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Shear criteria in the Grenville Province, Ontario, Canada

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Abstract—The Grenville Province of Canada is a major Proterozoic orogenic belt. Mapping and structural analysis shows that the central Ontario segment of this belt is composed of a stack of imbricated thrust nappes separated by mylonite zones. The mylonite zones were generated at high metamorphic grades and contain a distinctive assemblage of mesoscopic and microscopic asymmetric structures. These structures include rotated tectonic inclusions, rotated boudins and pinch-and-swell structures, sheath folds, rotated single-crystal porphyroclasts, single crystal 'fish', and shear band foliation. The shear asymmetry indicated by these structures is highly consistent between members of the assemblage, and over a large area of the Grenville province, and shows that the thrust nappes were transported to the northwest. The consistency of the structures is thought to be due to cyclical dynamic recrystallization leading to steady-state foliations in the mylonites.

INTRODUCTION

THE Grenville Province of Canada is a major Proterozoic orogenic belt. It trends NE–SW and stretches continuously from the Great Lakes in the west to the Labrador coast in the east. The belt in Canada is thus nearly 2000 km long, with a width of approximately 400 km.

The central Ontario segment of this belt (Fig. 1, Central Gneiss Belt) is divisible into several major thrust nappes separated by relatively thin shear zones (Davidson *et al.* 1982, Schwerdtner & Mawer 1982, Davidson 1984), based on detailed lithological mapping and structural analysis. The mylonites within these shear zones contain a distinctive assemblage of asymmetric structures which indicate a consistent sense of movement for the nappes. Syntectonic mineral textures and assemblages indicate the mylonites were formed at deep crustal levels.

In this paper, the various meso- and microstructural shear sense criteria found in the Grenville mylonites are described, and their reliability in deep-crustal situations evaluated and discussed. The main reason for this is to determine whether such shear sense criteria are comparable in geometry and reliability to those used for higher structural levels (e.g. Berthé *et al.* 1979, Simpson & Schmid 1983, Lister & Snoke 1984). There seems no immediately apparent *a priori* reason why they should be. At lower crustal conditions, different deformation and recrystallization mechanisms may operate, competency contrasts between various rock types may be vastly reduced, rates and styles of deformation may be considerably different, shear may be widely distributed rather than localized, and shear strains at the outcrop scale may be small. Hence, resultant small-scale structures might have a totally different significance with respect to the overall deformation.

THE HOST ROCKS, SHEAR ZONES AND MYLONITES

Most of the central Ontario segment of the Grenville Province consists of rocks of the Central Gneiss Belt (Wynne-Edwards 1972) (Fig. 1). These gneisses have both igneous and sedimentary protoliths, and are generally at high metamorphic grade (upper amphibolite to granulite grade, temperatures of 750–850°C; Davidson *et al.* 1982, Schwerdtner & Mawer 1982, Culshaw *et al.* 1983). Geobarometry and petrography of gneisses in the central part of this area indicate syntectonic pressures of 9–11 kbar (Anovitz & Essene 1985, 1986). Orthogneisses locally preserve primary igneous textures, but most gneisses are recrystallized and show typical high-grade annealing textures (Vernon 1968). The gneisses are

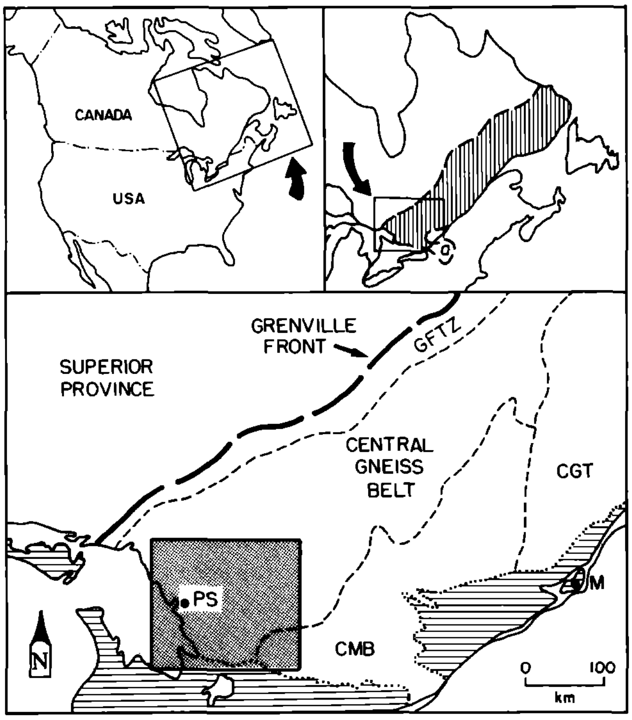

Fig. 1. Location map. Upper left—North America. Upper right—the Grenville Province (ruled). Lower-case 'a' indicates Adirondack Mountains. Lower—the western Grenville Province of Canada. Study area is shaded, and large-scale tectonic divisions are shown. GFTZ—Grenville Front Tectonic Zone; CGT—Central Granulite Terrain; CMB—Central Metasedimentary Belt; PS—town of Parry Sound; M—city of Montréal.

