Journal of Structural Geology, Vol. 14, No. 7, pp. 775 to 789, 1992
Printed in Great Britain

0191–8141/92 $05.00+0.00

Tectonic interpretations of systematic variations in quartz *c*-axis fabrics across the Thompson Belt

FRANK FUETEN

Department of Geological Sciences, Brock University, St. Catharines, Ontario, Canada L2S 3A1

(*Received* 12 *March* 1991; *accepted in revised form* 3 *March* 1992)

Abstract—The Thompson Belt is a linear NE-trending belt of Archean and early Proterozoic rocks forming the boundary between the Archean Superior and early Proterozoic Churchill provinces. The gneisses in the Belt record deformation which took place during the early Proterozoic Hudsonian orogeny.

Quartz *c*-axis fabrics were measured from gneisses collected along a transect across the western portion of the Thompson Belt. Well developed quartz *c*-axis fabrics were found in virtually all gneisses, even in coarse-grained, quartz-poor and weakly lineated rocks. Several distinctive *c*-axis fabric types were found to occur throughout the area and can be related to specific deformation events. Different *c*-axis fabric types can be linked to the activation of separate glide systems within quartz at different stages of the orogeny. Polar asymmetry within fabrics that should be symmetric, if they had formed from a population of grains with random orientations, are evidence that the present *c*-axis fabric has overprinted an earlier preferred crystallographic orientation. *c*-axis fabric variations in the Thompson Belt show similarities to variations observed in the Saxony granulite region.

Results of this study indicate that quartz *c*-axis fabric analysis can contribute to the knowledge of the regional deformation in the Thompson Belt. Regional quartz *c*-axis variations may prove to be useful for studying the deformation history of other high-grade gneissic terrains.

INTRODUCTION

QUARTZ *c*-axis fabrics are a powerful tool for the interpretation of plastically deformed rocks. Work based on quartz deformation experiments (e.g. Tullis *et al.* 1973, Kirby 1977), on numerical models (e.g. Lister 1979, Lister & Paterson 1979, Lister & Williams 1979, Jessell 1988) and on fabric analysis (e.g. Starkey 1979, Schmid *et al.* 1981) has contributed much towards the understanding of quartz *c*-axis fabrics. However, relatively few *c*-axis fabric studies have been conducted on a regional scale (e.g. Lister & Dornsiepen 1982, Law *et al.* 1984, Cuevas & Tubía 1990). The Saxony granulites have been the site of probably the most extensive *c*-axis fabric work (Behr 1961, 1980, Sander 1970, Hoffman 1975, Starkey 1979, Lister & Dornsiepen 1982). In the Saxony granulites a core of granulite-grade gneisses is rimmed by rocks deformed at progressively lower grade after the granulite metamorphism. Variations in *c*-axis fabrics observed in the Saxony granulites (e.g. Behr 1980, Lister & Dornsiepen 1982, Hobbs 1985) present the most comprehensive data on fabric transitions in high-grade gneissic terrains.

This paper presents the results of a regional *c*-axis fabric study across the Thompson Belt, a gneissic belt with similar metamorphic conditions to those of the Saxony granulites. Structural geology along a traverse across the Thompson Belt has been presented by Fueten & Robin (1989). This paper presents quartz petrofabric work along the same traverse. The rocks used in this study are typically coarse-grained, poorly lineated gneisses with highly variable quartz content. Results of this study show that systematic variations in the size and texture of quartz grains as well as in quartz *c*-axis fabrics across the map area help delineate domains which have different deformation histories. Distinct *c*-axis fabric types can be explained by the activation of separate glide systems in quartz at different stages of the deformation history of the Thompson Belt. This demonstrates that *c*-axis fabrics can be a useful tool for the studying of gneissic terrains; their use need not be confined to fine-grained mylonites. The variations in quartz *c*-axis fabrics observed in the Thompson Belt show similarities to those reported from the Saxony granulites.

GEOLOGICAL SETTING AND CURRENT TECTONIC MODEL

The Thompson Belt, located in northern Manitoba (Fig. 1), is a linear, NE-trending belt at the border between the Churchill province and the Pikwitonei region of the Superior province (Peredery *et al.* 1982, Green *et al.* 1985). It is thought to be the result of a plate collision during the Hudsonian orogeny, which in the Thompson Belt has been dated between 1.9 and 1.6 Ga (e.g. Green *et al.* 1985). Rocks in the Thompson Belt consist mainly of a series of felsic gneisses, considered to be the retrograded equivalents of the Kenoran Pikwitonei granulites (Scoates *et al.* 1977, Weber & Scoates 1978). At the western margin of the belt, the felsic gneisses are overlain by a Proterozoic suite of ultramafic, metavolcanic and metasedimentary rocks called the Ospwagan Group by Scoates *et al.* (1977).

At its eastern margin the Thompson Belt is in contact with the Pikwitonei domain. The Pikwitonei domain is considered to be the deep crustal equivalent of the Superior province and to be structurally continuous with it (Hubregtse 1980). Hudsonian deformation and amphibolite-grade metamorphism have overprinted the

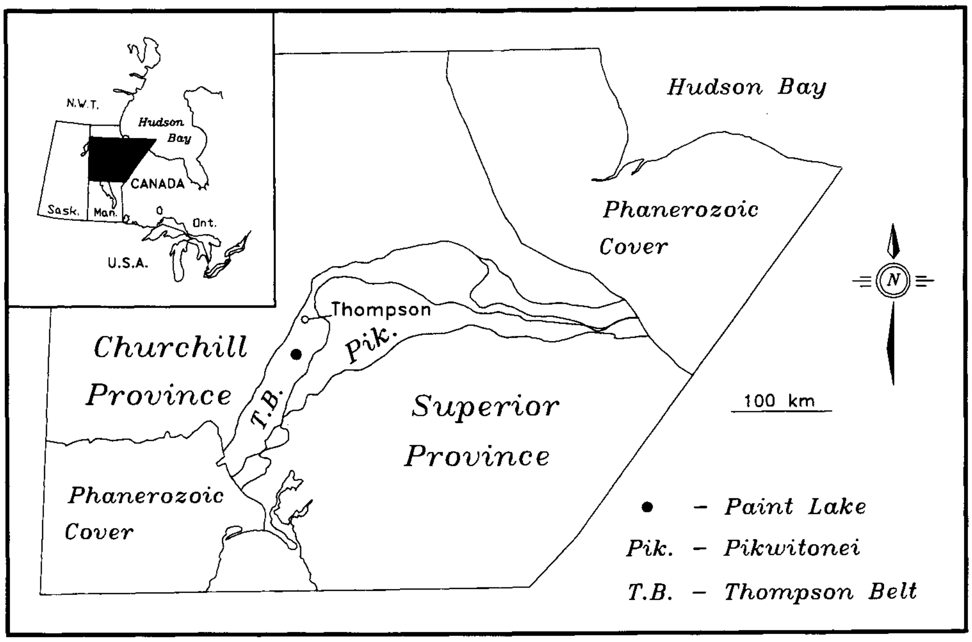

Fig. 1. Location of the Thompson Belt.

Kenoran granulite-grade metamorphism and E–W-trending structures (Hubregtse 1980) of the western margin of the Pikwitonei region.

The gneisses in the Thompson Belt are thus thought to have undergone several deformation events starting in the Archean (e.g. Green *et al.* 1985). Both gneisses and metasediments in the Thompson Belt owe their current structural attitude to the Hudsonian orogeny (Weber & Scoates 1978, Green *et al.* 1985, Fueten & Robin 1989).

Fueten & Robin (1989) showed that the Thompson Belt was an area of predominantly dip-slip movement for the recognizable part of its ductile deformation history, and that all structural features lie in a sub-vertical plane striking approximately parallel to the belt. The sense of shear has mainly been Superior-side-up. The shearing placed fault blocks of progressively higher metamorphic grade towards the south-east. Minor Churchill-side-up shearing took place during the late stages of the orogeny.

The work for this project was carried out at localities which provide a 45-km long transect across the Thompson Belt and into the western portion of the Pikwitonei domain (Fig. 2). This transect has been divided into three blocks (Fueten & Robin 1989) (Fig. 2), the North-West (NW), Centre and South-East (SE) blocks. The three blocks outlined in this transect are defined on the basis of their distinctive structural fabrics but metamorphic differences also exist between them. Their north-western and south-eastern boundaries are parallel to the foliation strike. The geology, structural data, the presence and use of kinematic indicators of sense of shear, as well as the basis for the definition of all three blocks is discussed in detail by Fueten & Robin (1989). The mesoscopic indicators used in the study included *S–C* relationships, shear bands, rotated inclusions (typically feldspars) and asymmetries of late minor folds. The locations of outcrops with several different types of convincing kinematic indicators and their sense are shown by circles in Fig. 2.

