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Post-collisional oblique convergence along the Thelon Tectonic Zone, north of the Bathurst Fault, NWT, Canada

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Abstract—The Thelon Tectonic Zone (TTZ) separates the Slave from the Churchill (Rae) structural provinces of the northwest Canadian Shield. Along the TTZ in the Tinney Hills–Overby Lake area, collision was initiated with northwestward overthrusting of granulite-facies gneiss onto the Slave province accompanied by thin-skinned shortening of the Proterozoic cover.

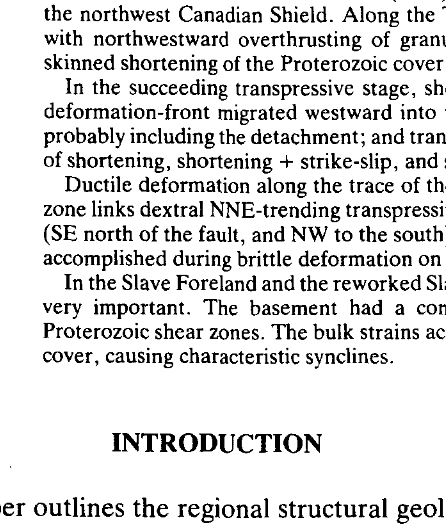
In the succeeding transpressive stage, shortening structures assumed a SE-, rather than NW-, vergence; a deformation-front migrated westward into the Slave craton-edge, causing thick-skinned folding of the cover, probably including the detachment; and transpression was partitioned, in craton edge and allochthon, into zones of shortening, shortening + strike-slip, and strike-slip.

Ductile deformation along the trace of the late NW-striking brittle Bathurst Fault occurred at this time; this zone links dextral NNE-trending transpressive zones, in which the shortening structures have opposite vergence (SE north of the fault, and NW to the south). The last episode of convergence, tectonic escape, may have been accomplished during brittle deformation on the Bathurst Fault.

In the Slave Foreland and the reworked Slave craton-edge, the role of heterogeneous basement deformation is very important. The basement had a complex Archean structure, which was overprinted by systems of Proterozoic shear zones. The bulk strains accomplished by these are expressed as upright folds in the stratiform cover, causing characteristic synclines.

INTRODUCTION

THIS paper outlines the regional structural geology and discusses the tectonics of a segment of the northwest margin of the Thelon Tectonic Zone (TTZ) (Thompson & Henderson 1983), north of the Bathurst Fault (Fig. 1). The TTZ lies along the boundary of the Slave and Churchill (Rae) structural provinces of the Canadian Precambrian Shield (Fig. 1). Its western border coincides with the Thelon Front (Wright 1967), recognized by earlier workers as marking a change in lithology, structure and metamorphism (Wright 1957, Fraser 1968) bounding the structural provinces (Stockwell 1961). The great length of the TTZ contrasts with the structural patterns of the Archean Slave Province and, although its original formation in the Archean cannot be ruled out (Thompson *et al.* 1987), it is clear that the bulk of plutonism and some metamorphism along the known parts of the TTZ and connected mobile belts is early Proterozoic, *ca* 2.02–1.91 Ga (van Breemen *et al.* 1987a,b). It has also been recently recognized that there was both syn-orogenic sedimentation (Campbell & Cecile 1981, Grotzinger & Gall 1986) and thin-skinned deformation related to the TTZ in the early Proterozoic (Tirrul 1985).



TTZ	Thelon Tectonic Zone
GSLSZ	Great Slave Lake Shear Zone
GS	Goulburn Supergroup
CS	Coronation Supergroup
GSS	Great Slave Lake Supergroup
PAL	Paleozoic Cover
BF	Bathurst Fault
MF	McDonald Fault

Fig. 1. Location map (after Hoffman 1987). The study area is outlined.

The TTZ has been interpreted as an analogue of a modern convergent orogen (Hoffman *et al.* 1986, Hoffman 1987), in agreement with earlier geophysical interpretations (Gibb & Thomas 1977, Gibb *et al.* 1983). Hoffman (1988) explained the Great Slave Lake shear zone (Fig. 1) as a continental transform fault with 300–700 km offset related to oblique collisional indentation along the TTZ of the Archean Churchill Province by the Archean Slave Province. In this model the TTZ is continuous with the Great Slave Lake shear zone (cf. Hanmer & Needham 1988) and is part of a 2250 × 80 km plutonic belt formed during both subduction and (micro)-continental collision between 1.91 and 2.02 Ga, with collision at approximately 1.96 Ga (Hoffman 1988). Hoffman (1987), proposed that during oblique convergence, strike-slip motion occurred immediately west of the cryptic suture, the strike-slip belts being overthrust during post-collisional indentation.

