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Quartz ribbons in high grade granite gneiss: modifications of dynamically formed quartz *c*-axis preferred orientation by oriented grain growth*

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Abstract—Quartz ribbons form a well-defined *LS* fabric in granitic gneisses sheared and metamorphosed in the upper-amphibolite facies. Boundaries of quartz grains are smooth and sub-perpendicular to ribbon walls, suggesting post-deformational growth, whereas *c*-axes display asymmetric girdle patterns consistent with the sense of shear indicated by mesoscopic fabrics. Subdivision of the microfabrics according to the proportion of ribbon length occupied by individual grains indicates that the *c*-axes of relatively short grains exhibit a cross-girdle pattern similar to that of the whole sample. Longer grains reproduce elements of the pattern of the short grains, suggesting that oriented grain growth occurred. Grain boundary mobility, which clearly ended in a post-deformational static regime, probably began during dynamic recrystallization. Owing to space limitations imposed by the feldspathic matrix, grain growth in the ribbons ceased before the initial dynamic fabric was erased. In summary, this study shows that the *c*-axes pattern of longer grains within quartz ribbons reproduces part of the dynamically formed pattern of the shorter grains, reflecting an oriented grain growth which concluded in a static episode, although possibly initiated in the dynamic regime.

INTRODUCTION

QUARTZ ribbons, similar to those described as "polycrystalline Type 3 ribbons" by Boullier & Bouchez (1978), are common in upper amphibolite facies granitoid gneisses from near the northwestern margin of the Central Metasedimentary Belt of the Grenville Province in southern Ontario. This contribution presents evidence that an important stage in microfabric development is marked by oriented metadynamic grain growth, during which elements of syntectonically formed *c*-axis preferred orientation are preserved.

Setting

The quartz-rich rocks under consideration are from north of Cardiff, Ontario, and lie on the south side of a broad zone of southeast dipping, generally highly strained gneisses, which follows the northern boundary of the Central Metasedimentary Belt. Samples come from three locations within a 5 km interval along strike. The zone of highly strained gneiss is considered to be the locus of deep-seated ductile thrusting northwestward of the metamorphosed supracrustal rocks onto older rocks of the Central Gneiss Belt (Culshaw 1983, Culshaw *et al.* 1983). A prominent stretching lineation lies parallel to the inferred direction of thrusting.

Granite gneiss forms layers, ranging in thickness from less than one metre to greater than a hundred metres, interleaved with supracrustal rocks, including quartzites which display exaggerated grain growth of microstructures of their quartz grains (Wilson 1973). The granite gneiss has a strong planar-linear fabric, with a *k* value (Flinn 1962) of around 1, defined by hornblende–biotite clusters and attenuated blade-like quartz aggregates. The quartz, which forms up to 30% of the rock, is set in a fine-grained matrix of microcline and albite.

Methods

Sections were cut and *c*-axes measured in both the *XZ* and *YZ* planes of the structural framework (Fig. 1). In