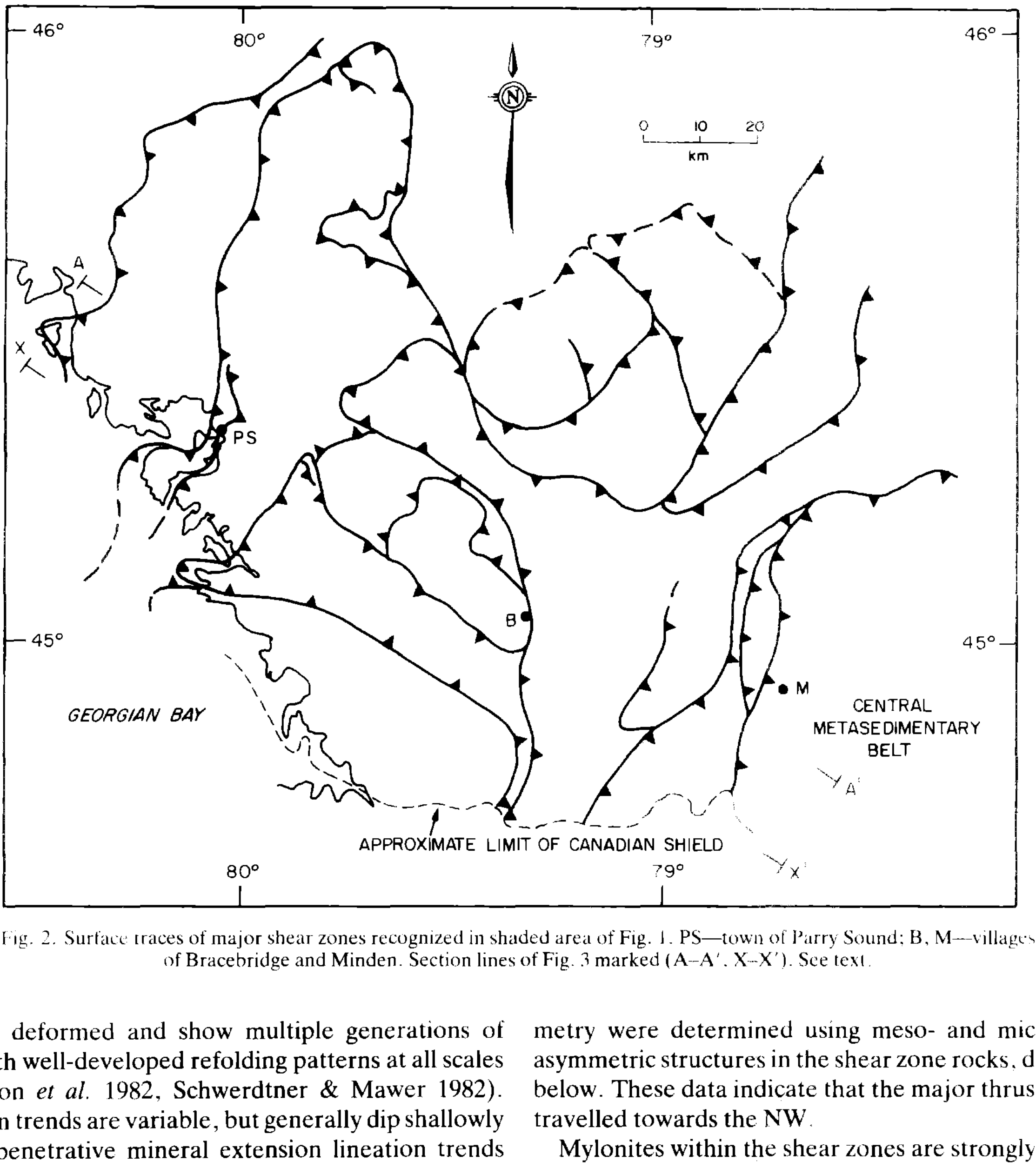

Fig. 2. Surface traces of major shear zones recognized in shaded area of Fig. 1. PS—town of Parry Sound; B, M—villages of Bracebridge and Minden. Section lines of Fig. 3 marked (A–A', X–X'). See text.

strongly deformed and show multiple generations of folds with well-developed refolding patterns at all scales (Davidson *et al.* 1982, Schwerdtner & Mawer 1982). Foliation trends are variable, but generally dip shallowly SE. A penetrative mineral extension lineation trends NW–SE and generally plunges SE. Elliptical domes with diameters of several km are common, and are late features as they fold foliation, lineation and pre-existing folds, and warp the shear zones on a regional scale. The domes internally show a unidirectional mineral extension lineation which again trends NW–SE.

Surface traces of the major shear zones in this part of the Grenville Province are sinuous and anastomosing (Fig. 2). The shear zones separate gneissic domains with quite different petrological, structural, metamorphic and geophysical character (Davidson *et al.* 1982, Schwerdtner & Mawer 1982, Culshaw *et al.* 1983, Lindia *et al.* 1983). The zones generally dip shallowly, and are commonly only about 500 m to 1 km in true thickness although zone boundaries are diffuse (Schwerdtner & Mawer 1982). The shear zones truncate the structural grain of underlying gneisses in many places. Figure 3 shows cross-sections constructed approximately parallel to the tectonic transport direction (section lines marked on Fig. 2). The transport direction was determined using extension lineation trends and senses of shear asymmetry were determined using meso- and microscopic asymmetric structures in the shear zone rocks, described below. These data indicate that the major thrust nappes travelled towards the NW.

Mylonites within the shear zones are strongly foliated and generally well-lineated. The mineral extension lineation within the mylonites again trends NW–SE, and is defined by elongate mafic minerals (pyroxene, amphibole, biotite and trains of garnet crystals), and elongate feldspar and quartz crystals, and recrystallized aggregates (White & Mawer 1986). Mineral foliation and compositional layering in the mylonites anastomose around ellipsoidal pods of less-deformed rocks, a feature typical of shear zones (e.g. Bell 1978). The mylonites generally, but not always, show a reduction in grain size when compared to their host gneisses.

The mylonites commonly show syntectonic retrograde mineral assemblages, although this retrogression is patchy and not pronounced (White & Mawer 1986). Irregular volumes of mylonite with syntectonic granulite grade assemblages can be found (Tremblay 1986, White *et al.* 1986). This relationship indicates that small amounts of hydrous fluids (or fluids with low water activities) reacted with the mylonites, that the fluid distribution was inhomogeneous, and that introduction of the fluids was syntectonic (see also White & Mawer

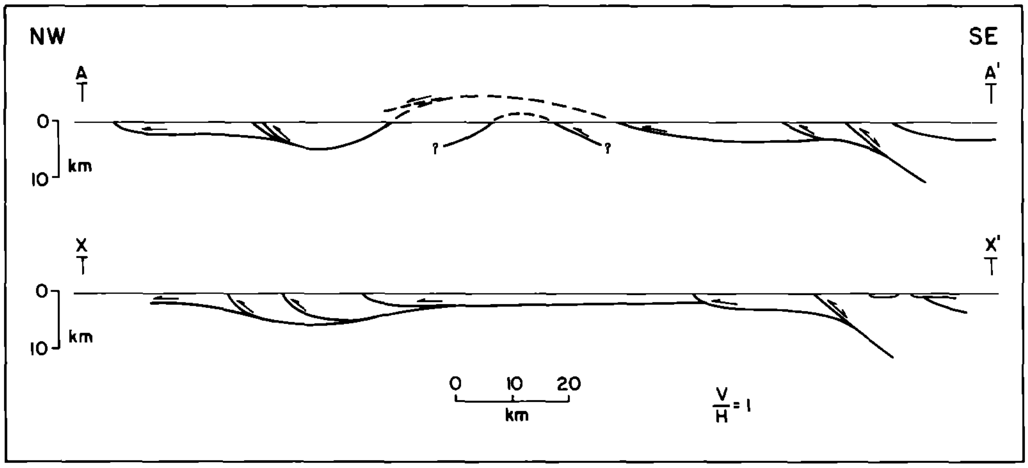

Fig. 3. Cross-sections constructed along lines A–A′ and X–X′ of Fig. 2. See text.

