded to subangular quartz grains in till 2d (early Wisconsinan), at North Cliff Section, Wellsch Valley, Saskatchewan.



(B) Multiple glacial crushing planes on quartz in till 4a (Middle Pleistocene), North Cliff Section, Wellsch Valley, Saskatchewan. Some subparallel planes appear to have been weathered.

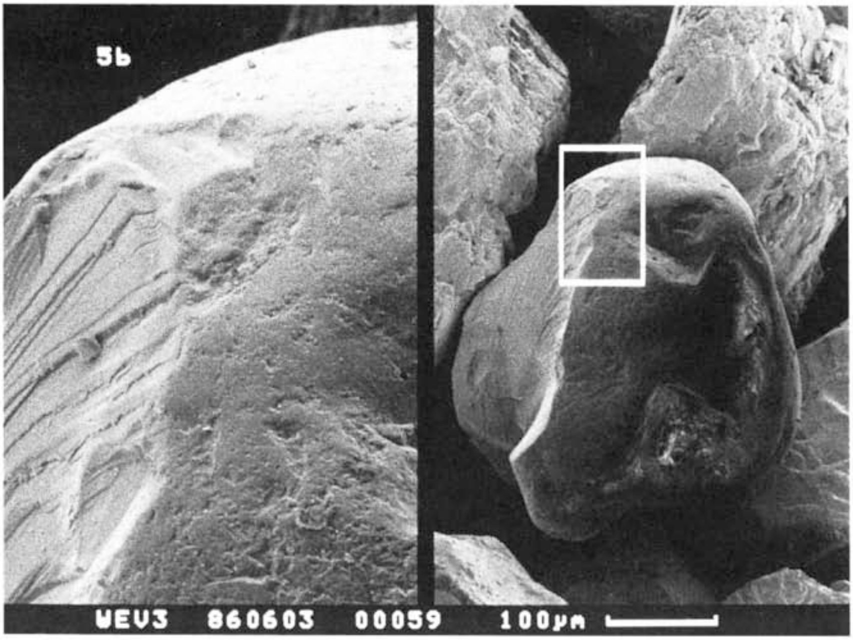
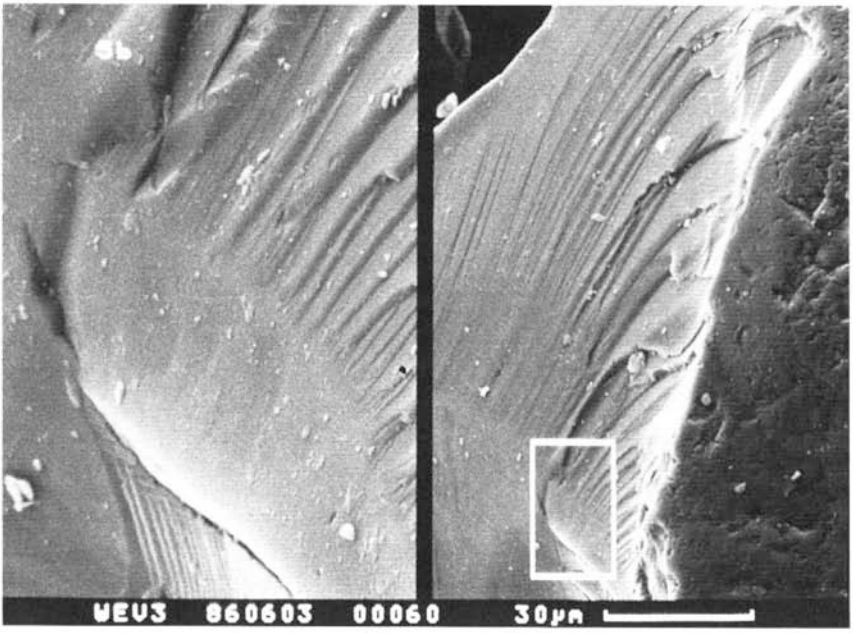


Fig. 6. (continued)

(C) Complex quartz grain in till 5b (Early Wisconsinan), North Cliff Section, Wellsch Valley, Saskatchewan. This grain was rounded by aeolian and/or fluvial action, slightly weathered, and later crushed.



(D) Enlargement in B showing multiple subparallel crushing planes.