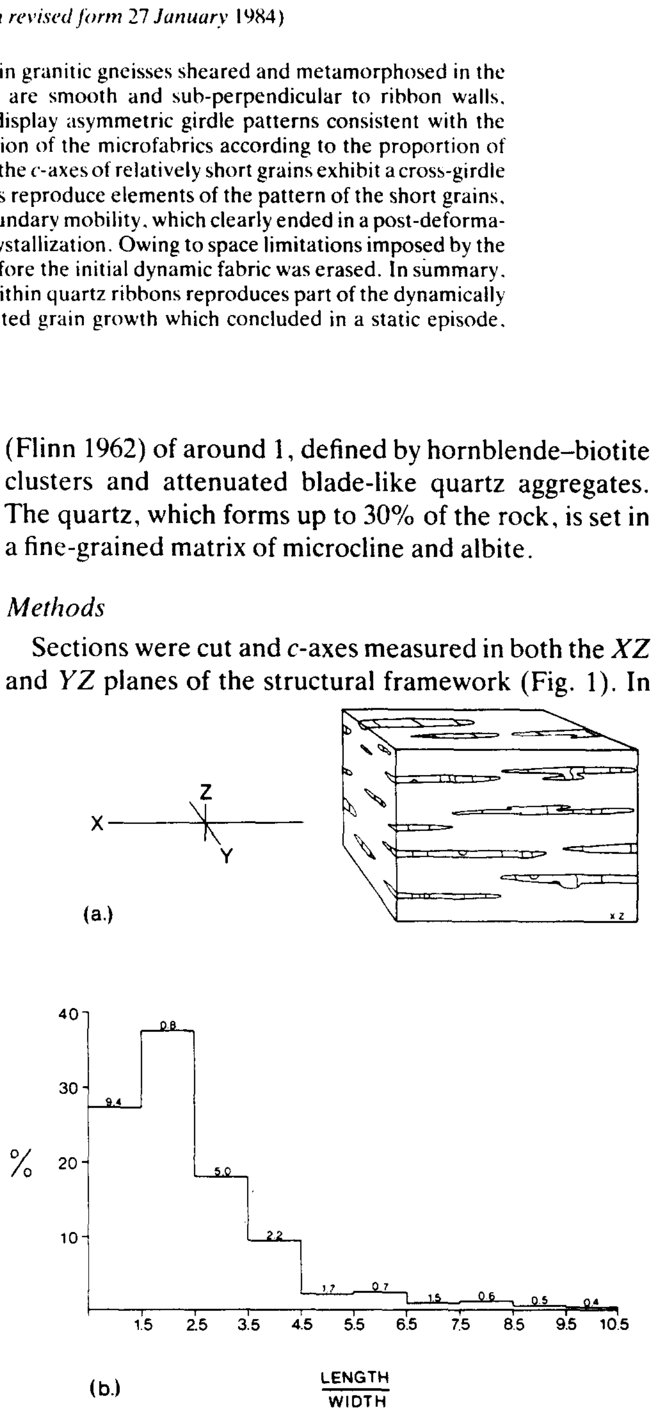

Fig. 1. Summary of fabric in granite gneiss from north of Cardiff, Ontario. (a) Mesoscopic fabric of quartz ribbons in a feldspathic matrix. (b) Frequency distribution of aspect ratios, measured in *XZ* section, of single grains from quartz ribbons; approximately 90% of the grains have length to width ratios of less than 4.5. Mean of seven samples, 1327 grains in total; standard deviation for each class is indicated above the appropriate column.

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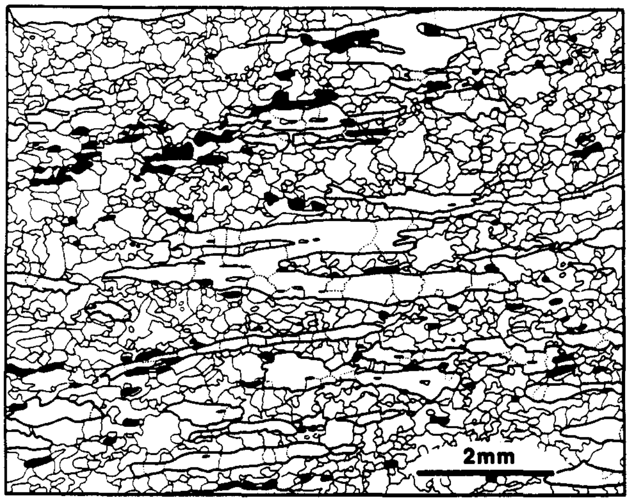

Fig. 2. Drawing from a photomicrograph of a quartz ribbon in a granite gneiss from north of Cardiff, Ontario. Sample 1691B, XZ section. Microcline and albite subequal in fine-grained matrix. Hornblende, biotite and opaques, black; quartz–feldspar boundaries, heavy lines; feldspar–feldspar boundaries, light lines; quartz–quartz boundaries dotted.

preferred orientation analysis the c-axis of every quartz grain present in the section was measured. Orientation diagrams were contoured using a counting circle $(100/N)\%$ of the net area (where N is the number of data), as recommended by Starkey (1977).

MICROSTRUCTURE

Approximately 15–20% of the ribbons consist of single grains of varied aspect ratios. The polycrystalline ribbons, generally one grain thick, are commonly composed of three or more grains. Although in the XZ section very elongate grains may account for most of the area of the ribbons, stubby grains with low aspect ratios are far more common (Fig. 1b).