1986). The mylonites also show spectacular crystal plastic deformation microstructures, including tight to isoclinally folded single crystals of alkali and plagioclase feldspars (White & Mawer 1986, fig. 2) and dynamic recrystallization of amphibole.

MESOSCOPIC SHEAR CRITERIA INDICATORS

While the mineral extension lineation measured in mylonite outcrops gives the *trend* of displacement across the shear zones, the *sense* of displacement is determined by structures which exhibit an asymmetry (with respect to foliation and shear zone boundaries) and which developed during the shearing process. The Grenville Province mylonites preserve a diverse assemblage of such asymmetric structures whose genetic relationship to the shearing is shown by three features.

First, the asymmetric structures generally have monoclinic symmetry, their mirror plane parallel to the extension lineation and perpendicular to the mylonitic foliation. Secondly, the asymmetric structures show a remarkably consistent sense of asymmetry, both among different features in the same outcrop and between widely separated outcrops. Their asymmetry is in the same sense and in the same direction as asymmetric folds and reclined gneissic domes in the host rocks. Thirdly, petrological criteria (e.g. Schwerdtner & Mawer 1982, Davidson 1984, White & Mawer 1986, 1987) indicate various asymmetric structures developed syntectonically with mylonite formation.

Mesoscopic asymmetric structures in the Grenville Province mylonites are better preserved than almost all microstructures. The main reasons for this are that at the microscopic scale dynamic and metadynamic (Petković-Djaić & Jonas 1972) recrystallization and grain boundary adjustment are pervasive. Fine textural details are not commonly preserved, except in the notable case of features developed from, and associated with, late pegmatites (see below). Structures developed at the scale of tens to hundreds of grains *are* preserved, however, although late syntectonic grain size and shape changes may make them less obvious than similar features developed in lower-grade mylonites. In the figures which illustrate the various asymmetric structures, generally only one structure is shown, but in all cases there are independent and supporting indicators present in the same outcrop.

Intrafolial folds are common in the shear zones of this part of the Grenville Province. They vary in tightness from open to isoclinal, are invariably asymmetric and are reclined towards the NW. Fold profiles can be harmonic or strongly disharmonic and classic sheath folds are not uncommon. The folds vary in amplitude from less than 1 cm to several tens of meters (Schwerdtner & Mawer 1982, Davidson *et al.* 1982). The asymmetric intrafolial folds in the shear zones consistently indicate a NW-directed overthrusting sense of displacement.

Extensional structures are very common in the shear zones. Both symmetric and asymmetric foliation boudinage occur (Platt & Vissers 1980), as well as the more normal pinch-and-swell structures (Fig. 4a) and boudinage of layers of different composition to the host mylonites (Fig. 4b). The asymmetric foliation boudinage structures are in effect macro-shear bands (White *et al.* 1980) and fulfil the same mechanical function: that is, localized strain softening in a highly strained, foliated mass. Pinch-and-swell structures and boudins in the shear zones commonly show rotation with respect to foliation and shear zone boundary. The senses of rotation are different, with swells rotating antithetically ('back-rotating') and boudin tips rotating synthetically with respect to overall shear sense (Fig. 4a & b). A model for this rotation has been proposed by Hanmer (1986). The respective senses of rotation of the structures are consistent and the structures thus form reliable sense-of-shear indicators in these rocks.

Tectonic inclusions are an extremely distinctive feature of the Grenville Province shear zones. They have been observed at all scales, and a wide range of rock types is represented in the inclusion suite. The inclusions may be (apparently) locally-derived, with compositions similar or identical to the shear zone wall rocks: for example, various types of ortho- and paragneiss, including granitic gneiss, gabbro, rusty-weathering graphitic schist. Exotic rock types are also common such as anorthositic gabbro and coronitic gabbro inclusions in felsic mylonites, meta-eclogite inclusions, felsic inclusions containing plagioclase–sapphirine–spinel segregations in upper amphibolite grade felsic mylonites. The tectonic inclusions are generally internally foliated, and their foliation is either discordant to the surrounding mylonitic foliation or sigmoidal with respect to it (Fig. 4c & d). Many inclusions are rotated, and can be interpreted to indicate NW-directed overthrusting (Fig. 4c) (Ghosh & Ramberg 1976). Some inclusions are extended and then folded, with similar asymmetry (Fig. 4d) (Passchier & Simpson 1986).

Pegmatite dykes and the remains thereof are found everywhere in these shear zones. Pegmatite dykes seem to be preferentially concentrated in the shear zones, and can form in excess of 15% of the total shear zone volume. The dykes are of several generations, shown by differing mineralogies and cross-cutting relationships. They are invariably deformed, sometimes intensely. The pegmatite dykes generally cross-cut the mylonitic foliation, albeit at very low angles when strongly deformed. Less-deformed pegmatites show partial dynamic recrystallization, and appear more-or-less intact. As deformation of the dykes becomes more intense, they start to disaggregate. Individual single-crystal porphyroclasts (but note brittle fracturing was not involved in their formation; see White & Mawer 1986) become more and more dispersed as deformation intensity increases, the whole mass joined by finely recrystallized pegmatite minerals (Fig. 5a & b) (White & Mawer 1986; see also Davidson *et al.* 1982, Schwerdtner & Mawer 1982, Davidson 1984). This progression is due to rotation of the pegmatite dykes towards the extension direction and their contemporaneous extension during shearing, the whole accommodated by dynamic recrystallization. Finally, in the most deformed pegmatites isolated porphyroclasts are observed, joined to one another by long, narrow recrystallized tails (Fig. 5a & b).