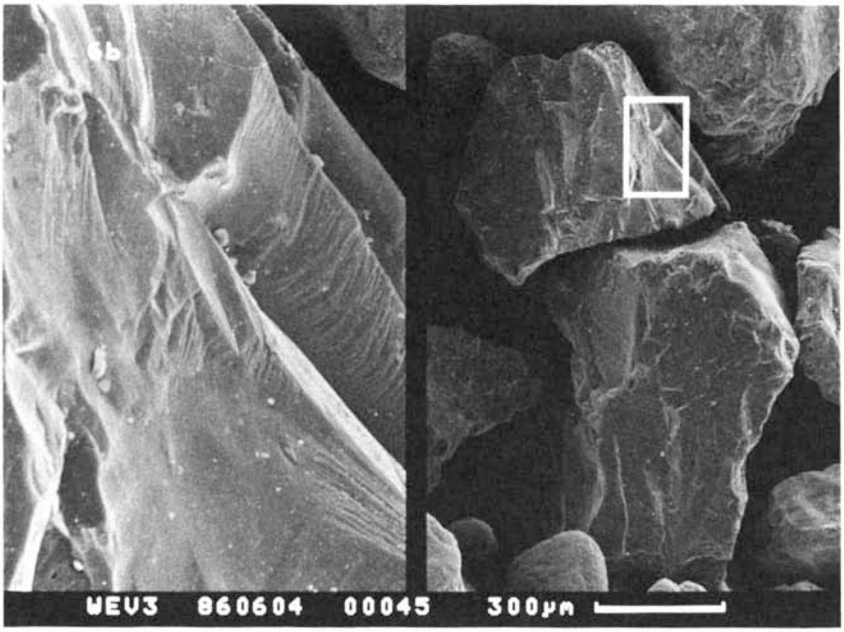
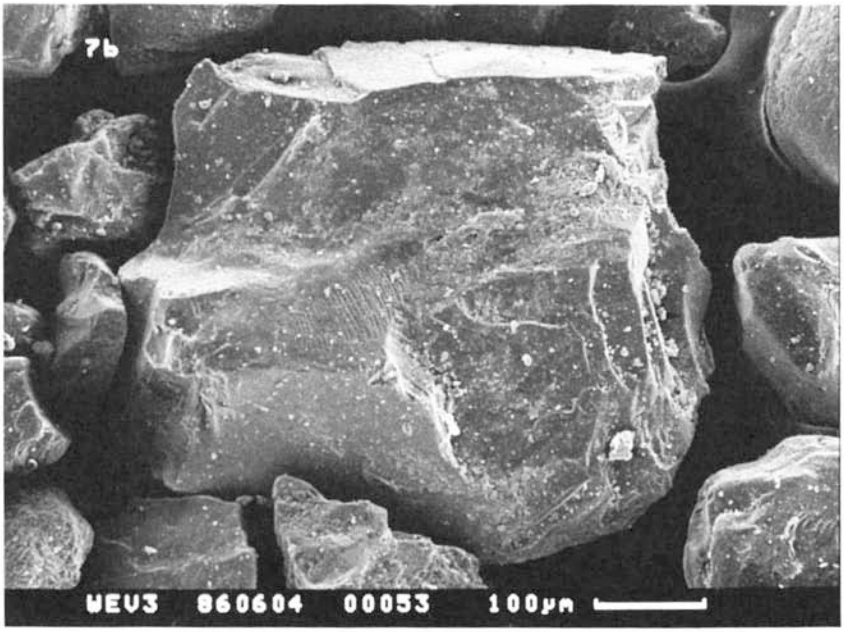


Fig. 6. (continued)

(E) Glacially-crushed quartz in till 6b (pre-Wisconsinan), North Cliff section, Wellsch Valley, Saskatchewan; enlargement shows microrelief of sharp-edged facets with multiple crushing planes.



(F) Subangular quartz grain in till 7b (middle Wisconsinan) in North Cliff section, Wellsch Valley, Saskatchewan, showing sharp facets.

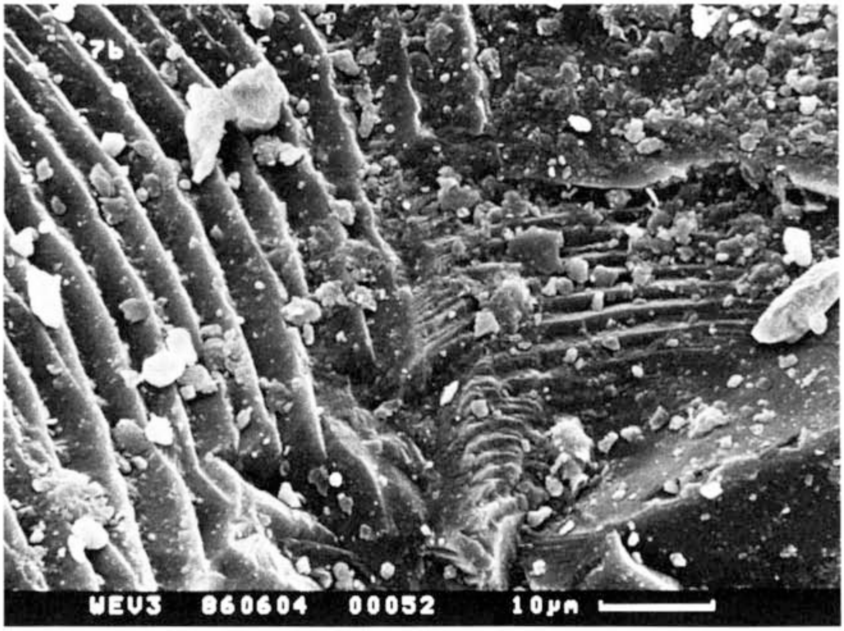


Fig. 6. (continued)
(G) Enlargement showing multiple crushing planes.