Grains within the ribbons are sub-rectangular in shape and usually composed of transecting elongate subgrains with small mutual misorientations. Quartz–quartz grain boundaries are quite smooth and tend to lie perpendicular to the long axis of ribbons (Fig. 2). Elongate feldspar grains lie both on the rare quartz–quartz boundaries which are oriented parallel to the long axis of the quartz grains and within the quartz grains.

C-AXIS PREFERRED ORIENTATIONS

C-axis patterns measured in the XZ plane differ from those measured in the YZ plane. This is shown both in individual samples (Fig. 3) and in a synoptic diagram constructed from several samples (Fig. 4). The individual XZ patterns display variably developed crossed girdles which have a wide opening angle. The synoptic XZ diagram shows a single weakly developed girdle lying parallel to one of the crossed girdles shown in Fig. 3 and markedly oblique to the lineation (X). The

Table 1. Comparison of total combined lengths of grains with number of grains in particular aspect ratio present in XZ thin sections; expressed, respectively, as percentages of total length, measured parallel to X, of all ribbons ($\% L_{tot}$) and of total number of grains of all sizes ($\% N_{tot}$); means of six samples

L/W	0–1.49	1.50–2.49	2.50–3.49	3.50–4.49	4.50–10.0
$\% L_{tot}$	15.01	28.32	20.66	13.88	22.17
S.D	6.46	3.25	2.94	2.25	5.91
$\% N_{tot}$	25.75	36.79	17.94	9.58	9.92
S.D.	9.29	0.93	4.52	2.21	4.6
$\frac{\% L_{tot}}{\% N_{tot}}$	0.58	0.77	1.15	1.45	2.24

YZ pattern for individual samples and for the synoptic diagram is a single girdle approximately perpendicular (i.e. close to YZ) or somewhat oblique to the lineation in the same sense as the single girdle of the XZ synoptic diagram. Although c-axes for individual samples measured in both XZ and YZ do not show a strong preferred orientation, the synoptic YZ pattern exhibits a single pronounced cluster about the Y structural axis.

It is apparent from the distribution of grain aspect ratios (Fig. 1b) that the XZ section will preferentially sample the stubbier grains. On the other hand, the more elongate grains, although fewer in number than the stubbier ones, comprise a relatively large proportion of the total combined lengths of the ribbons (Table 1). The YZ section, which lies perpendicular to the ribbons' lengths, will therefore sample more than the XZ section of these grains which form the highest proportion of the ribbons' lengths. Then, the contrast between the c-axis patterns for the YZ and XZ sections indicates that the shorter and longer grains differ in crystallographic orientation.

The proposed difference in c-axis preferred orientation has been checked by plotting c-axes, measured in the XZ plane, with respect to the proportion which an individual grain forms of the host ribbon's length (Fig. 5). In this plot the smaller grains (0–30% of the length of the host ribbon) display crudely defined crossed girdles. As expected from the predominance of these grains, 46% of the whole population of quartz grains, the pattern resembles that of the total sample (0–100%). The fewer grains (24% of the whole) of intermediate length (31–60%) display a pattern which has elements in common with those of both the shorter and longer grains. For the longest grains (91–100%), which constitute 23% of the whole grain population, only one full girdle is present, but clusters of axes remain near to the other; the complete girdle lies slightly oblique to the YZ plane. Finally, for each category of grain size, there is a concentration of c-axes close to Z. The girdle retained, inclined towards geographic southeast, is similar in orientation to those from the YZ sections in accordance with the suggestion that the latter sections preferentially intersect the longer grains.