The porphyroclasts are generally asymmetric with respect to the mylonitic foliation surrounding them (cf. Berthé *et al.* 1979, Simpson & Schmid 1983, Lister & Snoke 1984). Two distinct geometries are seen, apparently based mainly on porphyroclast aspect ratios, although intermediate shapes between these two end-members occur. Equant porphyroclasts (plagioclase, alkali feldspar, garnet and amphibole have been observed in outcrop) are rotated according to the model of Ghosh & Ramberg (1976): examples are Fig. 5(a) & (c), upper left grain of Fig. 6(a), and hornblende of Fig. 6(b). These are equivalent to the δ-porphyroclasts of Passchier and Simpson (1986). Elongate porphyroclasts (plagioclase, alkali feldspar, pyroxene, allanite and amphibole have been observed in outcrop) show recrystallized tails emanating from upper leading and lower trailing edges (Figs. 5b & d and 6). These are equivalent to the 'fish' of Lister & Snoke (1984) and the σ-porphyroclasts of Passchier & Simpson (1986). Both types of porphyroclast can be interpreted as showing a NW-directed overthrust sense of displacement across the shear zones, according to the models and observations referenced above. The rotation axis of the rotated porphyroclasts is approximately perpendicular to the extension lineation of the mylonites.

The δ-porphyroclasts may be derived from σ-porphyroclasts in deep-crustal settings like the Grenville Province by progressive dynamic recrystallization (see also Passchier & Simpson 1986). This is shown in

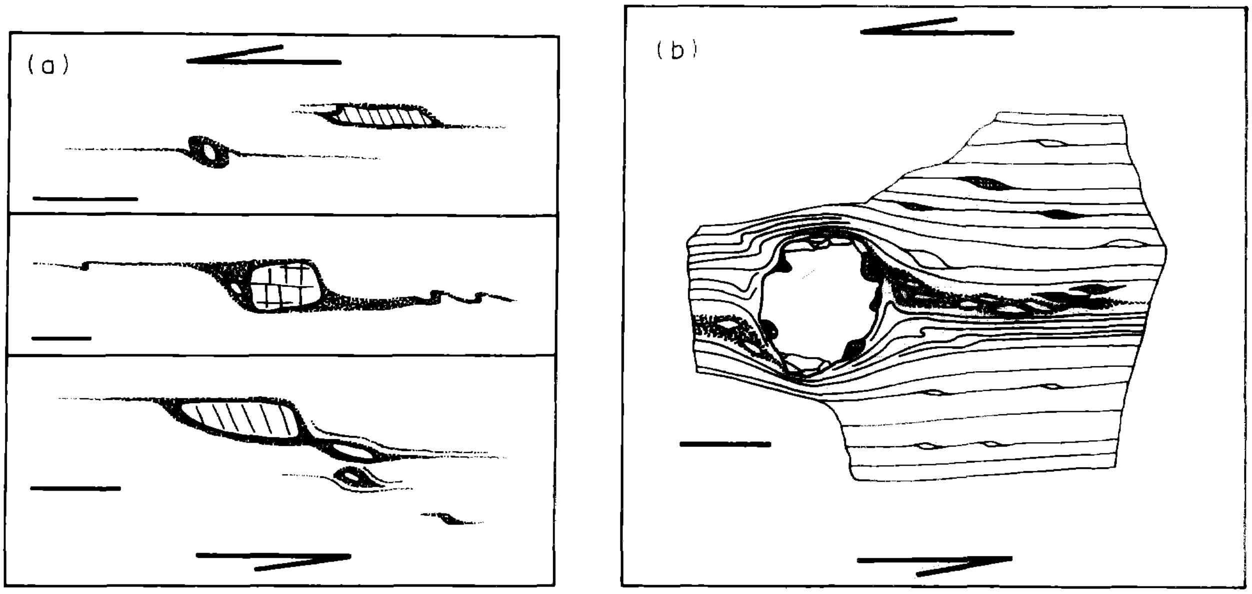

Fig. 6(a). Tracings from polished sections of granitic mylonites, showing K-feldspar porphyroclasts and recrystallized mantles and tails. Top left-hand crystal is a δ-porphyroclast, the others are σ-porphyroclasts. All from vertical sections, viewed towards NE, tops displaced to left. Scale bars 1 cm. (b) Tracing from a polished section of granitic mylonite, matrix foliation trends shown by fine lines. Large rotated δ-porphyroclast and smaller σ-porphyroclasts of amphibole (unornamented), and σ-porphyroclasts of K-feldspar (cross-hatched). Vertical section viewed towards NE, top displaced to left. Scale bar 2cm.