The study area is the Tinney Hills–Overby Lake (Thol) map sheet, a 110 × 100 km tract composed largely of crystalline basement rocks lying at the intersection of the western side of the TTZ and the Bathurst Fault (Fig. 1). It is based on compilation of the results of three seasons of 1:250,000 scale regional mapping of more than 10,000 km^2 (Thompson & Ashton 1984, Thompson *et al.* 1985, 1986). This contribution primarily documents basement structures of the Thol map sheet formed during post-collisional convergence along the TTZ. It is argued that most structures in the map area can be understood as expressions of a second stage of post-collisional transpression (Harland 1971) and that the presence of a zone of ductile deformation parallel to the NW-trending Bathurst Fault (Fig. 1) had an important role, in separating zones of significantly different post-collisional history.

LITHOLOGIES

Lithologies are outlined in Thompson & Ashton (1984), Thompson *et al.* (1985, 1986). The Proterozoic cover rocks overlie basement in the west and form several small inliers (Fig. 2). They are dominated by the Goulburn Supergroup (Gb, Figs. 2 and 3) (Campbell & Cecile 1981). In this the basal shallow-shelf quartzite and carbonate sequence (Kimerot Platform) was drowned by the syn-orogenic Bear Creek Foredeep flysch–molasse wedge during the formation of the TTZ (Grotzinger & Gall 1986). The western basement rocks are primarily metasedimentary rocks of the Archean Yellowknife Supergroup of the Slave Province (YkS, Fig. 2), affected by Archean metamorphism (van Breemen *et al.* 1987b). These range from biotite-rich schist and metagreywacke (±cordierite, andalusite and/or staurolite), through sillimanite-bearing rocks, closely associated with bodies of two-mica granite, to sillimanite-bearing migmatite (Thompson *et al.* 1986) (Fig. 2). Granitoid gneisses migmatized in the late Archean (van Breemen *et al.* 1987b), and plutons of tonalitic to dioritic composition, can be traced with near continuity eastward from the northwest where they become volumetrically important (Gg, Fig. 2). Metadiabase–metagabbro bodies, which cut Archean metamorphic fabrics, are abundant in these rocks as far as the granulites (Thompson *et al.* 1986).

To the east of the Slave Province rocks, extending beyond the map boundary, is an allochthonous zone composed of locally retrogressed granulites of unknown