The direction of inclination towards X within the XZ plane of the single c-axis girdle of both the synoptic XZ diagram and the diagram of the longer grains is in agreement with the suggested regional shear sense,

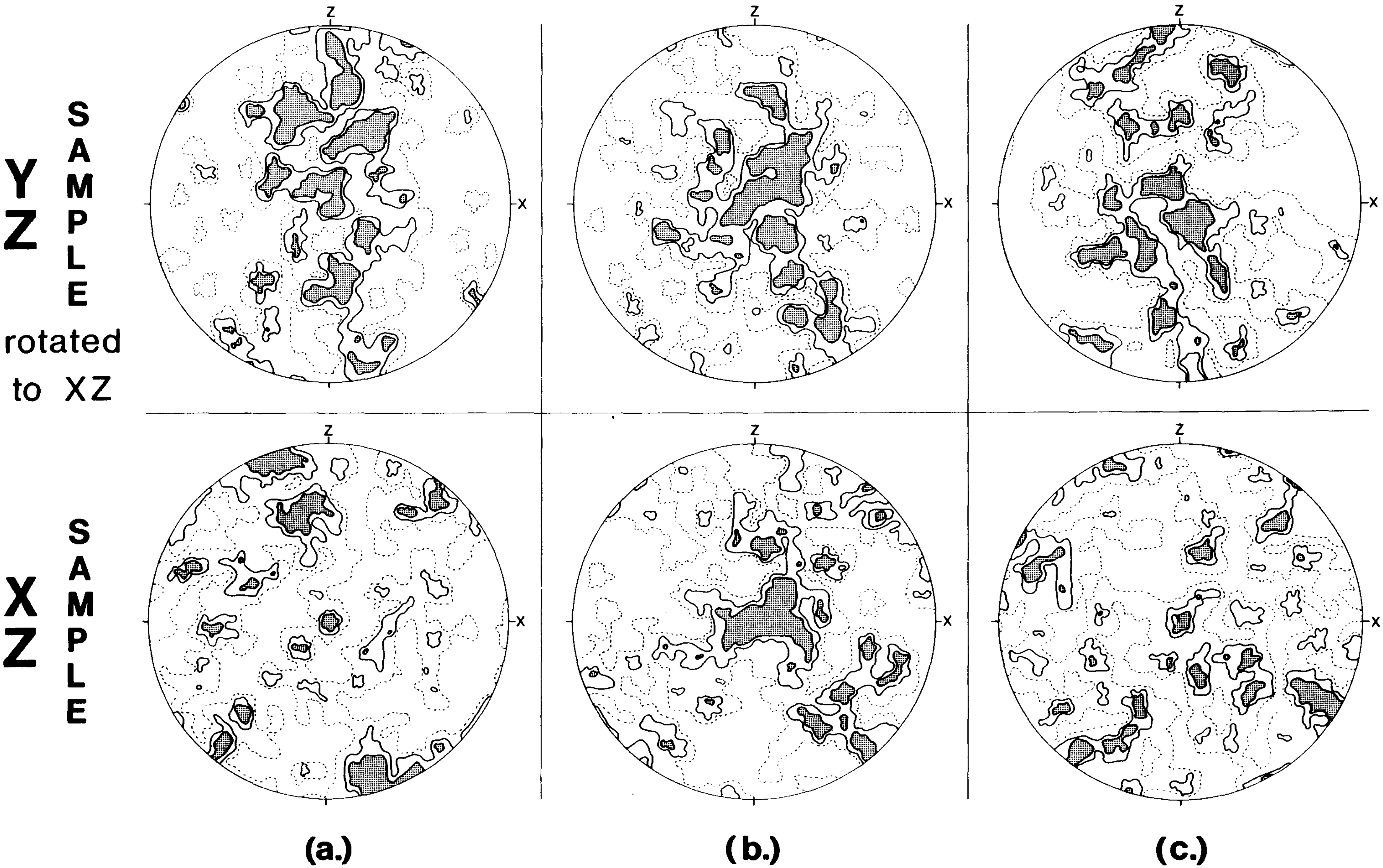

Fig. 3. Comparison of quartz ribbon *c*-axis orientations measured in *YZ* and *XZ* thin sections in three samples of granite gneiss from Cardiff, Ontario. All data presented in the *XZ* plane, foliation dips gently southeast which is to the right in the figure. Contours at 1, 2 and 3%/0.5% area. Sample numbers: (a) 497C, (b) 24101B, (c) 25101B.