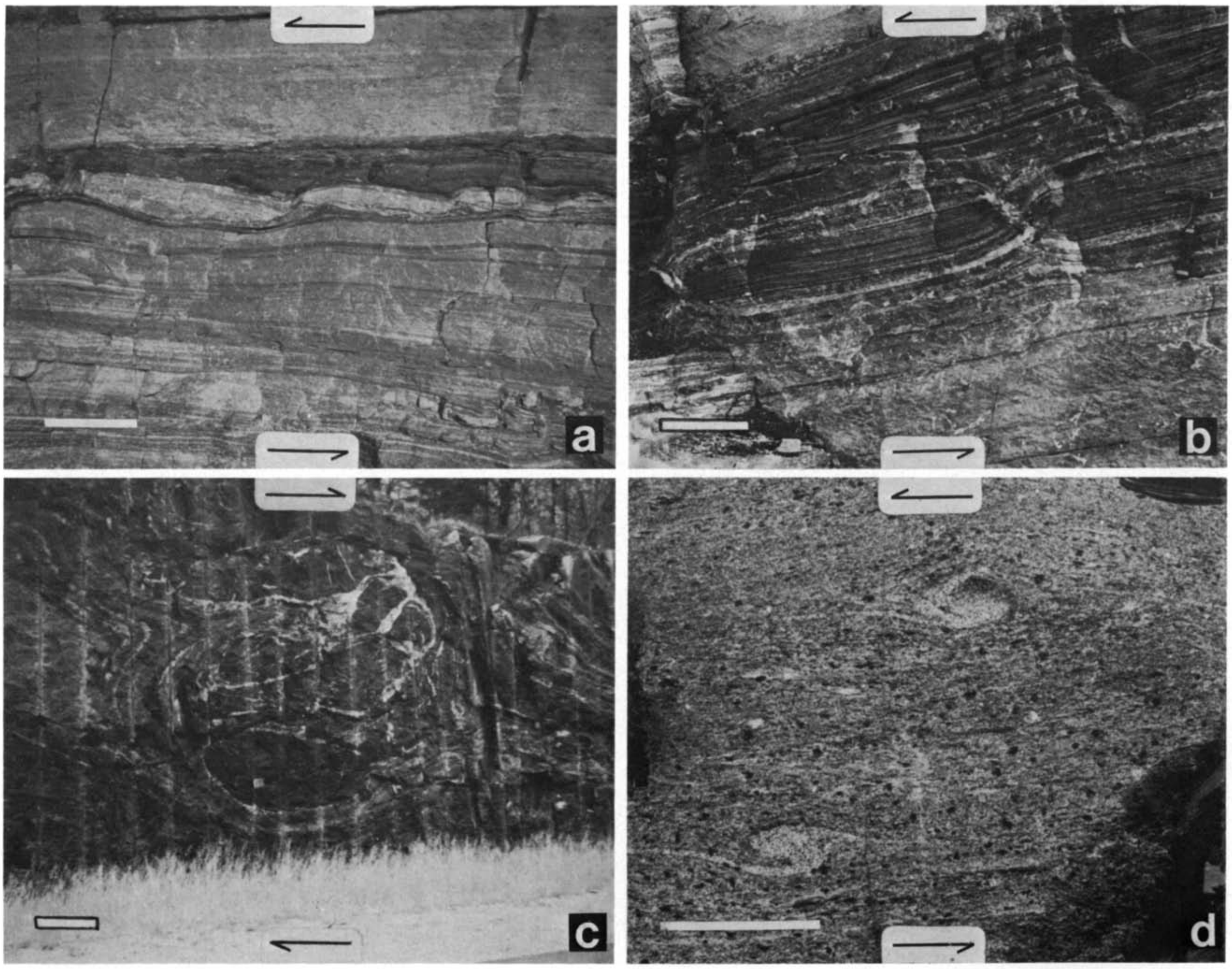

Fig. 4(a). Back-rotated pinch-and-swell structures. View towards NE, top displaced to left. Scale bar 30 cm. (b) Rotated boudins; view towards NE, top displaced to left. Note pegmatite in boudin necks. Scale bar 30 cm. (c) Large rotated tectonic inclusion. Regional foliation dips shallowly to right; view towards SW, top displaced to right. Scale bar 1 m. (d) Extended and folded tectonic inclusions. View towards NE, top displaced to left. Scale bar 10 cm.