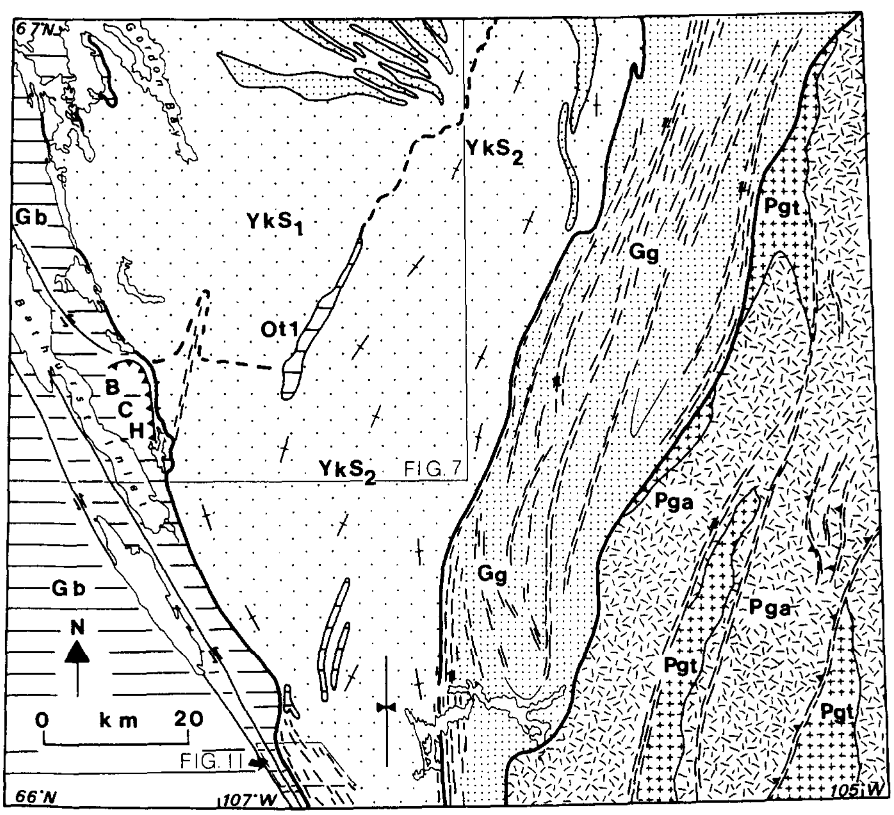


Fig. 2. Lithotectonic map of Tinney Hills–Overby Lake map sheet. Based on Thompson & Ashton (1984), Thompson *et al.* (1985, 1986), Tirrul (1985) and air-photo interpretation, structural mapping and compilation by author. *Lithologies:* Gb, Goulburn Supergroup (Proterozoic); YkS, Yellowknife Supergroup (Archean); Gg, granitoid orthogneiss and migmatite (Archean); Pga, granulites and retrogressed equivalents (Proterozoic); Pgt, granitoid orthogneiss (Proterozoic). *Tectonic subdivisions:* (i) Foreland, YkS$_1$, thin-skinned fold and thrust belt in cover (Gb) preserved at Bear Creek Hills (BCH); Archean metamorphism predominant. (ii) Reworked edge of Slave craton, YkS$_2$ and Gg; Proterozoic deformation and metamorphic overprint on Archean; cover synforms indicated (Ot 1, Outlier No. 1). (iii) Allochthon, Pga and Pgt, Proterozoic metamorphism and plutonism. *Structures:* crossed-bars, retrograde shear zones in YkS$_2$; dashes, continuous strike-slip and thrust (indicated) mylonite and mylonite gneiss zones; thin-skinned detachment indicated at BCH; continuous lines with shear-couple, faults of Bathurst fault system.

