# Till-forming processes beneath parts of the Cordilleran Ice Sheet, British Columbia, Canada:
## *Macroscale and microscale evidence and a new statistical technique for analyzing microstructure data*

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### *Introduction*

This paper presents the first integrated macroscale and microscale examination of subgalcial till associated with the last-glacial (Fraser Glaciation) Cordilleran Ice Sheet (CIS). A new statistical approach to quantifying till micromorphology (multivariate hierarchical cluster analysis for compositional data) is described and implemented. Till macrostructures, pebble (macro-) fabrics and microstructures support previous assertions that primary till in this region formed through a combination of lodgement and deformation processes in a temperate subglacial environment. Microscale observations suggest that subglacial till below the CIS experienced both ductile and brittle deformation, including grain rotation and squeeze flow of sediment between grains under moist conditions, and micoshearing, grain stacking and grain fracturing under well-drained conditions. Cluster analysis of microstructure data and qualitative observations made from thin sections suggest that the relative frequency of countable microstructures in this till is influenced by topography in relation to ice-flow direction (bed drainage conditions) as well as by the frequency and distribution of voids in the till matrix and skeletal grain shapes.

*Micromorphological analysis* included a qualitative assessment of microscale features as well as quantitative analysis of a subset of discrete microstructure types. These included turbates, necking structures, grain lineations, grain stacks and crushed grains. Subjectivity was minimized by restricting our observations to discrete (countable) microstructures using a set of strict criteria (Table 1). Multivariate hierarchical cluster analysis was then applied to the data to detect levels of similarity or difference between thin sections that may be indicative of spatial and/or temporal variations in subglacial conditions. When applied to a suite of thin sections from a single till unit over a wide geographic area, this technique can expose relationships that may exist between till micromorphology and the geomorphology of the study area. A limitation of this approach is that it is dependent on the relative abundance of certain microstructures, which, in turn, is somewhat dependent on till granulometry and void spacing.

*Macroscale observations* included an assessment of till texture and macroscale deformation structures (shear and fracture planes) both in the till and in the underlying substrate, the presence (or absence) and orientation (or trend) of glacigenic wear features on pebbles, and the strength, shape and orientation of macrofabrics (Fig. 1).

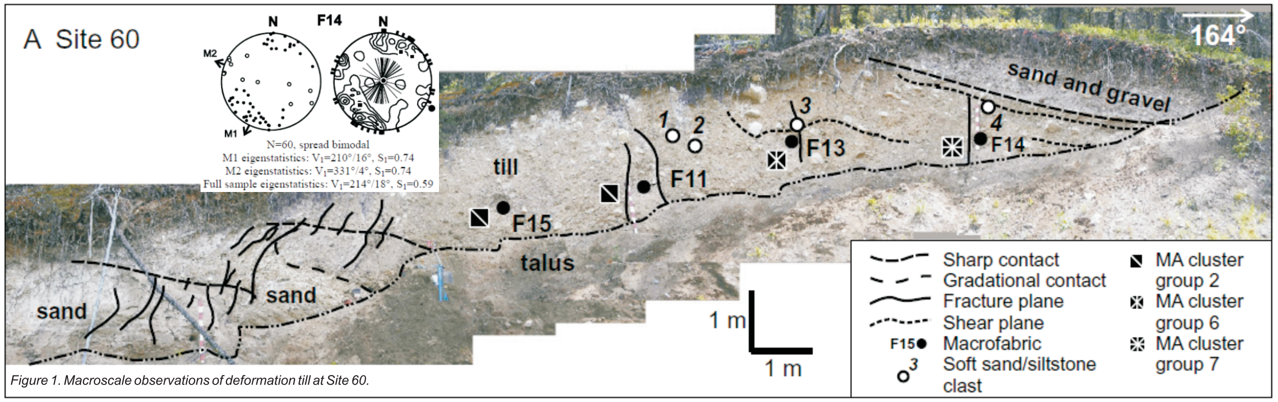


*Figure 1. Macroscale observations of deformation till at Site 60.*

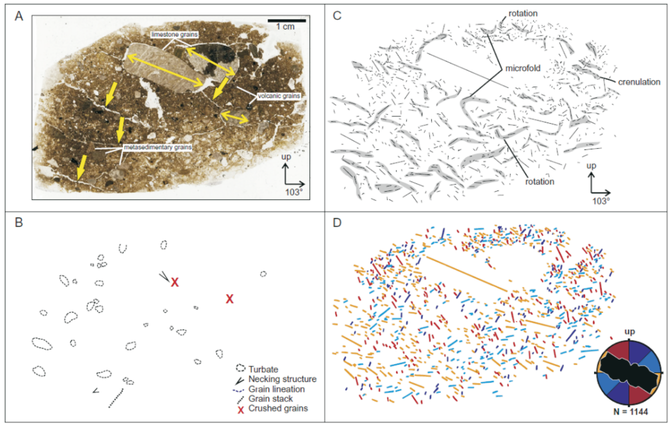
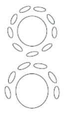
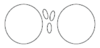
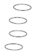
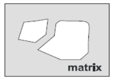
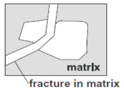


*Figure 2. Microphotograph (A) and microstructure map (B) of thin section S20F7 from Site 20. Microfabric domains are highlighted in 'C'. In 'D', grain orientations are colour-coded according to their orientation, and the four orientation classes are shown in the rose diagram.*