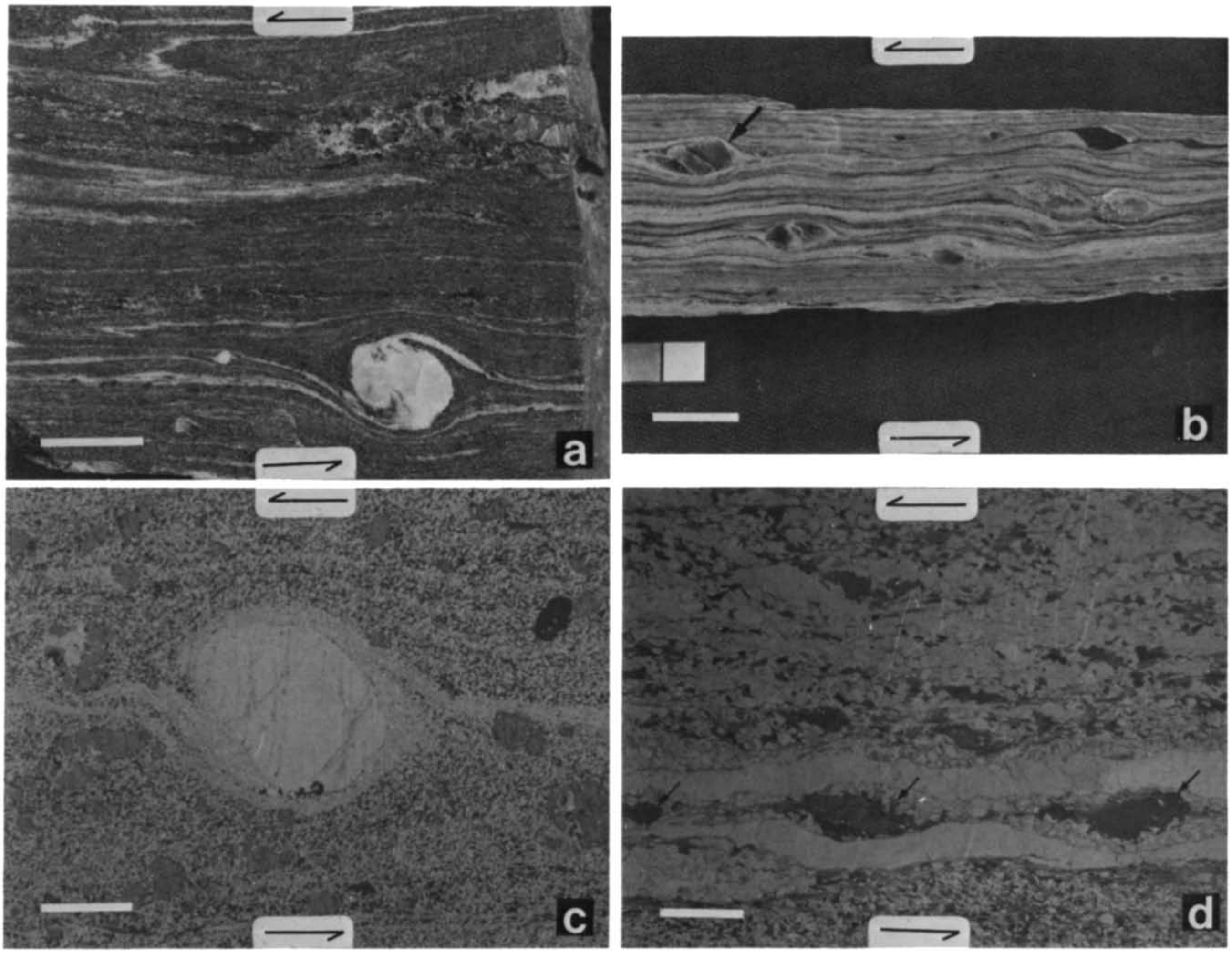

Fig. 5(a). Section of leucogabbro mylonite with rotated plagioclase porphyroclast and asymmetric folds of recrystallized tails. Vertical section, view to NE, top displaced to left. Scale bar 2 cm. (b) Section of granitic mylonite with feldspar and amphibole σ-porphyroclasts (most feldspar crystals are K-feldspar, plagioclase arrowed). Also note weakly-developed open shear bands. Vertical section, view to NE, top displaced to left. Scale bar 2 cm. (c) Rotated plagioclase δ-porphyroclast in leucogabbro mylonite. Recrystallized tails extend to ends of oversize thin section with no decrease in thickness—right hand tail is 61 mm long. Vertical section, view towards NE, top displaced to left. Plane polarized light. Scale bar 2 mm. (d) 'School' of hornblende 'fish' (arrowed) in leucogabbro mylonite. Vertical section, view to NE, top displaced to left. Plane polarized light. Scale bar 2 mm.

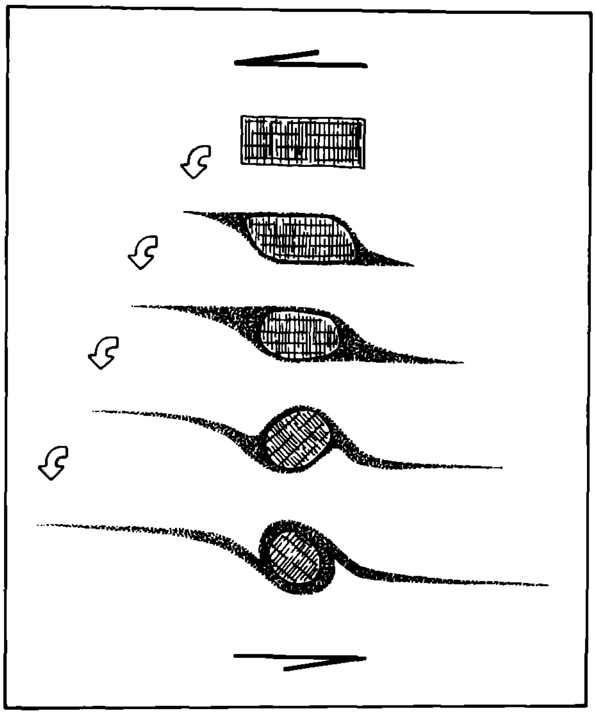

Fig. 7. Schematic diagram showing sequence of development of δ-porphyroclasts from σ-porphyroclasts, due to dynamic recrystallization causing decrease in porphyroclast aspect ratio, and subsequent porphyroclast rotation.

schematic form in Fig. 7. All steps of the process have been observed in outcrop or thin section in the Grenville Province mylonites.

Shear band foliation (White *et al.* 1980) is observed locally in the mylonites. It is generally developed in finer-grained mylonites with strong dimensional preferred orientation of mafic grains or quartz ribbons, or both. It seems to have developed late in the history of the zones, as it commonly overprints earlier structures. The shear bands also indicate NW-directed overthrusting.

MICROSCOPIC SHEAR CRITERIA INDICATORS

While microscale asymmetric features occur everywhere in the Grenville Province mylonites, they are commonly not as obvious as similar features in lower-grade rocks. There are probably two reasons for this. First, high syntectonic temperatures allowed rapid dynamic recrystallization and grain boundary adjustments, both of which tended not to allow high grain strains to accumulate (though the late syntectonic pegmatites are an obvious exception to this; White & Mawer 1986, 1987). Second, late metadynamic and static recrystallization (e.g. Culshaw & Fyson 1984) have further tended to obscure the geometry of such features. Nevertheless, asymmetric structures developed at the scale of tens to hundreds of matrix grains are preserved, and can be reliably interpreted in terms of shear sense.

Asymmetric single-crystal porphyroclasts are ubiquitous in the high-grade mylonites, and range in scale from those observable in outcrop to those 1 mm or less in diameter (Figs. 5a–d and 6). Two distinct shape groups are seen (again corresponding to the δ- and σ-types of Passchier & Simpson 1986), as well as intermediate shapes. They are commonly feldspar crystals; plagioclase, microperthitic K-feldspar and microcline have been observed. Several other minerals occur as porphyroclasts, including garnet, hornblende, clinopyroxene, sphene, biotite and allanite. They have identical geometry to the mesoscopic porphyroclasts, and invariably indicate the same sense of shear. Individual porphyroclasts are generally connected by long recrystallized tails of the same mineral (e.g. Fig. 5c & d). These porphyroclasts show spectacular internal crystal-plastic deformation effects, such as extreme stretching, wide core-and-mantle structures and folding (individual feldspar crystals), and dynamic recrystallization (feldspar and hornblende crystals; White & Mawer 1986, 1987; H.-R. Wenk pers. comm. 1986).

Shear bands are locally observed, and are geometrically similar to the mesoscopic examples. They indicate the same shear asymmetry.

Other indicators of shear sense are present. Rarely, oblique grain-shape foliations (e.g. Lister & Snoke 1984, Burg 1986) are seen in the mylonites. These appear to be late-stage features, and are generally not well developed. When found, they can be interpreted to show the same shear asymmetry as other indicators in the same thin section and hand sample.

Asymmetric quartz *c*-axis preferred orientations can be measured, although a problem is that the rocks richest in quartz (mylonitic meta-arkose and granitic gneiss) are commonly quite coarse-grained and it can be difficult to measure enough grains to ensure good counting statistics (in any case, such rocks may only develop relatively weak preferred orientations; Starkey & Cutforth 1978). A further problem in these rocks is the common metadynamic recrystallization (Petković-Djaić & Jonas 1972, Culshaw & Fyson 1984). This further coarsens quartz grain size and makes preferred orientations diffuse, although it does not completely destroy them. The limited work done with such patterns to date (Culshaw 1983, Mawer 1983, Culshaw & Fyson 1984) has shown that weak asymmetric single girdles occur, inclined to the mylonitic foliation in a sense consistent with NW-direction overthrusting across the shear zones (e.g. Price 1985).