TECHNIQUE

Extensive quartz *c*-axis fabric work has been carried out in the NW Block and Centre Block. Virtually all rocks containing more than 10% quartz in these two blocks were found to show some type of preferred crystallographic orientation of quartz. In contrast, work on the SE Block found that while some quartzose rocks contained a preferred crystallographic fabric, others did not. The SE Block is a transitional zone between the Pikwitonei and the Thompson Belt, making it difficult to separate Archean from Proterozoic quartz fabrics. In the NW and the Centre Blocks, the Hudsonian orogeny has sufficiently overprinted all rocks so that all quartz fabrics in these two blocks contain information about some aspect of the Hudsonian orogeny. This paper exclusively discusses the quartz fabrics obtained within these two blocks.

A variety of gneisses were selected for quartz *c*-axis measurements, including specimens which were coarse grained, poorly lineated and contained less than 30% quartz. Samples were taken in granulite-grade and amphibolite-grade rocks as well as from rocks which have been locally retrogressed. Quartz *c*-axis samples from all preserved metamorphic stages are present.

The quartz grain size in the gneisses varies widely, from less than 10 μm to greater than 10,000 μm (1 cm). Within a single thin section, the grain size may vary by several orders of magnitude. The average grain size was visually estimated and is in the range of hundreds to more than 1000 μm, which is much greater than in most other *c*-axis studies. Thin sections with an average, visually estimated, quartz grain size of less than 500 μm were arbitrarily considered to be fine grained, while sections with an average grain size greater than 500 μm were considered to be coarse grained. Average grain sizes of less than 100 μm or greater than 1000 μm are rare.

The presence of a preferred crystallographic orientation was initially determined by insertion of a mica plate and subsequently confirmed by Universal-stage measurements. Wherever possible 200 quartz grains were measured in each thin section. In some cases the grain size was so large that fewer than 200 grains could be measured. All samples on which fabric analyses were attempted and which have 50 or more measured grains are presented here. Due to the similarity in orientation of the gneisses in the Thompson Belt, all fabrics are presented in roughly the same plane; perpendicular to the trend of the Thompson Belt, vertical, with the top of the net up (Fig. 3). The orientation of the plane of the net varies by up to 25° due to local variations in the strike of the gneissic foliation. Each *c*-axis diagram is oriented such that the top–bottom axis of the diagram represents the great circle of the foliation, with the lineation at the intersection between the top–bottom axis and the perimeter of the net (Fig. 3). The kinematic Y axis is in the centre of the net, the X axis at the top and the Z axis is at the intersection of the equatorial axis with the perimeter of the net. All fabric diagrams are viewed looking northeast. If peaks within individual quadrants are discussed, they are referred to as lying within the NE-top or NW-top quadrant, as shown in Fig. 3.

All *c*-axis fabrics were contoured using a Gaussian weighting function described by Robin & Jowett (1986). Rather than a counting circle, the method uses a continuous spherical Gaussian counting function, which results in smoother contours. Following the suggestion of Kamb (1959) for the size of a counting circle, the *kurtosis* (k) of the Gaussian function is chosen such that $E = 3\sigma$, where E is the *expected value* of the counts for the N data points, and σ is the expected *standard deviation* of the counts if the N data points are drawn randomly from an isotropic population. The lowest contour shown for counts equals the *expected value* E. Higher contours are every 2σ. The orientation of the highest count value is referred to as the mode, while other highs are referred to as peaks. All statistical information available for each net is given in Fueten (1990).

Fabric classification and kinematics

The wide variety of rocks examined here yielded a number of diverse *c*-axis fabrics. All *c*-axis fabrics are presented in Figs. 4 and 5. Many of the fabrics are not the ideal type fabrics commonly reported in the literature, making classification difficult in some cases. The fabrics have been classified in order to be able to discuss similarities and differences in regional occurrence of fabrics. When possible, *c*-axis fabrics are classified as small-circle girdles, single girdles, crossed girdles, or as fabrics dominated by point maxima. The terminology follows that used by Lister & Williams (1979). Single girdle fabrics (e.g. Fig. 4, Section 6-19) are the most easily identified fabrics. In these, the lowest contour roughly follows a single, steeply dipping girdle, which is thought to result from the alignment of one or several glide planes with the shear plane (Simpson & Schmid

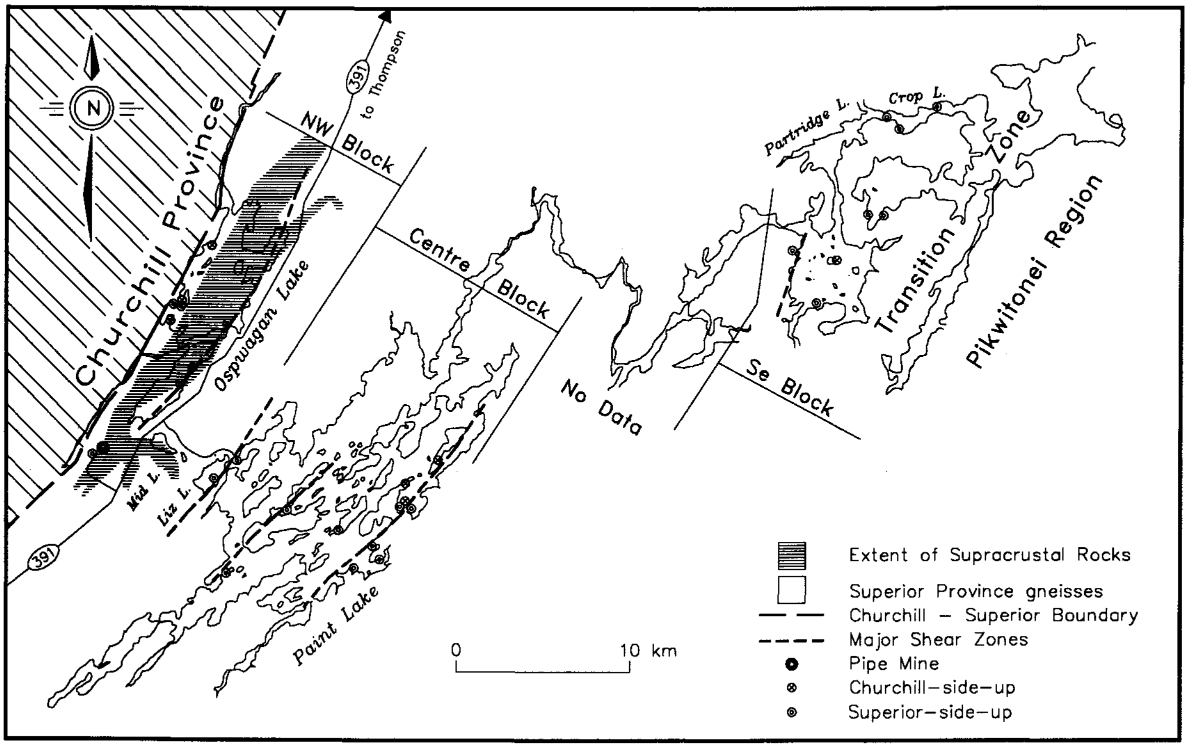

Fig. 2. Map area and regions. Extent of supracrustals and location of Churchill–Superior boundary modified after Coats *et al.* 1972.

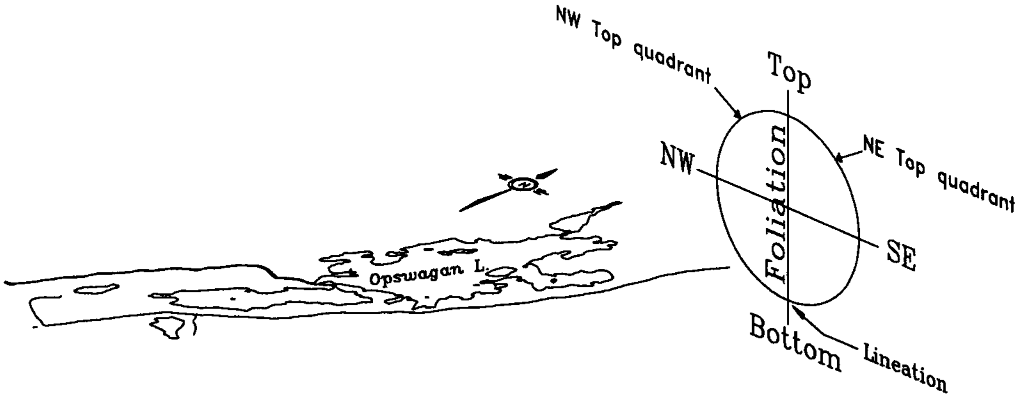

Fig. 3. Relative position of quartz *c*-axis fabric diagrams with respect to foliation, lineation and the geographical position with regard to the Thompson Belt.