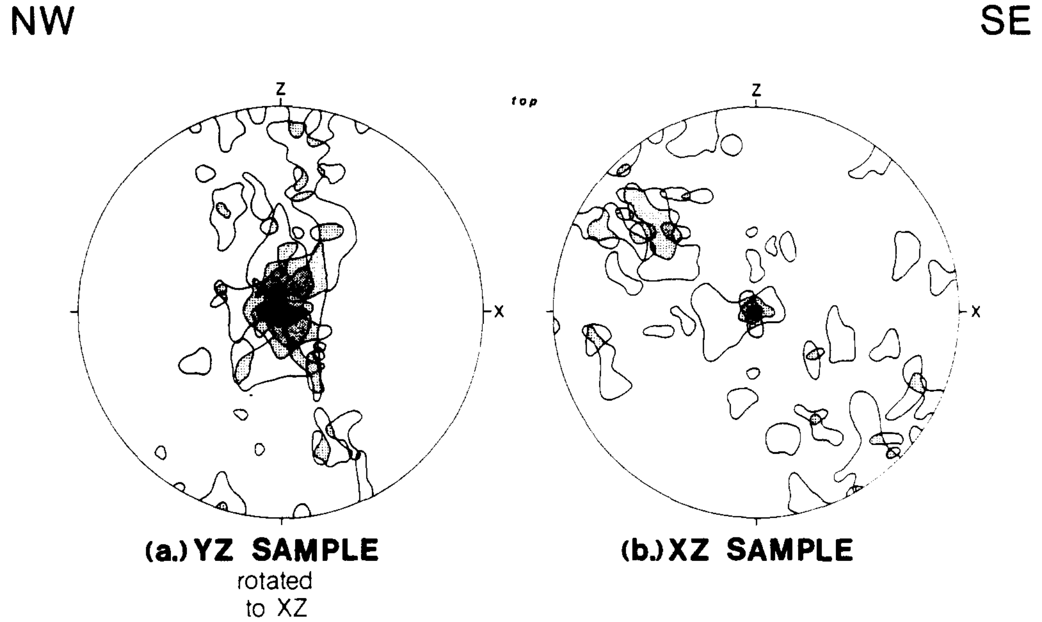

Fig. 4. Synoptic diagram of *c*-axis preferred orientations measured in *YZ* and *XZ* thin sections for quartz ribbons in granite gneiss from north of Cardiff, Ontario. 3%/1% area contours are shown for six samples in (a) and nine samples in (b). 1, 2 and 3-fold overlaps indicated by increasing density of shading. All data presented in *XZ* section, southeast to right.

derived independently from mesoscopic structures, of upper layers moving northwest (Culshaw 1983, Culshaw *et al.* 1983).

DISCUSSION

Boullier & Bouchez (1978) and Spry (1969) discussed similar microstructures and suggest that (i) static grain growth is important in microstructural development, although, as the first authors suggest, it will not necessarily result in the loss of the previously formed lattice preferred orientation; (ii) growth takes place by movement of boundaries parallel to the ribbon length and (iii) grains with favoured orientations may grow at the expense of others.

Within the ribbons the smooth morphology of the quartz–quartz boundaries and their alignment perpendicular to the elongation of the ribbons are to be expected if growth occurred during secondary recrystallization in a static regime. In fact, the development of smooth boundaries across the ribbons reduces the area and thus the energy of the boundaries; the direction of grain boundary migration parallel to the ribbons is naturally constrained by the geometry of the feldspathic walls of the ribbons. Another argument for an episode of static grain boundary migration in the ribbons is given circumstantially by the close spatial association of the granite gneisses with quartzites in which an exaggerated grain growth microstructure is present. Such a microstructure, which results in a drastic reduction of grain boundary area, is usually considered as forming during the end stage of secondary recrystallization (Wilson 1973, White 1976, Bouchez & Pêcher 1981).