DISCUSSION

Indicators of shear asymmetry in the high-grade Grenville Province mylonites are remarkably similar to features described from lower-grade shear zones (e.g. Berthé *et al.* 1979, White *et al.* 1980, Simpson & Schmid 1983, Lister & Snoke 1984, Weijermars & Rondeel 1984, Mawer & White 1987), and are localized in relatively narrow zones (Davidson *et al.* 1982, Schwerdtner & Mawer 1982). This suggests that *relative* competence contrasts in these rocks are similar to those in lower grade rocks. Further, although deformation mechanisms, rates and microscopic deformation style in such high-grade rocks are different from those at lower grades (e.g. Goode 1978, Frost & Ashby 1982, White & Mawer 1986, 1987), the resultant structures are quite similar. This indicates that major shear zones can be delineated in old, highly deformed rocks. Such delineation (or otherwise) is fundamental to determining Archaean and Proterozoic tectonic styles.

The major differences come at the microscopic scale. Efficient dynamic recrystallization and very late- to post-tectonic recrystallization and grain boundary movement in high-grade shear zones can severely modify the micro-scale appearance of shear asymmetry indicators. For example, oblique foliations defined by elongate subgrains and dynamically recrystallized grains (e.g. Burg 1986, Law *et al.* 1986), may have been removed, or perhaps were never strongly developed. Quartz *c*-axis preferred orientation, if not considerably weakened, can result from uncommon slip system combinations (cf. Mainprice *et al.* 1986) and be difficult to interpret. The pattern of *c*-axis preferred orientation can be diffuse and difficult to recognize due to large grain size and corresponding difficulty in determining a statistically-valid number of axial orientations within a homogeneously-deformed domain. Characteristic dynamic recrystallization textures may be destroyed by metadynamic or static recrystallization. Optical deformation features (e.g. undulose extinction, and subgrains) and TEM-scale features (e.g. dislocation arrays and networks) can be minimized or removed due to efficient dislocation climb via rapid diffusion rates at high temperatures (White & Mawer 1986, 1987). Different deformation mechanisms may have operated, perhaps making a major contribution to the total deformation (e.g. Nabarro-Herring creep as opposed to dislocation creep; Frost & Ashby 1982, White & Mawer 1986) and yielding unfamiliar or ambiguous microstructures.

The assemblage of shear asymmetry indicators in the high-grade Grenville Province mylonites described above shows remarkable consistency; in single outcrops, from outcrop to outcrop, and across several thousand square km of terrain. The assemblage indicates that displacement across the shear zones was directed towards the NW, in overthrust sense. At least the part of the Grenville Province northwest of the Central Metasedimentary Belt boundary (Fig. 1) consists of a series of imbricated thrust nappes which may have caused considerable crustal thickening. This last point is not yet proven: while displacement across the shear zones seems to have been considerable (at least tens of km; Mawer 1983, Davidson 1984), it is extremely difficult to quantify finite strain in these zones; and while the present dip of the shear zones is not great, this says little about their original dip nor do the asymmetric structures. They indicate that the bulk deformation was *non-coaxial* but not whether the bulk deformation was *rotational* (see Lister & Williams 1983). All that can be said at present is that much of the rock in this part of the Grenville Province was, at one time, at crustal depths of 30–40 km (e.g. Anovitz & Essene 1985, 1986). Whether this was at the base of a moderately thick crust, or half-way down a doubled crust, remains to be shown. A promising way to tackle this problem is by attempting to erect P–T–t paths (e.g. Spear & Selverstone 1983, England & Thompson 1984), and preliminary work has begun towards this end. These data can then be used to better constrain deep-crustal deformation mechanisms (e.g. Goode 1978, White & Mawer 1986, 1987).

The consistency of shear asymmetry indicators over large areas deserves comment. Overall deformation in the Grenville Province shear zones appears remarkably homogeneous. This homogeneity seems to be the reason for the unambiguous nature and reliability of members of the assemblage of shear indicators. The homogeneity probably results from efficient dynamic recrystallization at elevated syntectonic temperatures. It has been proposed that a steady-state foliation in the sense of unchanging orientation and intensity (Means 1981) developed in some of these shear zones (Mawer 1983, Hanmer 1984), due to cyclical and pervasive dynamic recrystallization.

CONCLUSIONS

(1) High-grade shear zones in the western Grenville Province (Ontario, Canada) exhibit an assemblage of asymmetric structures which indicate the displacement sense. These structures are very similar to features developed in lower-grade shear zones.

(2) The shear asymmetry indicators are remarkably consistent in mylonites outcropping over an area of several thousand square km (at least). They indicate that this region consists of a stack of imbricated thrust nappes, emplaced towards the NW. The consistency of shear indicators seems due to the overall homogeneity of deformation in the shear zones. This homogeneity is probably due to efficient and cyclical dynamic recrystallization, leading to steady-state foliations.

(3) Ancient, high-grade, multiply-deformed gneisses can preserve structures indicative of large-scale shear zones, although these structures are commonly not as obvious as those developed in lower-grade rocks. This fact may have considerable bearing on models of Archaean and early Proterozoic tectonics; 'type areas' for delineation of ancient tectonic styles generally have not been examined in fine detail.

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REFERENCES

Anovitz, L. M., & Essene, E. J. 1985. Metamorphism in the Grenville Province, Ontario. *EOS* **66**, 385–386.

Anovitz, L. M. & Essene, E. J. 1986. Thermobarometry in the Grenville Province, Ontario. GAC/MAC/CGU Joint Annual Meeting, Program with Abstracts 11, 41.

Bell, T. H. 1978. Progressive deformation and reorientation of fold axes in a ductile mylonite zone: the Woodroffe Thrust. *Tectonophysics* **44**, 285–320.

Berthé, D., Choukroune, P. & Jegouzo, P. 1979. Orthogneiss, mylonite and non-coaxial deformation of granites: the example of the South Amorican Shear Zone. *J. Struct. geol.* **1**, 31–42.

Burg, J. P. 1986. Quartz shape fabric variations and *c*-axis fabrics in a ribbon mylonite: arguments for an oscillating foliation. *J. Struct. Geol.* **8**, 123–131.

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. *Geol. Surv. Pap. Can.* **83-1B**, 243–252.