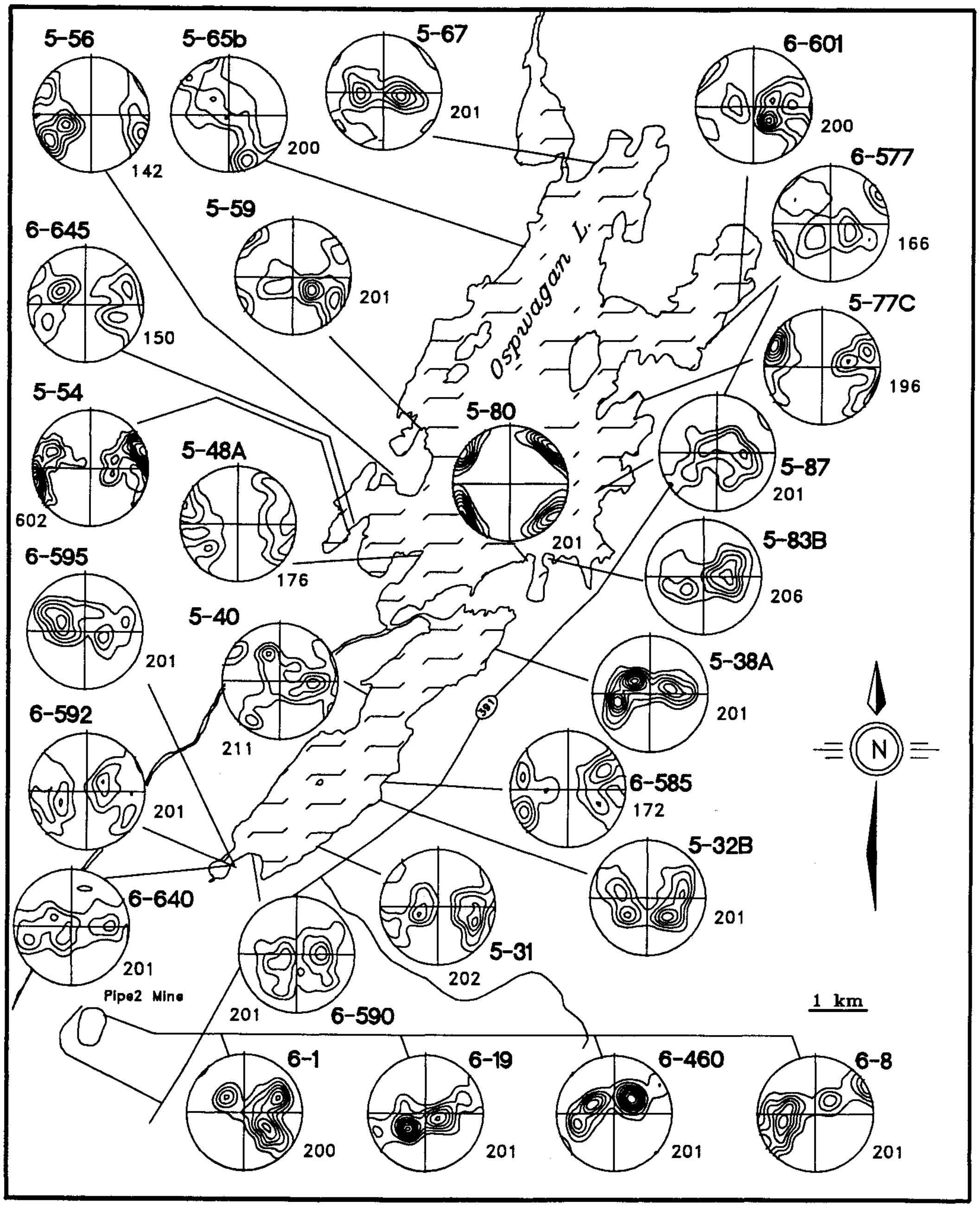

Fig. 4. NW Block. *c*-axis fabrics oriented as Fig. 4, and their locations. Bold numbers are section numbers. Small numbers are number of grains measured. Section 6-19, 6-460 and 6-8 (southern portion of figure) are good examples of single girdle fabrics which indicate a Superior-side-up sense of shear. In contrast, Section 5-65b in the north-western portion of the map displays a single girdle fabric which indicates a Churchill-side-up sense of shear.

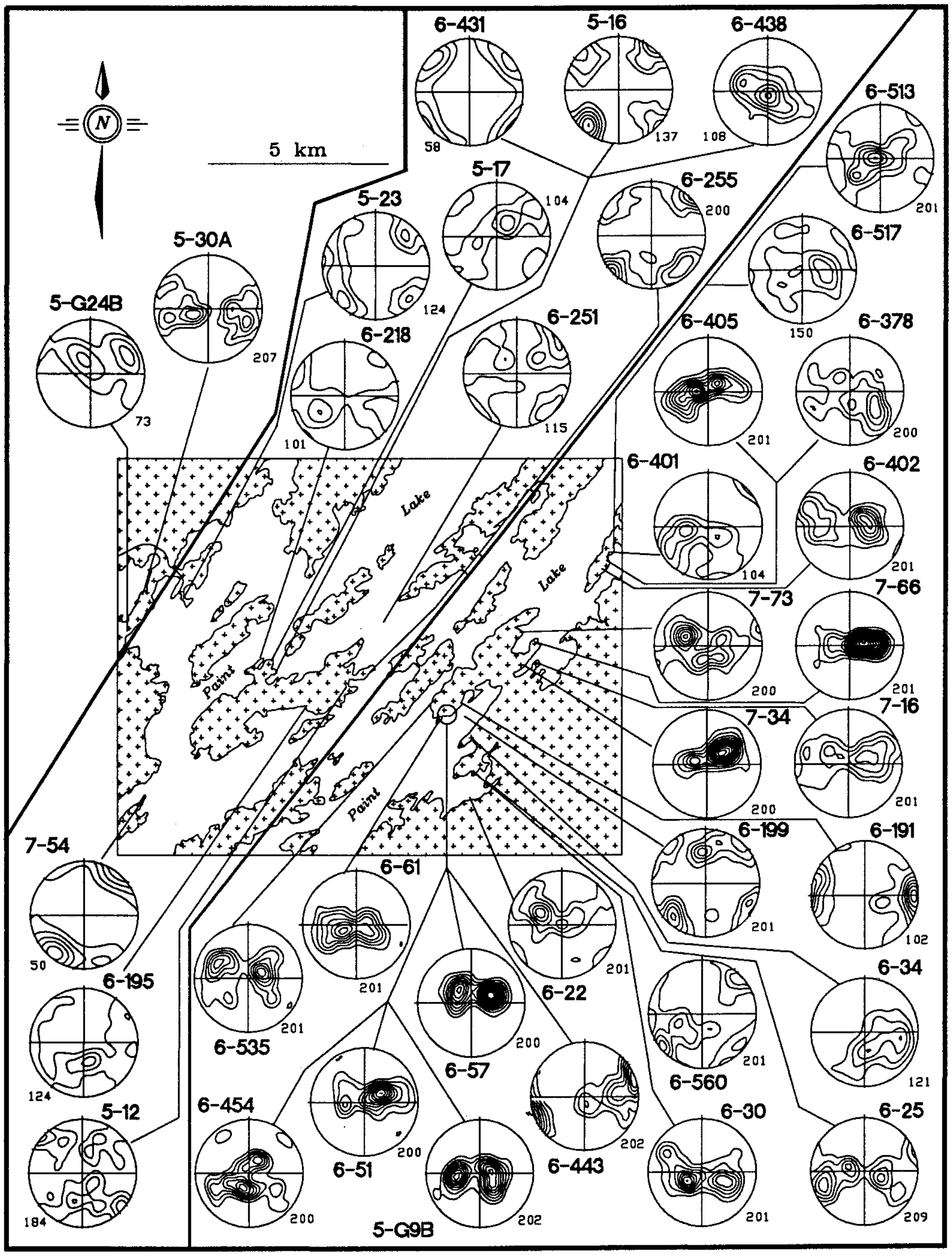

Fig. 5. Centre Block. *c*-axis fabrics and locations. Numbering as Fig. 4. Bold lines separate three sub-regions.

1983). Several distinct maxima may be located within the great circle. One of the requirements for a fabric to be classified as a single girdle is that the angular width of the girdle be relatively small and the contours must extend nearly continuously across the net. Fabrics such as Fig. 5, Section 7-34 are classified by their point maxima, rather than as single girdles. The sense of asymmetry (Fig. 6) of the girdle with respect to the foliation plane is used as a kinematic indicator. For example, Section 6-19 (Fig. 4) indicates Superior-side-up (east-over-west).