Our interpretations of glacially-induced textures discussed herein are as follows:

1. Very high relief and edge sharpness on grains affected by continental glaciation. Overall, nearly all glacially-crushed grains have higher relief when compared with grains in coastal and aeolian environments (Krinsley and Doornkamp, 1973). This was confirmed in our comparative analysis of dune and fluvial/lacustrine quartz samples from the Cummins site at Thunder Bay, Ontario.

2. Even though the mountain tills contain many coarse-grained particles (for example, pebbles and cobbles) relative to tills emplaced by continental glaciers, there appears to be little variation in the size of conchoidal fractures (as postulated by Krinsley and Donahue, 1968).

3. Subparallel steps noted by several workers (Krinsley and Takahashi, 1962; Krinsley and Doornkamp, 1973) appear common on most grains, but the frequency varies with the mode of glaciation.

4. Arc-shaped steps are most common on grains affected by continental glaciation and may be related to glacial abrasion and greater basal shear stress.

Textures 2 to 4 (table 1) have been produced experimentally by grinding crushed grains in ice on a quartz plate (Krinsley and Donahue, 1968). Along with the glacially crushed grains we noted occasional grains that appeared rounded and with "v" shapes (similar to those described by Krinsley and Donahue, 1968), perhaps caused by fluvial/lacustrine action, and without any of the characteristic glacial textures as well as some specimens with surfaces reflecting more complex paleoenvironmental histories.

A summary of surface features on sand grains of glacial origin is given in table 1. The common surface features include conchoidal fractures of variable size, curved grooves and scratches, straight grooves or scratches, sharp angular features, medium to high relief, subparallel crushing planes, and crescentic gouges. Features related to pre- and postdepositional weathering and aeolian/fluvial rounding are also included.

The grains studied here also have surface features similar to those reported by Margolis and Kennett (1971) from subantarctic deep-sea cores and by Whalley and Krinsley (1974) from glacial environments. Grains prepared in the laboratory to yield pseudo-glacial textures have been described by Margolis and Kennett (1971). These experimentally produced grains showed a greater number of curved and linear grooves relative to samples from glacial sediments, which is consistent with the interpretation of textures studied here. Because some of the grains summarized in table 1 have surfaces that do not show glacially-produced textures, we must conclude that primary and glacially-abraded quartz grains may sometimes display similar surface features (Margolis and Krinsley, 1973; Bull, 1981). The textures described in table 1 taken together appear useful as glacial paleoenvironmental indicators and as indicators of the relative shear stress and possibly transport distance factors in mountain versus continental ice.

CONCLUSIONS

The data suggest that profound differences in quartz sand grain morphology from differing glacial environments may result from lower

TABLE 1

Surface features on quartz grains

	Figure
1. Large-scale conchoidal fractures (>1 μg)	4C
2. Curved grooves or scratches	5A, 5C
3. Straight grooves or scratches	4A, 4B, 5A, 5C
4. Sharp angular features	5A, 5B, 5C, 5D, 6A, 6E, 6F, 6G
5. Rounded features	6A, 6C, 6D
6. Medium relief	4A, 4B
7. High relief	5B, 5C
8. Subparallel crushing planes	4A, 4B, 4C, 5A, 5B, 5C, 5D, 6A
9. Crescentic gouges	4B, 4C
10. Solution etching	4D, 6A, 6B
11. Preweathered surface	4B, 4C, 6C, 6D
12. Postdepositional weathering of crushing planes	6B
13. Precipitation features	4D, 6F, 6G
14. Adhering particles	4C, 5A, 6A, 6B, 6F, 6G

shear stresses and mechanical abrasion in thinner mountain ice compared with thicker continental glaciers. In general, the frequency of parallel crushing planes resulting from differential shear stress and conchoidal steps produced by differential mechanical abrasion were observed to increase markedly from alpine to continental till samples. Moreover, clast relief (including edge sharpness and angularity) became more pronounced in continental tills when compared with alpine samples. Because the number of samples studied was small, with only three field areas examined, we encourage other workers to test the relationships discussed in this report by analyzing quartz grains in the sand size fractions from other mountain and continental localities.

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