*Table 1.* Criteria for the identification of discrete microstructures.

| Microstructure | Criteria[1] | Accepted | Not accepted |
|---|---|---|---|
| Turbates | Turbates were identified based on the circular arrangement of skeletal grains (cf. van der Meer 1993; Larsen *et al.* 2007). The majority of elongate grains of a similar size must be subparallel to the edges of the core stone on a minimum of 3 out of 4 sides. Turbate structures without core stones were rarely observed, but those that were counted consisted of encircling grains, with inter-particle distances smaller than the dimensions of the particles along the path of the circle. |  |  |
| Necking structures | Includes preferred alignment of small grains between two adjacent large grains (sizes are relative) (cf. Larsen *et al.* 2006a). Counted necking structures did not include aligned particles that were part of turbates. |  |  |
| Grain lineations | Identified by a minimum of three elongate grains aligned end-to-end (cf. Hiemstra & Rijsdijk 2003; Larsen *et al.* 2007). The distance between grains must be less than their lengths along the path of the lineation. |  |  |
| Grain stacks | Includes a series of a minimum of four grains forming a subvertical stack (cf. Larsen *et al.* 2007). Only the flat edges (as opposed to corners) of the grains face each other. The distances between these grains must be smaller than their 'along-path' dimensions. |  |  |
| Crushed or broken grains | Evidence of crushing or breakage must include separate pieces of the same grain suspended in the matrix (cf. Larsen *et al.* 2007). Pieces of a broken grain on either side of a fracture in the matrix were not included to avoid counting grains that may have been fractured during thin section grinding. |  matrix |  matrix<br>fracture in matrix |

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[1]Owing to the lack of birefringent clays and the clast-rich nature of the till, microstructure identification relied primarily on skeletal grain arrangements. Plasmic fabrics (e.g. Brewer 1976; Hiemstra & Rijsdijk 2003; Thomason & Iverson 2006) were not used to identify microstructures. See text for details.

### *Results*

Cluster analysis seems to support previously proposed drainage conditions: till thin sections from topographically constrained areas are typically dominated by ductile-type microstructures (turbates, necking structures), whereas thin sections from the topographically unconstrained plateaus are dominated by brittle-type microstructures, as expected under better-drained subglacial conditions (Fig. 4). However, examination of the till micromorphology on the plateaus suggests that the frequency and distribution of voids in the till matrix, till texture and skeletal grain shapes may have adversely affected the preservation of microstructures in these areas, skewing the results.

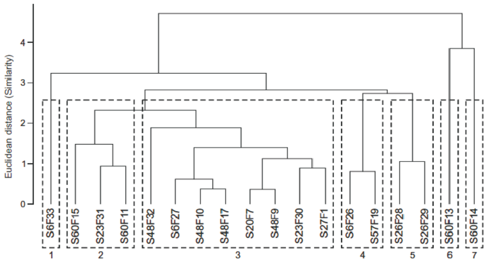

*Figure 3. A dendrogram showing cluster analysis results. At a similarity level of 2.5, all thin sections fall into one of 7 groups.*

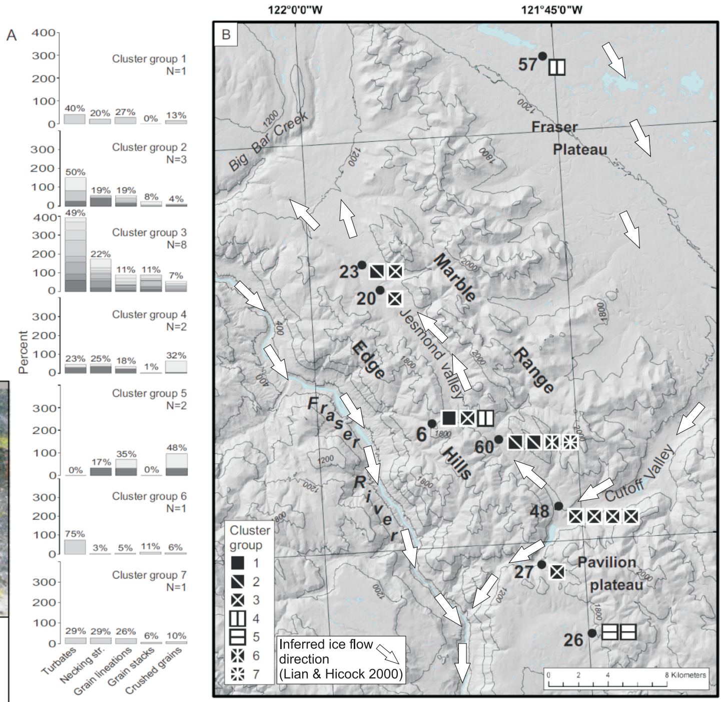

*Figure 4. A)Stacked bar plots for each cluster group in Figure 3. The relative proportions of turbates, necking structures, grain lineations, grain stacks and crushed grains for each thin section are shown as a single layer in the stack. 'N' is the total number of thin sections in each group. B) The geography of MA cluster groups for all sites examined. Cluster groups comprising at least 50% of 'ductile'-type microstructures are shown as black-filled symbols. All others are white-filled symbols.*