Crossed girdle fabrics are subdivided into Type I crossed girdles and Type II crossed girdles. Skeletal outlines of these two types, which may be drawn by linking individual maxima, are shown in Fig. 6. Type II crossed girdles are centred about the *Y* axis, while individual branches of the Type I crossed girdle intersect away from the *Y* position. The kinematic interpretation of the crossed girdles is based on extensive numerical modelling (Lister *et al.* 1978, Lister 1979, 1981, Lister & Paterson 1979, Lister & Williams 1979, Lister & Hobbs 1980). A coaxial overprint may modify the crossed girdles (Lister & Williams 1979, fig. 13) (Fig. 6) further complicating the kinematic interpretation of the analysis. The fabric skeletons shown in Fig. 6 represent the idealized shape of contoured fabric diagrams. One complicating factor for the recognition of the Type II crossed girdles is that patterns may have strongly developed *c*-axis maxima but lack a significant concentration of *c*-axes along the girdle. Lister & Dornsiepen (1982) considered similar fabrics in the Saxony granulites to be crossed girdle fabrics. In this study, fabrics will be classified by their maxima.

Two types of contoured patterns are interpreted as Type I girdles. In Fig. 5, Section 6-513 shows a strong *Y* maximum elongate along one almost continuous major girdle. A second weaker branch intersects or comes close to intersecting the major girdle. The weaker branch does not intersect at *Y*. This section closely resembles the idealized fabric skeleton of a Type I crossed girdle. The second, more common type of pattern interpreted as Type 1 crossed girdles is that of Fig. 4, Section 6-585 in the NW Block, and from Fig. 5, Sections 5-30a and 6-25 from the Centre Block. To obtain the sense of shear from these girdles the side containing the mode was sometimes considered to be the leading edge and was used to obtain the sense of shear. Alternatively, an asymmetrical development in the shape of the contoured surface was used.

Small circle girdles, centred about the *Z* axis may be difficult to distinguish from Type I cross girdles. For example Section 6-585 (Fig. 7) can equally well be described as a Type I crossed girdle or as a small-circle girdle. Section 5-48A (Fig. 4) is perhaps the most convincing small-circle girdle in this study as it contains maxima symmetrical about *Z*. While it is the only fabric in this study clearly identified as a small-circle girdle fabric, it is acknowledged that some fabrics, such as Sections 5-56 and 6-645 (Fig. 4), may be interpreted as small-circle girdle fabrics, or may represent some intermediate between small-circle fabrics and Type I crossed girdles.

The identification of *c*-axis fabrics by point maxima originates from Fairbairn (1949). Lister & Dornsiepen (1982) adapted Fairbairn's use to the modern system of *X*, *Y* and *Z* axes (Fig. 8). Point maxima provide an exact means to describe the orientations of peaks within a fabric diagram. Since many fabric diagrams in this study are dominated by pointed peaks, rather than the ridges of girdles, the point maxima terminology is used where applicable. There are some redundancies between the use of point maxima and the crossed girdle terminology. Fabrics, such as in Fig. 4, Section 5-80 in the NW Block, and Fig. 5, Section 5-16 in the Centre Block, show no girdle but have been classified as Type II crossed girdles by Lister & Dornsiepen (1982) and Fueten *et al.* (1991).

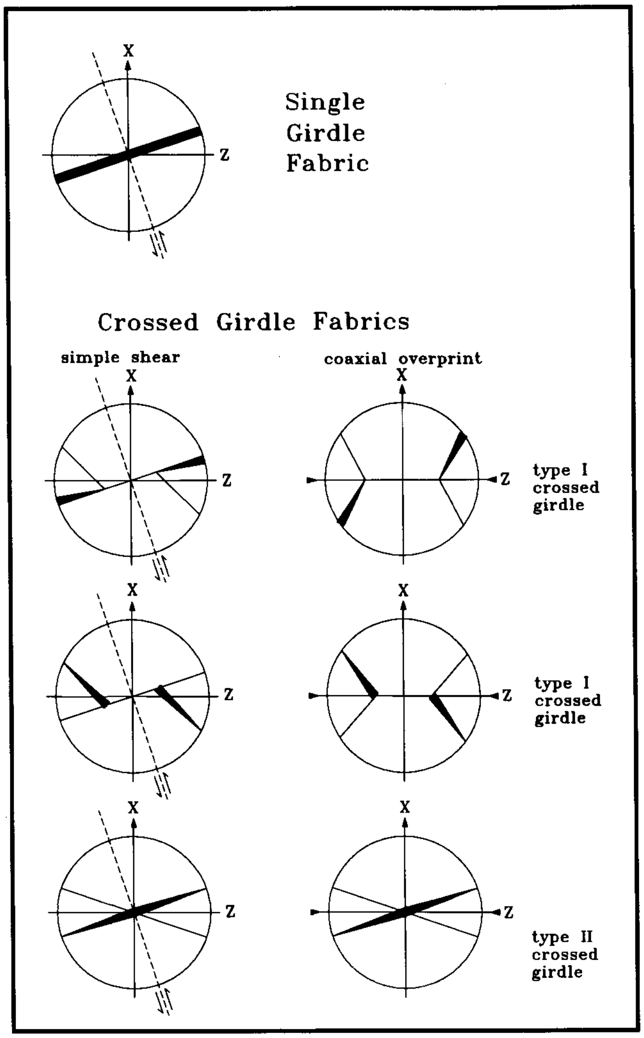

Fig. 6. Fabric skeletons used for single and crossed girdle classification, modified after Lister & Williams (1980). These are idealized skeletons for a sinistral sense of shear on the indicated shear plane. Compare with Section 6-8 (south-east corner of Fig. 4) and Section 6-513 (north-east corner of Fig. 4).

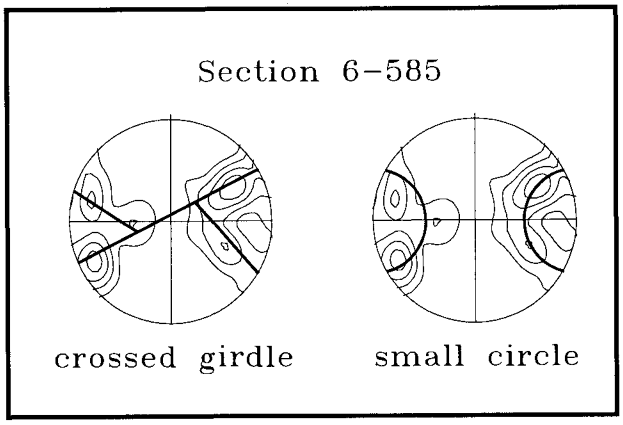

Fig. 7. Possible interpretations for fabric of Section 6-585 (Fig. 4).

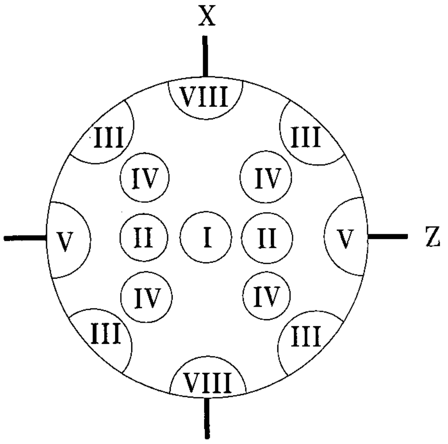

Fig. 8. Position of point maxima used to describe *c*-axis fabric. Kinematic *Y* axes is at the centre of the net. Modified after Lister & Dornsiepen (1982).

In this study, that fabric will be referred to as a Maxima III fabric.

In several fabrics, the shape of the contours or the position of peaks made it impossible to classify these fabrics according to the criteria listed above. These fabrics will be referred to as unclassified.

QUARTZ *c*-AXIS FABRIC VARIATIONS

NW Block geology

All occurrences of the Proterozoic Ospwagan Group are contained within this block and its inferred north-eastern extension. The northwestern edge of the block is the poorly exposed contact with the Kisseynew gneisses of the Churchill province.

Fueten *et al.* (1986), using metamorphic assemblages, estimated the peak temperatures at Pipe 2 Mine, located within the NW Block, to be 575–625°C. The orientation of the *mode* of gneissic foliation corresponds to a strike of about 050° and a dip of 84° to the south-west. The predominant lineation present within these gneisses is one defined by the alignment of strongly inequant patches of quartz and feldspar grains. This lineation, interpreted to be a stretching lineation, is nearly vertical.

The majority of mesoscopic kinematic indicators (Fueten & Robin 1989) in the NW Block indicate the Superior (SE) side has moved up with respect to the Churchill (NW) side. The three outcrops which indicate the opposite sense of movement lie along a limited area on the western shore of Lower Ospwagan Lake.