A case may be made that this episode of static grain growth closed a period of oriented grain growth initiated in the dynamic regime. By oriented grain growth it is implied that some grains have a greater growth rate by virtue of their orientations than other grains with less favoured orientations. In the case of the quartz ribbons the hypothesis that some grains grew at the expense of others is supported by the presence of a range of grain sizes from long to short grains. The contention that oriented grain growth took place is founded on the fact that the longer grains have specific lattice preferred orientations which appear to be a development of part of the pattern displayed by the shorter grains. The *c*-axes distribution of the smaller grains apparently reflects the earlier kinematic history since it has monoclinic symmetry with respect to the fabric, which clearly results from lattice orientation during shear strain, the sense of which can be independently deduced from other arguments. It is less clear why the static grain growth does not continue and eventually destroy the dynamic lattice preferred orientation. In the adjacent quartzites, for example, grain boundary mobility was not impeded by non-quartz phases. In this case three-dimensional grain growth may have developed until all vestiges of the former lattice preferred orientation were erased (Wilson 1973, Culshaw 1983). By way of contrast, in the quartz ribbons, if grain boundary mobility perpendicular to the ribbon walls was stopped relatively soon after initiation due to space limitations imposed by the feldspathic matrix, then the initial dynamic *c*-axis preferred orientation may be preserved. Although it is noteworthy that this destruction of the lattice preferred orientation need not always take place because in the experimental annealing of ice (Wilson 1982) and quartz (Green *et al.* 1970) which have been deformed at high temperature, the dynamic lattice preferred orientation remains little changed or is strengthened, and it appears that the static annealing in these experiments is metadynamic recrystallization in the sense described here.