Culshaw, N. G. & Fyson, W. K. 1984. Quartz ribbons in high grade granite gneiss: modifications of dynamically formed quartz *c*-axis preferred orientation by oriented grain growth. *J. Struct. Geol.* **6**, 663–668.

Davidson, A. 1984. Tectonic boundaries within the Grenville Province of the Canadian Shield. *J. Geodyn.* **1**, 433–444.

Davidson, A., Culshaw, N. G., & Nadeau, L. 1982. A tectonometamorphic framework for part of the Grenville Province, Parry Sound Region, Ontario. *Geol. Surv. Pap. Can.* **82-1A**, 175–190.

England, P. C. & Thompson, A. B. 1984. Pressure–temperature–time paths of regional metamorphism I. Heat transfer during the evolution of regions of thickened continental crust. *J. Petrol.* **25**, 894–928.

Frost, H. J. & Ashby, M. F. 1982. *Deformation-Mechanism Maps*. Pergamon Press, Oxford.

Ghosh, S. K. & Ramberg, H. 1976. Reorientation of inclusions by combination of pure shear and simple shear. *Tectonophysics* **34**, 1–70.

Goode, A. D. T. 1978. High temperature, high strain rate deformation in the lower crustal Kalka Intrusion, central Australia. *Contr. Miner. Petrol.* **66**, 137–148.

Hanmer, S. K. 1984. Strain-insensitive foliations in polymineralic rocks. *Can. J. Earth Sci.* **21**, 1410–1414.

Hanmer, S. K. 1986. Asymmetrical pull-aparts and foliation fish as kinematic indicators. *J. Struct. Geol.* **8**, 111–122.

Law, R. D., Casey, M. & Knipe, R. J. 1986. Kinematic and tectonic significance of microstructures and crystallographic fabrics within quartz mylonites from the Assynt and Eriboll regions of the Moine thrust zone, NW Scotland. *Trans. R. Soc. Edinb., Earth Sci.* **77**, 99–125.

Lindia, F. M., Thomas, M. D. & Davidson, A. 1983. Geological significance of Bouguer gravity anomalies in the region of Parry Sound Domain, Grenville Province, Ontario. *Geol. Surv. Pap. Can.* **83-1B**, 261–266.

Lister, G. S. & Snoke, A. W. 1984. *S–C* mylonites. *J. Struct. Geol.* **6**, 617–638.

Lister, G. S. & Williams, P. F. 1983. The partitioning of deformation in flowing rock masses. *Tectonophysics* **92**, 1–33.

Mainprice, D., Bouchez, J. L., Blumenfeld, P. & Tubià, J. M. 1986. Dominant *c*-slip in naturally deformed quartz: implications for dramatic plastic softening at high temperature. *Geology* **14**, 819–822.

Mawer, C. K. 1983. Characteristics of Grenville mylonites, and considerations of strain in shear zones. *J. Struct. Geol.* **5**, 550–551.

Mawer, C. K. & White, J. C. 1987. Sense of displacement on the Cobequid–Chedabucto Fault System, Nova Scotia, Canada. *Can. J. Earth Sci.* **24**, 217–223.

Means, W. D. 1981. The concept of steady-state foliation. *Tectonophysics* **78**, 179–199.

Passchier, C. W. & Simpson, C. 1986. Porphyroclast systems as kinematic indicators. *J. Struct. Geol.* **8**, 831–843.

Petković-Djaić, R. A. & Jonas, J. J. 1972. Static recrystallization of austenite between intervals of hot working. *J. Iron Steel Inst.* **210**, 256–261.

Platt, J. P. & Vissers, R. L. M. 1980. Extensional structures in anisotropic rocks. *J. Struct. Geol.* **2**, 397–410.

Price, G. P. 1985. Preferred orientations in quartzites. In: *Preferred Orientation in Deformed Metals and Rocks: An Introduction to Modern Texture Analysis* (edited by Wenk H.-R.). Academic Press, New York, 385–406.

Schwerdtner, W. M. & Mawer, C. K. 1982. Geology of the Gravenhurst region, Grenville Structural Province, Ontario. *Geol. Surv. Pap. Can.* **82-1B**, 195–207.

Simpson, C. & Schmid, S. M. 1983. An evaluation of criteria to deduce the sense of movement in sheared rocks. *Bull. geol. Soc. Am.* **94**, 1281–1288.

Spear, F. S. & Selverstone, J. 1983. Quantitative P–T paths from zoned minerals: theory and tectonic applications. *Contr. Miner. Petrol.* **83**, 348–357.

Starkey, J. & Cutforth, C. 1978. A demonstration of the interdependence of the degree of quartz preferred orientation and the quartz content of deformed rocks. *Can. J. Earth Sci.* **15**, 841–847.

Tremblay, M.-L. 1986. Structural and microstructural study of the Parry Sound Shear Zone. GAC/MAC/CGU Joint Annual Meeting, Program with Abstracts, **11**, 138.

Vernon, R. H. 1968. Microstructures of high grade rocks at Broken Hill, Australia. *J. Petrol.* **9**, 1–22.

Weijermars, R. & Rondeel, H. E. 1984. Shear band foliation as an indicator of sense of shear: field observations in central Spain. *Geology* **12**, 603–606.

White, J. C. & Mawer, C. K. 1986. Extreme ductility of feldspars from a mylonite, Parry Sound, Canada. *J. Struct. Geol.* **8**, 133–143.

White, J. C. & Mawer, C. K. 1987. Dynamic recrystallization of feldspars from a mylonite zone, Grenville Province, Canada. *J. geophys. Res.* In review.

White, J. C., Tremblay, M.-L., Maitland, G. W. & Mawer, C. K. 1986. Deformation microstructures from granulite facies terrains, Grenville Province, Ontario. GAC/MAC/CGU Joint Annual Meeting, Program with Abstracts, **11**, 144.

White, S. H., Burrows, S. E., Carreras, J., Shaw, N. D. & Humphreys, F. J. 1980. On mylonites in ductile shear zones. *J. Struct. Geol.* **2**, 175–187.

Wynne-Edwards, H. R. 1972. The Grenville Province. In: *Variations in Tectonic Style in Canada* (edited by Price, R. A. & Douglas, R. J. W.). *Geol. Ass. Can. Special Paper* **11**, 263–334.