NW Block c-axis fabrics

In most sections in the NW Block the average quartz grain size ranges between 100 and 500 μm. The NW Block is the only block in the Thompson Belt that was found to contain well developed single girdle fabrics (Fig. 4, Sections 6-8, 6-460, 6-19 and 5-65b). These indicate a Superior-side-up sense of shear at the Pipe 2 mine (Fig. 4, Sections 6-19, 6-460 and 6-8) and Churchill-side-up sense on the north-west shore of Lower Ospwagan Lake (Fig. 4, Section 5-65b), confirming the sense of shear obtained by mesoscopic kinematic indicators (Fueten & Robin 1989).

Several Type I crossed girdles (Fig. 4, Sections 6-592, 5-40 and 5-54) were found in this block. Two (Fig. 4, Sections 6-592 and 6-585) girdles have been used as kinematic indicators and yield a Superior-side-up sense of shear. For Section 6-585 this confirms the sense of shear obtained from mesoscopic kinematic indicators; however for Section 6-592 no other unequivocal kinematic indicators were found. Fabrics from Sections 5-56, 6-645 and 6-585 are tentatively classified as Type I crossed girdles, but may alternatively be interpreted as small-circle girdles. Section 5-48A yielded the most convincing small-circle girdle in this study. In three samples located close to the north-west shore of Lower Ospwagan Lake (Fig. 4, Sections 5-54, 6-645 and 5-56) quartz occurs as ribbons which may be more than 1 cm in length and reach aspect ratios in access of 20:1 (Fig. 9a).

The fabric with the most intensely developed peaks at point Maxima III (Fig. 4, Section 5-80) in this study comes from the NW Block. The NE-top Maximum III is higher than the NW-top Maximum III by a difference of 2σ. Several fabric diagrams (Fig. 4, Sections 5-83b, 6-590, 6-595, 5-67, 6-577 and 5-87) are dominated by peaks at or near the Maxima II positions. One diagram (5-32b) has peaks at all four Maxima IV positions and is the only one of this type. The remaining fabrics have not been classified.

Centre Block geology

A granulite grade, shown by two coexisting pyroxenes, is preserved in many places within the Centre Block. Russell (1981) calculated two-pyroxene temperatures of 910°C ± 70°C, whereas Paktunç & Baer (1986) estimate temperatures ranging from 700 to 850°C, depending on the geothermometer used, and pressures of 0.9–0.97 GPa (9–9.7 kbar). Russell (1981) interpreted the age of the granulite metamorphism as Archean, while Coats *et al.* (1972) believed it to be Hudsonian. When orthopyroxene is present, except for some retrogression, the minerals are in excellent textural equilibrium and exhibit a remarkable lack of deformation features such as kink bands, undulatory extinction or exsolution. Fueten & Robin (1989) therefore considered the granulite grade to have been achieved during the Hudsonian orogeny. Muscovite and chlorite are found, irregularly, in the south-eastern portion of the Centre Block as alteration products of feldspar and biotite. The degree of alteration ranges from minor to an almost complete replacement of the biotite, massive sericitization of feldspar, and occurrence of large muscovite grains.

Gneissic foliation in the block is near vertical and has an average strike of 045°. Many of the outcrops of felsic gneiss in this block show a weak, subvertical lineation visible on the foliation face. The lineation is composed of elongated quartz and feldspar grains or aggregates of grains and is considered to be a coarse-grained or recrystallized stretching lineation.

In the central part of the block gneissic layering is straight and continuous over the length of an outcrop, with layer thicknesses varying between 2 and 15 cm. This zone measures 1–2 km across strike, contains an outcrop of coarse-grained mylonite and is interpreted to be a wide granulite-grade shear zone (Fueten & Robin 1989).

Close to the south-east shore of Paint Lake, over a width of several kilometres, a number of mylonites occur, separated by regions of rocks which have a less well developed shape fabric. Some mylonites within this area show signs of recrystallization of quartz to large (>2 mm and up to 1.5 cm) grains, some overgrowing many enclosed grains of feldspar and biotite. Quartz in other mylonite zones has sub-millimetre grain size and sutured grain boundaries.

The majority of other kinematic indicators in the Centre Block, two of which are in the wide shear zone, also indicate Superior-side-up. The one consistent exception (three outcrops), which records a Churchill-side-up sense, is a less than 75 m-wide zone, in the south-eastern part of this block. The most intense chlorite alteration is associated with outcrops along this zone, with quartz showing no signs of post deformational recrystallization to a large grain size.

Centre Block c-*axis fabrics*

On the basis of the *c*-axis fabric data, the Centre Block has been divided into three sub-regions. The boundaries, shown in Fig. 5, do not imply the location of faults but simply separate the different fabric types.

(1) NW region of Centre Block. The border between the NW and the Centre Block is a mylonite zone. The quartz fabric (Fig. 5, Section 5-30a) from this mylonite is a Type I crossed girdle, which confirms the Superior-side-up sense of shear obtained by other kinematic indicators. The quartz grain size in the mylonite ranges between 100 and 500 μm. On the north-east shore of Paint Lake the expression of this shear zone is less homogeneous as blocks of amphibolites and minor folds disrupt the shear zone. The quartz fabric of a sample from that area (Fig. 5, Section 5-G24B) has not been classified.

(2) Central region of Centre Block. This region contains the wide granulite-grade shear zone discussed above. Most samples have a quartz grain size in excess of 1000 μm (Fig. 9b, Section 5-16). Most quartz *c*-axis fabrics from this region have well developed, relatively isolated Maxima III. Some show Maxima I and have connections between maxima. In a more detailed study on the same specimens, Fueten *et al.* (1991) demonstrate that these rocks contain a small number of large quartz grains with their *c*-axes at the Maximum I position. In the fabrics in which one Maximum III is higher than the other (Fig. 5, Sections 5-16,6-255 and 6-251), the higher Maximum III is always in the NE-top quadrant of the net.

(3) SE region of Centre Block. This sub-region of the Centre Block contains several Superior-side-up mylonite zones, which do not contain any orthopyroxene, as well as the Churchill-side-up mylonite zone. The complex shearing history of this area is reflected in the quartz *c*-axis fabrics. Two sections (Fig. 5, Sections 6-199 and 6-560) have maxima near the Maxima III position. These same two sections are the only ones in this region which contain orthopyroxene.

Type I cross girdles (Fig. 5, Sections 6-22?, 6-25 and 6-513) are present at several locations. Sections 6-25 and 6-513 are well enough defined to be used as kinematic indicators and yield a Superior-side-up sense. In Section 6-454, interpreted as a poorly developed crossed girdle, quartz grains have amoeboid shapes which cross-foliation trains (Fig. 9c, Sections 6-454) and have sutured grain boundaries indicative of grain boundary migration.

Five fabric diagrams (Fig. 5, Sections 7-66, 7-34, 6-57, 6-51 and 5-G9b) are dominated by well-developed peaks at Maxima II. In all but Section 7-66, two peaks are present and usually one is dominant. The eastern peak defines the mode and greatly dominates over the western peak in all but Section 5-G9B. The modes obtained in these sections are much higher than those for similar diagrams in the NW block, even though the same number of measurements are involved. Most sections with peaks at Maxima II can be correlated with the Churchill-side-up shear event. Section 7-34 comes from an outcrop which lies on the Churchill-side-up shear zone. Section 7-66 was obtained from an outcrop near this shear zone which contained no mesoscopic kinematic indicators.

Quartz grains in sections with the Maxima II fabric may be coarse or fine-grained. In some coarse-grained samples amoeboid shaped quartz grains have inclusions of fish-shaped feldspar or mica grains. In some cases (e.g. Fig. 9d, Section 6-57) foliation trains of micas and feldspars pin the grain boundaries of the quartz grains and therefore limit their size. All five sections contain chlorite, which ranges in abundance between less than 1 and 5%. This chlorite, when coarse grained, is undeformed while coarse biotite grains in these samples are folded. One sample (5-G9B) which contains a 2 mm wide vertical ultra-mylonite exhibits evidence for two separate shear events with opposing senses of motion. Several millimetres away from the ultra-mylonite, fish-shaped inclusions of feldspars are contained within coarse quartz grains. The asymmetry of the feldspar grains indicates a Superior-side-up sense of shear. The deflection of the fabric into the ultramylonite zone indicates a Churchill-side-up sense of shear. Undulatory extinction in several large biotites associated with tailed feldspars indicates that the Churchill-side-up shearing postdates the the Superior-side-up shearing.

In six fabric diagrams (Fig. 5, Sections 6-405, 6-402, 7-16, 6-30, 6-61 and 6-535) peaks are developed at or near Maxima II. These do not however have the same tight definition of the lowest contour or the height of the mode as the above discussed sections. All but Sections 6-535 and 6-30 come from outcrops close to those of the above discussed sections with Maxima II dominated fabrics.

Sections 6-191 and 6-443 have one tightly defined mode near Maxima V. They are the only two sections with this fabric. Average quartz grain size in Section 6-443 is 50 μm while quartz grain size in Section 6-191 is on the order of 5000 μm.