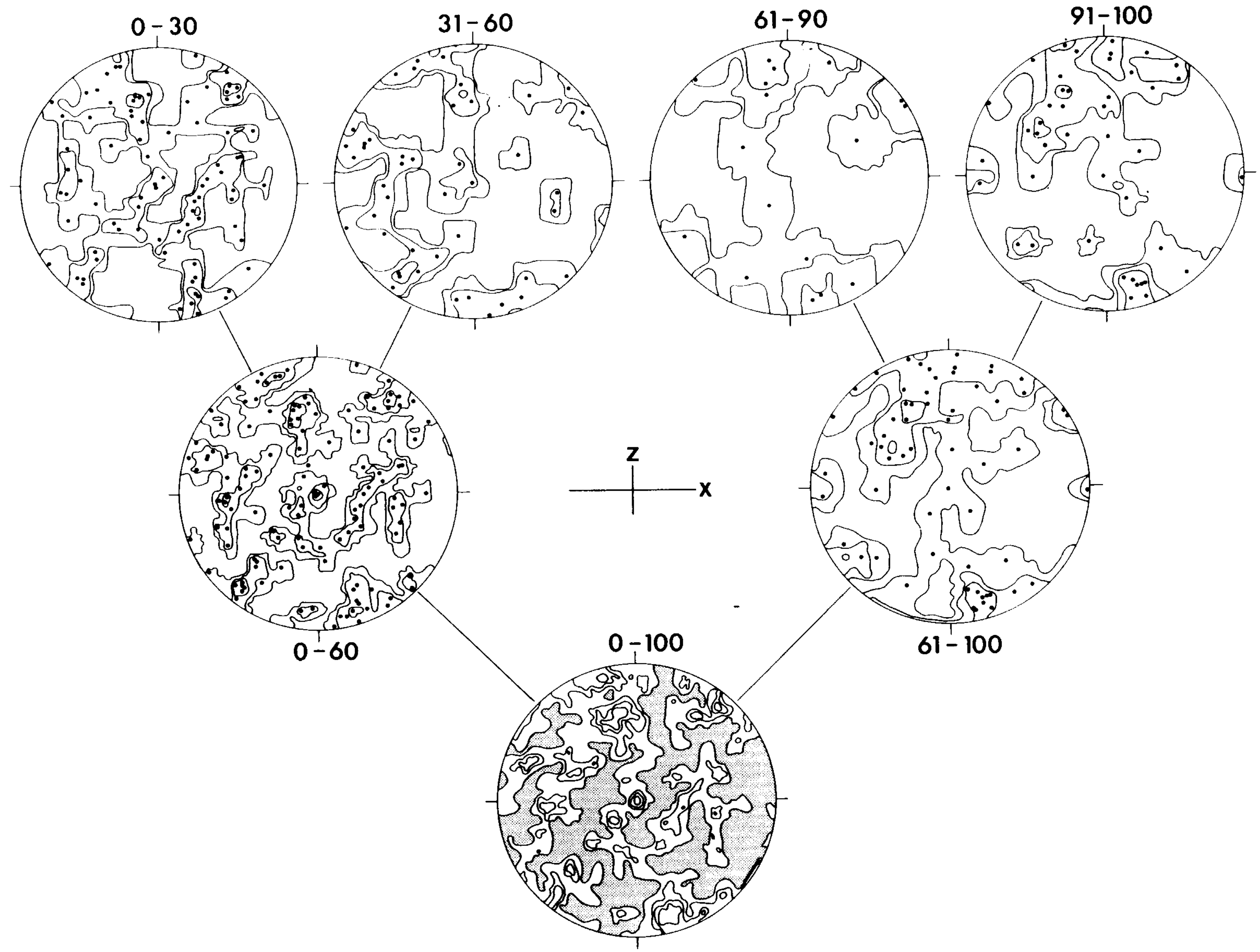

Fig. 5. Variation of c-axis preferred orientation of quartz grains with respect to their length. The different ranges of length (shown for each diagram) are expressed as a percentage of the host ribbon's length measured in the XZ section. Granite gneiss from north of Cardiff, Ontario, sample 497C. Diagrams with poles: contours at 1, 2 and 3 points/(100/N)% of area (where N is number of data). Diagram with shaded pole-free area: contours at 1, 2, 3 and 4 points/(100/N)% of area.

In summary, this microstructural and *c*-axis preferred orientation study is considered to illustrate the case, which is probably common in high-temperature quartz tectonites, of metadynamic grain growth, according to Sellars' (1978) terminology, reconciling both static and dynamic stages of the history. Such an oriented grain growth may be in part analogous to that described in dynamically recrystallizing camphor by Urai & Humphreys (1981) where the grains which grew were those with planes of easiest slip lying in the flow plane.

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REFERENCES

Beck, P. A. 1953. Notes on the theory of annealing textures. *Acta Metallurgica* **1**, 230–233.

Bouchez, J-L & Pêcher, A. 1981. The Himalayan main central thrust pile and its quartz-rich tectonites in central Nepal. *Tectonophysics* **78**, 23–60.

Boullier, A-M & Bouchez, J-L. 1978. Le quartz en rubans dans les mylonites. *Bull. Soc. géol. Fr.* **22**, 253–262.

Culshaw, N. G. 1983. Geology, structure and microfabric of Grenville Rocks, Cardiff Area, Ontario. Unpublished Ph.D. thesis, University of Ottawa.

Culshaw, N. G., Davidson, A. & Nadeau, L. 1983. Structural subdivisions of the Grenville Province in the Parry Sound-Algonquin Region, Ontario. In: Current Research, Part B, *Geol. Surv. Can., Paper* **83-1B**, 243–252.

Flinn, D. 1962. On folding during three dimensional progressive deformation. *Q. Jl geol. Soc. Lond.* **118**, 385–433.

Green, H. V., Griggs, D. T. & Christie, J. M. 1970. Syntectonic and annealing recrystallization of fine grained quartz aggregates. In: *Experimental and Natural Rock Deformation* (edited by Paulitsch, J.). Springer, New York, 272–335.

Sellars, C. M. 1978. Recrystallization of metals during hot deformation. *Phil. Trans. R. Soc.* **A288**, 147–158.

Spry, A. 1969. *Metamorphic Textures*. Pergamon Press, Oxford.

Starkey, J. 1977. The contouring of orientation data represented in spherical projection. *Can. J. Earth Sci.* **14**, 268–277.

White, S. 1976. The effects of strain in the microstructures, fabrics and deformation mechanisms in quartzites. *Phil. Trans. R. Soc.* **A283**, 69–86.

Wilson, C. J. L. 1973. The prograde microfabric in a deformed quartzite sequence, Mount Isa, Australia. *Tectonophysics* **19**, 39–81.

Wilson, C. J. L. 1982. Texture and grain growth during the annealing of ice. *Textures and Microstructures* **5**, 19–31.

Urai, J. L. & Humphreys, F. J. 1981. The development of shear zones in polycrystalline camphor. *Tectonophysics* **78**, 677–685.