Section 7-73 (Fig. 5) contains significant maxima but appears to be a hybrid of different fabric types. Several fabric diagrams (Fig. 5, Section 6-34, 6-401, 6-378 and 6-517) have not been classified. In these diagrams the lowest contour covers a large percentage of the net, while the maxima have low peak values for the number of data points involved. All of these come from outcrops very close to the distinct Churchill-side-up shear zone. It

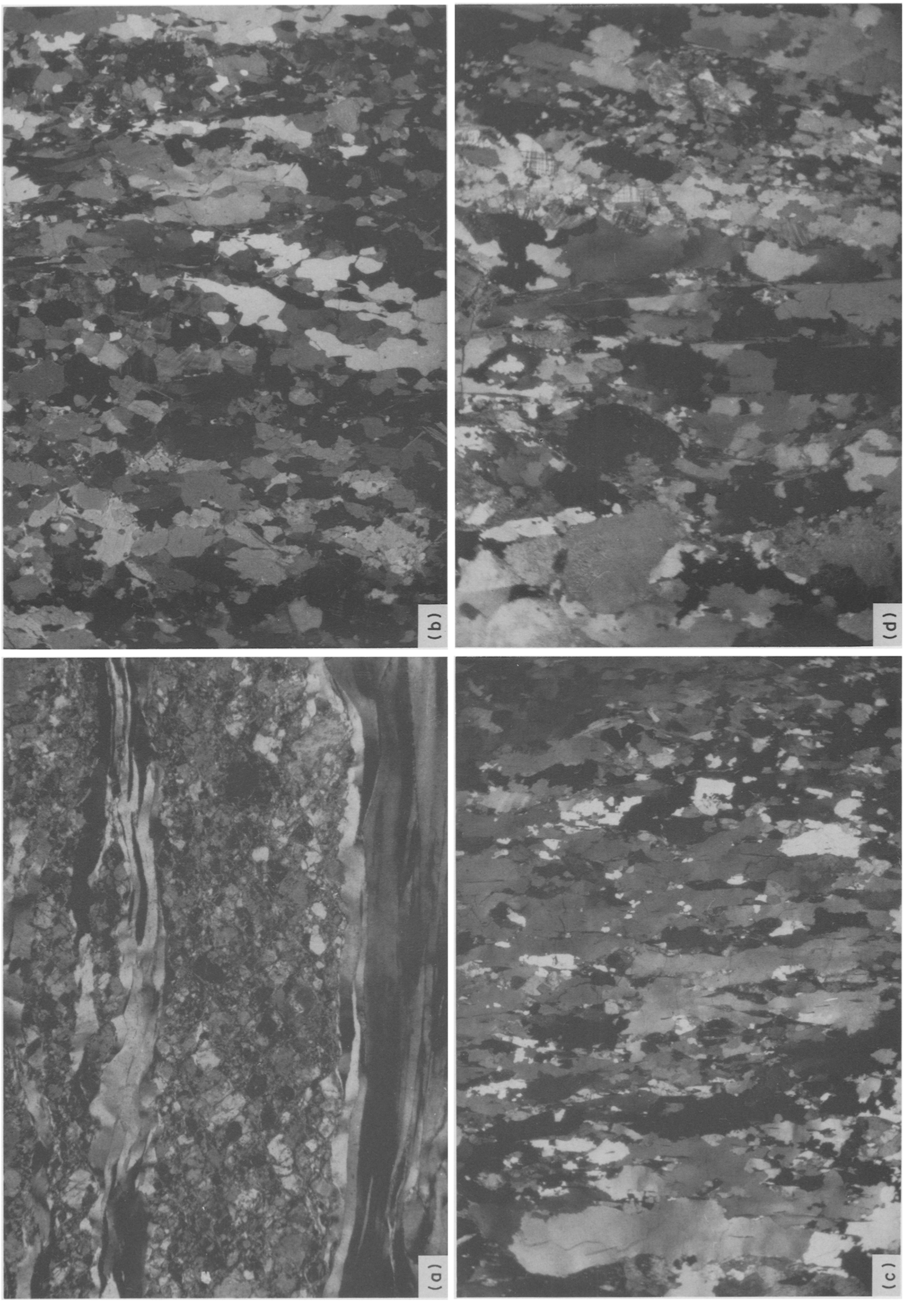

Fig. 9. Figure illustrating the variety of textures within the gneisses studied. All photomicrographs are oriented perpendicular to the foliation and parallel to the lineation. Long dimension of all photomicrographs is 6 mm. (a) Photomicrograph of quartz ribbons within Section 5-54. (b) Photomicrograph of Section 5-16. (c) Photomicrograph of Section 6-454. Large, amoeboid quartz grains with a large number of inclusions of feldspar- and mica-fish. (d) Photomicrograph of Section 6-57. Grain boundaries of coarse quartz grains are pinned by trains of micas.

is likely that these samples were affected by the late shearing and that the fabrics are at some intermediate stage of modification.

DISCUSSION

Grain size variations

There is a variation in quartz grain size between the two blocks. In the NW Block the quartz grain size generally ranges between 100 and 500 μm, in the Centre Block, quartz grain sizes are generally between 500 and 1000 μm but individual grains with sizes on the order of 10,000 μm are common. In the SE portion of the Centre Block, grain sizes can range from 10 to 10,000 μm. Some of the smallest as well as largest grain sizes are associated with the late Churchill-side-up event.

Significance of the presence of c*-axis fabrics*

Starkey & Cuthforth (1978) demonstrated that a relationship exists between the amount of quartz and the degree of preferred crystallographic orientation in the suite of rocks they examined. In the present work well defined and classifiable crystallographic preferred orientations of quartz were found in most samples, independent of quartz content. Even sections in which only just over 50 grains could be measured (e.g. Fig. 5, Sections 6-431 and 7-54) had *c*-axis concentrations well above the expected value. There was also no relationship between the size of quartz grains or the relative strength of the lineation and the existence of a strong preferred orientation of quartz. Both well- and poorly-lineated gneisses were found to have well-developed *c*-axis fabrics.

The Thompson Belt gneisses studied here are thought to have undergone a considerable amount of deformation, a characteristic probably true for most gneissic terrains. The *c*-axis fabrics from these rocks can be used as kinematic indicators, and yield other information, discussed below. Quartz *c*-axis fabrics therefore are a useful tool in the study of the deformation of gneissic terrains, and their use need not be restricted to fine-grained quartzite mylonite zones or rocks with strong stretching lineations.

Quartz c*-axis fabrics as kinematic indicators*

c-axis fabrics that can be used as kinematic indicators confirmed the sense of motion inferred by mesoscopic indicators in the thin section (e.g. rotated inclusions, *S–C* relationships, shear bands) or in the outcrop (e.g. minor folds). The rocks used in this study are exclusively quartzo-feldspathic gneisses, which all have a good potential for developing microscopic structures which can be used as kinematic indicators. The relationship between *c*-axis fabrics and structures studied here is such that rocks which develop a *c*-axis fabric that can be used as a kinematic indicator almost always develop other structures which can be used independently as kinematic indicators. The presence of structures such as rotated feldspar grains does not, however, guarantee a quartz *c*-axis fabric which can also serve as a kinematic indicator. Rocks affected by the Churchill-side-up shearing in the Centre Block may contain mesoscopic kinematic indicators but *c*-axis fabrics may not show a strong crystallographic preferred orientation (e.g. Fig. 5, Section 6-378), or may have well defined fabrics (e.g. Fig. 5, Section 7-66) which cannot be used as a kinematic indicator.

Quartz deformation experiments (Tullis *et al.* 1973) and numerical modelling (Lister 1979, Lister & Paterson 1979, Lister & Williams 1979) of quartz deformation suggest that more than 10% shortening or shear strains of 1 or greater are required to produce a well-defined preferred crystallographic orientation in quartzites. The existence of well developed *c*-axis fabrics in the Thompson Belt indicates that crystal plasticity was a dominant deformation mechanism. It is reasonable to assume that a shear event that produced mesoscopic kinematic indicators also produced a *c*-axis fabric which can be used as a kinematic indicator. The simplest explanation for a fabric that does not show a strong crystallographic preferred orientation in rocks in which mesoscopic kinematic indicators are present is that the rocks were affected by a late imposed strain event. This event was strong enough to destroy an earlier *c*-axis fabric, but not strong enough to visibly rearrange the earlier formed mesoscopic asymmetric structures. The sensitivity of *c*-axis fabrics to an imposed strain is therefore greater than the sensitivity of most other mesoscopic indicators. It should be noted that in this study there is no evidence that poorly developed fabrics are due to annealing recrystallization.

Glide systems

Optically measured *c*-axis orientations do not totally constrain the orientation of the crystal lattice; e.g. the orientation of $\langle a \rangle$ is not uniquely defined. However it is possible to argue for the operation of certain glide systems for some distinctive fabrics. In the Centre Block different fabrics can be explained by the activations of different glide systems.

In the central portion of the Centre Block, fabrics have peaks near Maxima III and as shown by Fueten *et al.* (1991) near Maximum I and have been interpreted as Type II crossed girdles. Similar patterns have been found in the Saxony granulites. Starkey (1979) attributes the Maximum I to slip on the prism $\langle a \rangle$ system. He further suggests that the Maxima III are due to slip on positive and/or negative rhombs (r,z) but also finds evidence that basal slip may have been important. Lister & Dornsiepen (1982) suggest this pattern to be the result of a balance between the basal $\langle a \rangle$ and the prism $\langle a \rangle$ systems. Based on a detailed analysis Fueten *et al.* (1991) attribute this fabric to glide on the basal $\langle a \rangle$ and prism $\langle a \rangle$ systems. These fabrics in the Centre Block are associated with granulite-grade assemblages; all samples which contain orthopyroxene exhibit this fabric.

The majority of samples with Maxima II fabrics are from rocks affected by the retrogressive metamorphism associated with the late Churchill-side-up shearing event. The shear planes for these samples are subvertical, the modes for the fabrics are in a plane perpendicular to both foliation and lineation. If this mode is largely due to a single slip end direction, the easiest slip system that can be suggested (Schmid *et al.* 1981) on the basis of this geometry is slip on positive or negative rhombs, in the ⟨*a*⟩ direction.

The fabrics displayed in Fig. 5 by Sections 6-191 and 6-443 with a peak at Maximum V are in positions in which glide on the basal planes is maximized (Schmid *et al.* 1981, Knipe & Law 1987).

The granulite deformation in the Centre Block predates the late retrogressive metamorphism of the Churchill-side-up shearing event. The *c*-axis fabrics attributed to these events are best explained by the operation of different glide systems. Different stages of the orogeny may therefore have had separate dominant glide systems and the resultant *c*-axis fabrics are preserved.

Symmetry

The Maxima II fabrics associated with the Churchill-side-up shearing have a strong polar asymmetry. Wherever the difference between the maxima is 10σ or more (the largest difference is 22σ for Section 7-66), the eastern maxima is consistently stronger. These fabrics likely formed by glide on positive or negative rhombs in the ⟨*a*⟩ direction (Schmid *et al.* 1981). To obtain the Maxima II, the positive or negative rhombs are parallel to the N–S great circle of the net, i.e. parallel to the foliation plane. The ⟨*a*⟩ direction will be at the intersection of the N–S axis of the net and the perimeter of the net. The pronounced polar asymmetry cannot be explained as a kinematic indicator because for this orientation of the slip system, a grain may have its *c*-axis at either Maximum II, regardless of kinematic sense of shear. If this fabric develops from a random population of quartz grains there is no reason grains with their *c*-axis on the eastern Maximum II should be favoured over grains with their *c*-axis at the western Maximum II. As these fabrics are associated with the late Churchill-side-up shearing, it is likely these rocks had some preferred crystallographic orientation of quartz prior to the shear event that resulted in the present fabric. The most reasonable explanation for the consistent and pronounced asymmetry is that the fabric was derived from a non-random population of quartz. The exact nature of the prior preferred orientation is unknown.

A similar, though weaker argument may be made for several of the Maxima III fabrics in the Centre Block. This fabric has been interpreted as resulting from a coaxial episode of deformation (Lister & Dorsiepen 1982). In five of these sections, the NE-top Maxima III is more strongly developed than the NW-top Maxima III. The only similar fabric diagram (Fig. 4, Section 5-80) in the NW Block also has a more strongly developed NE-top Maxima III. Fueten *et al.* (1991) argue that Maxima III are the result of glide on the basal plane in the ⟨*a*⟩ direction. During coaxial deformation the glide systems are oriented at 45° to the *Z* axis, maximizing the resolved shear stresses. Shear stresses are equally maximized for two 45° positions, resulting in two Maxima III at 90° from each other. The development of this fabric from a random population should therefore lead to an equal development of both Maxima III. Kinematic indicators in the granulite mylonite in the area of the Maxima III fabrics indicate a Superior-side-up sense of shear. It is therefore likely that the quartz in this zone possessed a previous asymmetric fabric. For this fabric however one could argue that the asymmetry is due to late or minor non-coaxial overprint.

The polar asymmetry of fabrics which should be symmetric, had they developed from a ramdom population of quartz grains, indicates that the fabric is the result of an overprinting of a previous preferred crystallographic alignment and thus indicates several deformation events.

Distribution of fabric types and regional tectonic implications

The 63 fabric diagrams presented in Fig. 4 and 5 show a great variation. It is however possible to group the occurrence of different quartz *c*-axis fabric types within a regional tectonic context.

The NW Block, with the lowest metamorphic grade of regional extent, is the Block in which the greatest variety of fabrics is present. It is the only block in which well developed single girdle fabrics and small-circle girdle fabrics are found. Fabrics dominated by Maxima II do not have modes as significant as those in the Centre Block and there is no mesoscopic evidence for a relationship between this fabric and Churchill-side-up shearing. Several fabrics (e.g. Fig. 4, Section 5-87) are not easily classifiable fabrics. The contours however do indicate that there is a non-random alignment of quartz *c*-axes.

Type I crossed girdle fabrics occur in both the NW and the Centre Block. These sections contain biotite + hornblende or biotite + muscovite assemblages, but no section with a Type I girdle has been found to contain orthopyroxene.

In the Centre Block all sections measured in this study which contained orthopyroxene also had Maxima III fabrics which may be considered Type II crossed girdles. The only fabric of this type in the NW Block (Fig. 4, Section 5-80) contains the most sharply defined Maxima III and has a chlorite + muscovite + biotite assemblage. The development of fabrics with Maxima III is thus not exclusively linked to granulite-grade rocks. This fabric (Lister & Dornsiepen 1982, Fueten *et al.* 1991) has been interpreted to be the result of a coaxial episode of deformation.

Two types of fabric are associated with the late Churchill-side-up shear event in the Centre Block; fabrics which are dominated by Maxima II and the majority of fabrics which cannot be classified (e.g. Fig. 5, Section

6-517) are near outcrops associated with the Churchill-side-up shear event.

This distribution of *c*-axis fabrics can be considered in the context of the tectonic model for the Thompson Belt. In the central region of the Centre Block an area approximately 5 km wide, measured across strike contains Maxima III fabrics. This is the widest domain found in this study in which only one type of fabric is present. The fabric itself (Lister & Dornsiepen 1982, Fueten *et al.* 1991) has been interpreted as being due to a coaxial episode of deformation. Fueten *et al.* (1991) show that the most likely stress directions for this event are a horizontal σ_1 which trends perpendicular to the Thompson Belt, while σ_3 is vertical. The rocks in which this fabric occurs have been interpreted (Fueten & Robin 1989) as belonging to a 1 km wide granulite-grade mylonite zone with Superior-side-up kinematic indicators.

This region was therefore first deformed with at least a component of simple shear, and then, after the cessation of the simple shear event, was subjected to a significant episode of essentially coaxial deformation. This would explain the consistent asymmetry in the fabrics found in this region. During the episode of coaxial deformation the granulite-grade assemblages were preserved. The only two sections (Fig. 5, Sections 6-199 and 6-560) outside the central portion of this block which contain orthopyroxene, also have a fabric which may be interpreted as Maxima III fabrics. It is therefore suggested that in the Centre Block, regions which escaped the retrogression and retained their granulite grade assemblage formed competent blocks, which experienced coaxial deformation for the remainder of the orogenic event. The simple shear component of the deformation was concentrated in the retrogressed, hydrated and less competent gneisses.

In the NW Block (Fig. 4, Section 5-80) the Maxima III fabric and the small-circle girdle fabrics suggest deformation in a flattening field. This implies that several factors can produce a region which becomes more competent than the surrounding rocks and undergoes only coaxial deformation. In general, in the NW Block, the deformation is more heterogeneous than in the Centre Block. Fabric diagrams from rocks along strike with each other, or geographically close, may show significant differences in their fabric. This indicates that in the NW Block the amphibolite-grade deformation took place in narrow deformation zones, with a more heterogeneous stress distribution. One reason for the heterogeneous stress distribution in the NW Block is the wide range of lithologies (e.g. Proterozoic sediments, gneisses and mafics) providing a large range of competencies.

It is proposed that the deformation in the Thompson Belt progressed as follows: when the granulite deformation ceased, after the Centre Block had been thrust up amongst rocks of lower metamorphic grade, the central portion of the Centre Block became competent. Rocks surrounding the present granulite region were mechanically weakened by fluid influx and metamorphic reactions. This weakening was significant enough to concentrate the simple-shear component in the lower grade rocks. The several kilometre wide granulite region was affected only by coaxial strain for the remainder of the orogeny. The deformation in lower grade rocks took place on narrow (<1 km) wide shear zones. Deformation on narrow shear zones, combined with more heterogeneous lithologies led to a more heterogeneous deformation in the NW Block.

The *c*-axis fabrics are records of different stages of the Hudsonian orogeny. This implies that the approximate kinematic directions responsible for these fabrics are also preserved. Due to the similarity in the orientation of the gneisses of the Thompson Belt, it follows that the kinematic Z axis for all classifiable fabrics has been approximately horizontal and perpendicular to the trend of the Thompson Belt, while the kinematic X axis is approximately vertical. These orientations, preserved at different stages of the orogeny support the tectonic model by Fueten & Robin (1989), in which the Thompson Belt is considered to be a zone of dip-slip movement with vertical elongation and horizontal shortening.

Comparison with Saxony granulites

The Saxony granulites are the site of arguably the most extensive study of *c*-axis fabrics. In the Saxony granulites a granulite core, 40 × 15 km (Starkey 1979), is rimmed by rocks of progressively lower grade. The suite of mylonites ranges from greenschist to granulite grade (Behr 1980), with peak metamorphic conditions of approximately 800°C and 11 kb (Behr 1980). In the granulite-grade rocks the matrix quartz grain size ranges between 100 and 500 μm while relict grains may measure more than 1 mm in diameter (Starkey 1979). In grain size distribution the Saxony granulites therefore appear to be similar to the gneisses of the Thompson Belt. The highest metamorphic grade in the Saxony granulites has similar temperatures, but higher pressures, than the granulite grade in the Thompson Belt. Behr (1980) presents fluid inclusion data for the Saxony granulites, which are not available for the Thompson Belt.

Behr (1961, 1980), Hoffman (1974, 1975) and Lister & Dornsiepen (1982, fig. 2) report systematic variations in the quartz *c*-axis fabric with metamorphic grade. The highest metamorphic grade in the Saxony granulites is characterized by a small-circle girdle fabric. In the Thompson Belt the only small-circle girdle fabrics were found in the block with the lowest metamorphic grade. In the rim of the Saxony granulites and in portions of upper-amphibolite facies rocks, small-circle fabrics grade into Type II crossed girdles with three mutually orthogonal Maxima at positions I and III. These fabrics are identical to the Maxima III fabrics found in the central portions of the Centre Block. The Thompson Belt granulite temperatures of 700–850°C (Paktunç & Baer 1986) compare well with the temperature range of 600°–850° over which these fabrics are found in the Saxony granulites. The pressures of the Thompson Belt granulites (9–9.7 kb, Paktunç & Baer 1986) are higher than those of the Saxony granulites (approximately 4–7 kb, Behr 1980).

The angle between the individual girdles of the Type 1 and Type II crossed girdle fabrics of the Saxony granulites decreases gradually with decreasing metamorphic grade, but is also affected by changes in lithology (Lister & Dornsiepen 1982). In the Thompson Belt Type I crossed girdles are found in both the NW and the Centre Block, but no systematic changes in opening angle were observed. The fabrics occur in rocks with a hornblende–biotite assemblage as well as in rocks with a biotite–muscovite–chlorite assemblage. In both the Thompson Belt and the Saxony granulites, Type I crossed girdles appear to have formed over a wide range of temperature.

With decreasing metamorphic grade, crossed girdle fabrics in the Saxony granulites grade into fabrics with peaks developed at Maxima II or between Maxima I and II (Behr 1980). Behr (1980) considers fabrics with peaks at Maxima I or II to occur at 250–400°C and 1–2 kb. Hoffman (1974, 1975) notes the appearance of fabrics at Maxima I or II at conditions of approximately 6 kb and 600°C and indicates a tendency for this fabric to develop better towards greenschist facies. In the Thompson Belt, fabrics with tightly developed peaks between Maxima I and II are associated with the late Churchill-side-up shear event which is linked to chlorite alteration.

Single girdle fabrics with peaks at Maxima I occur in the Saxony granulite terrain (Lister & Dornsiepen 1982, fig. 2). Behr (1980) does not distinguish between metamorphic conditions for fabrics with peaks at Maxima I or II. In the Thompson Belt single girdles only occur in the NW Block. These however do not have peaks at Maxima I but always have maxima which are approximately 10° away from the Maxima I position.

In summary, the fabric variations reported in the Saxony granulites compare well with those observed in the Thompson Belt gneisses. The two major differences are: (1) the small-circle girdle fabric found at the highest metamorphic grade in the Saxony granulites occurs at the lowest metamorphic grade here; and (2) fabrics with peaks at Maxima I, present at the lowest metamorphic grade in the Saxony granulites, are not present at the lowest metamorphic grade in the Thompson Belt gneisses. In both Saxony granulites and Thompson Belt gneisses, Type II crossed girdles with peaks at Maxima I and III occur in granulite-grade rocks. However in the Thompson Belt the strongest Maxima III fabric occurs at a lower metamorphic grade. Type I crossed girdles are found in a range of amphibolite-grade conditions in both localities. The variation in angles between the crossed girdles observed in the Saxony granulites was not observed in the Thompson Belt gneisses. However a much more extensive study would be needed in the Thompson Belt to detect such changes. Fabrics with peaks close to Maxima II are present in both localities at 'low' metamorphic grades.

Overall there is some correlation in the variation of fabrics between the Thompson Belt and the Saxony granulites. This suggests that temperature is a very significant factor influencing the fabric development by controlling the activation of a glide system. However the observed differences indicate that other factors, such as heterogeneity in rock type and deformation, also strongly influence the occurrence of fabrics. The differences appear to be most pronounced in the retrogressed blocks, suggesting that the deformation is more heterogenous here. The similarity between fabrics may suggest that granulite regions which are preserved between lower metamorphic grade shear zones, undergo a significant amount of coaxial deformation with only a minor non-coaxial component. The weakening of rocks by fluid influx and metamorphic reactions associated with retrogression is significant enough to concentrate the simple shear component in the lower grade rocks and to give rise to more heterogeneous deformation in those regions.

CONCLUSIONS

(1) Well developed quartz *c*-axis fabrics were found in many gneisses, even if they were coarse grained and poorly lineated. In a regional study some rocks yield *c*-axis fabrics that are difficult to classify; however these ambiguities do not detract from the overall usefulness of this method. Quartz *c*-axis fabrics are potentially useful in the study of most gneissic terrains.

(2) In the quartzo-feldspathic rocks studied here, *c*-axis fabrics that could be used as kinematic indicators were almost only found in rocks which also contained other asymmetric structures which could have served as kinematic indicators. The development of a *c*-axis fabric, which is useful as a kinematic indicator therefore requires as much strain as the development of other kinematic indicators in the rock. However the destruction of that fabric requires less strain than the destruction of other kinematic indicators.

(3) Fabrics with peaks at Maxima II formed primarily by glide on positive or negative rhombs in the ⟨*a*⟩ direction. The Maxima III and I fabrics formed by glide on the basal ⟨*a*⟩ and on the prism ⟨*a*⟩ system. Fabrics with a peak at Maximum V indicate basal glide. Different slip systems therefore formed the easy glide systems at different times of the orogeny.

(4) Maxima II fabrics and Maxima III fabrics were found to be consistently asymmetric. These fabrics should be symmetric if they had formed from a random population. Polar asymmetry in fabrics which should be symmetric is taken as evidence that the fabric is a secondary fabric, overprinting an earlier preferred crystallographic orientation.

(5) A variety of *c*-axis fabrics in the Thompson Belt are preserved throughout a significant portion of the orogeny. The fabrics can be explained in the context of the tectonic model for the Thompson Belt. The region of preserved granulite grade formed a competent block, which deformed coaxially, for the remainder of the orogeny. Simple-shear deformation took place on narrow discrete shear zones. In the NW Block, compe-

tency contrasts due to differences in lithologies probably contributed to a more heterogeneous deformation.

(6) There is some similarity between the distribution of *c*-axis fabrics in the Thompson Belt and the Saxony granulites.

The study of the quartz *c*-axis fabrics in the gneisses of the Thompson Belt has added to the knowledge of the regional deformation. The quartz *c*-axis fabric work supports the tectonic model of the Thompson Belt proposed by Fueten & Robin (1989). The results of the work presented here suggest that regional quartz *c*-axis fabric variations, tedious as the work may be, will be useful for studying the deformation history of other high-grade gneiss terrains.

Acknowledgements—The manuscript has greatly benefitted from reviews by R. D. Law and G. S. Lister. The author also wishes to thank P. MacKinnon, J. R. Henderson, P.-Y. F. Robin and J. Starkey for reviews and comments. Support for this work was provided by contracts from the Department of Supplies and Services Canada and Natural Sciences and Engineering Research Council operating grants to P.-Y. F. Robin.

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