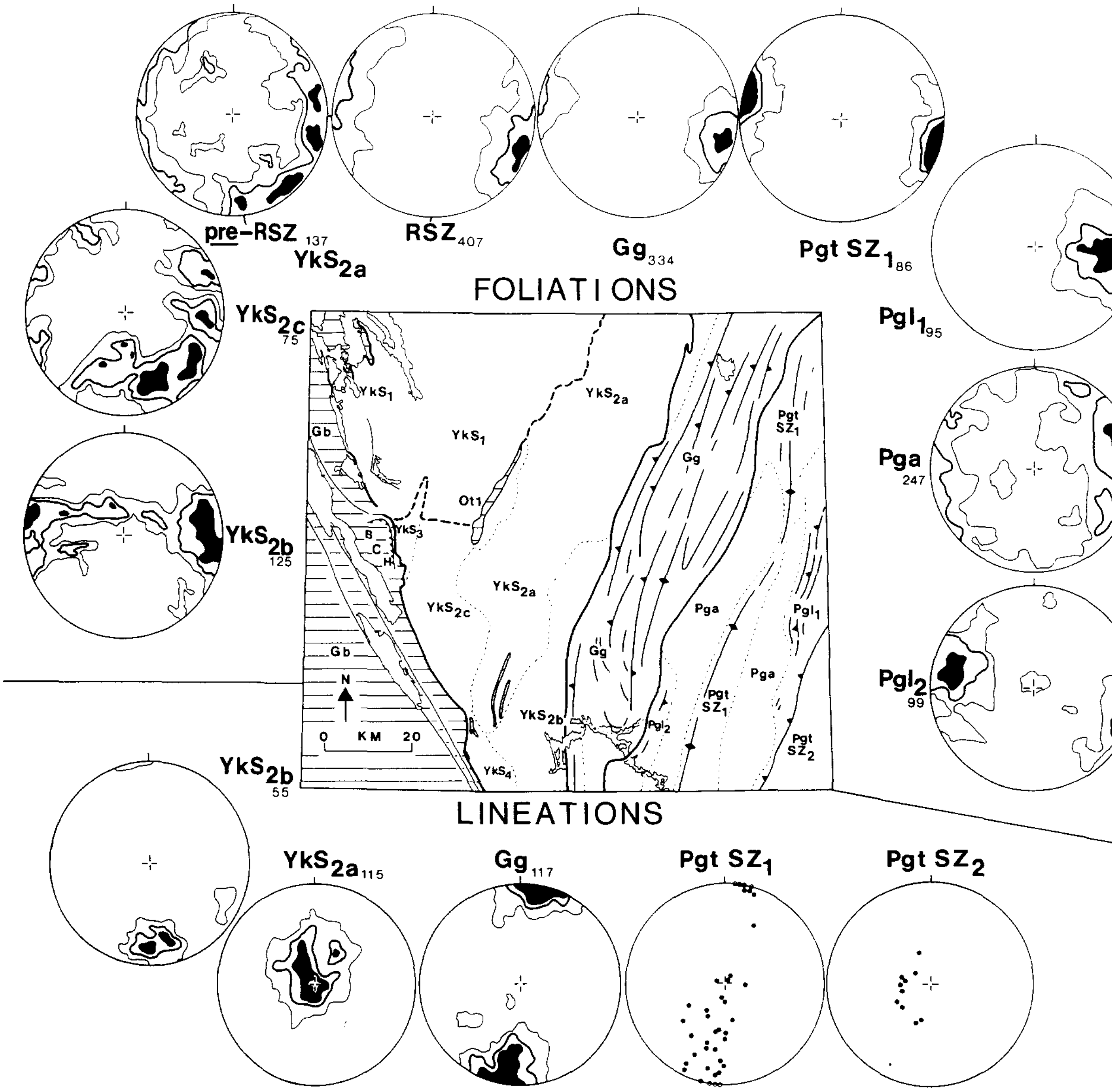


Fig. 3. Stereonets of foliations and lineations from basement rocks in Thol map sheet. Lithotectonic abbreviations are keyed to those of Fig. 2 with additional subdivisions: Pga, Pgl_{1-2}, granulites with irregular structure, pronounced layering; $PgtSZ_{1-2}$, retrograde shear zones associated with Proterozoic granites. Data from YkS3 and 4 shown in Figs. 10 and 11, respectively. Number of data in each diagram are indicated; contours are 1, 1–2, ≥3%; stereonets of structural data, and in other diagrams, are lower-hemisphere, equal-area projections.

protolith-age (Pg_a, Fig. 2). The metamorphism has been variously associated with arc magmatism (Hoffman 1987) or an ensialic origin (Thompson 1988). These include layered gneisses of metasedimentary and plutonic origin. The granulites are interlayered with elongate plutons of generally megacrystic, Proterozoic granitoid (Pgt, Fig. 2). The age of the granulite-facies metamorphism is between 1.98 and 2.00 Ga. The granitoids were emplaced in the interval 1.908–2.02 Ga (van Breemen *et al.* 1987b). The swarm of metadiabase, present in the edge of the Slave craton, is absent (Thompson *et al.* 1986).

TECTONIC ZONES

The map area is transected by three structurally distinct, TTZ-parallel tectonic zones, which are shown together with the major lithological units in Fig. 2. These can be further subdivided according to their fabric geometry, as illustrated in Fig. 3. This tectonic zoning resembles that of other Precambrian 'fronts' (cf. Gibb *et al.* 1983, Rivers *et al.* 1989).

The tectonic zones can be described as follows. (i) The foreland, in which Archean structural patterns are preserved (YkS_1, Figs. 3 and 7). The Proterozoic cover (Gb) is involved in thin-skinned deformation (Tirrul 1985). (ii) The craton-edge lies to the east, and is that part of the Slave craton that was remobilized in the Proterozoic (YkS_{2a-c} and Gg, Fig. 3). (iii) Proterozoic granulites and granites comprise the allochthonous zone (Pg_a and Pgt, Fig. 2, further subdivided in Fig. 3). The boundary of the reworked craton with the allochthon corresponds to a change from a magnetic low to a magnetic striping of high relief. This boundary, and its correlative along the TTZ, has been proposed by Hoffman (1987) to be the cryptic suture.

The Bathurst Fault transects these zones and is enclosed within a corridor of earlier ductile deformation (YkS_{3-4}, Fig. 3). As outlined below, on a regional scale, the fault separates structures of contrasting vergence within the TTZ.

PROTEROZOIC METAMORPHISM AND MICROSTRUCTURE

The results of microkinematic analysis of all Proterozoic tectonites, and microstructural and mineral assemblage data for the Yellowknife metasediments are shown in Fig. 4 and illustrated in Figs. 5 and 6. These are briefly described here to give the necessary background for descriptions of the larger scale structures.

The Yellowknife Supergroup in the reworked craton-edge and along the Bathurst Fault contains abundant metapelitic rocks, allowing control of the metamorphic grade of Proterozoic deformation within zones of retrograde schist (RSZ). Figure 4(a) shows a metamorphic zonation of the RSZ. In general, grade diminishes away from the TTZ, toward the foreland and the Bathurst Fault, where the RSZ formed in the greenschist facies (Fig. 4a). Highest grade assemblages (ga–bi–sill ± staur ± ky), at the eastern edge of the metasediments, are indicative of upper amphibolite facies. Mylonitic gneiss and mylonite within both the Archean granitoid gneisses of the reworked craton-edge (Gg, Fig. 2), and the allochthonous Proterozoic gneisses and granitoids (Pga and Pgt, Fig. 2) typically contain epidote and dark brown biotite ± pale amphibole, indicative of medium- to low-grade (amphibolite and greenschist-facies) conditions of metamorphism. In the allochthon these

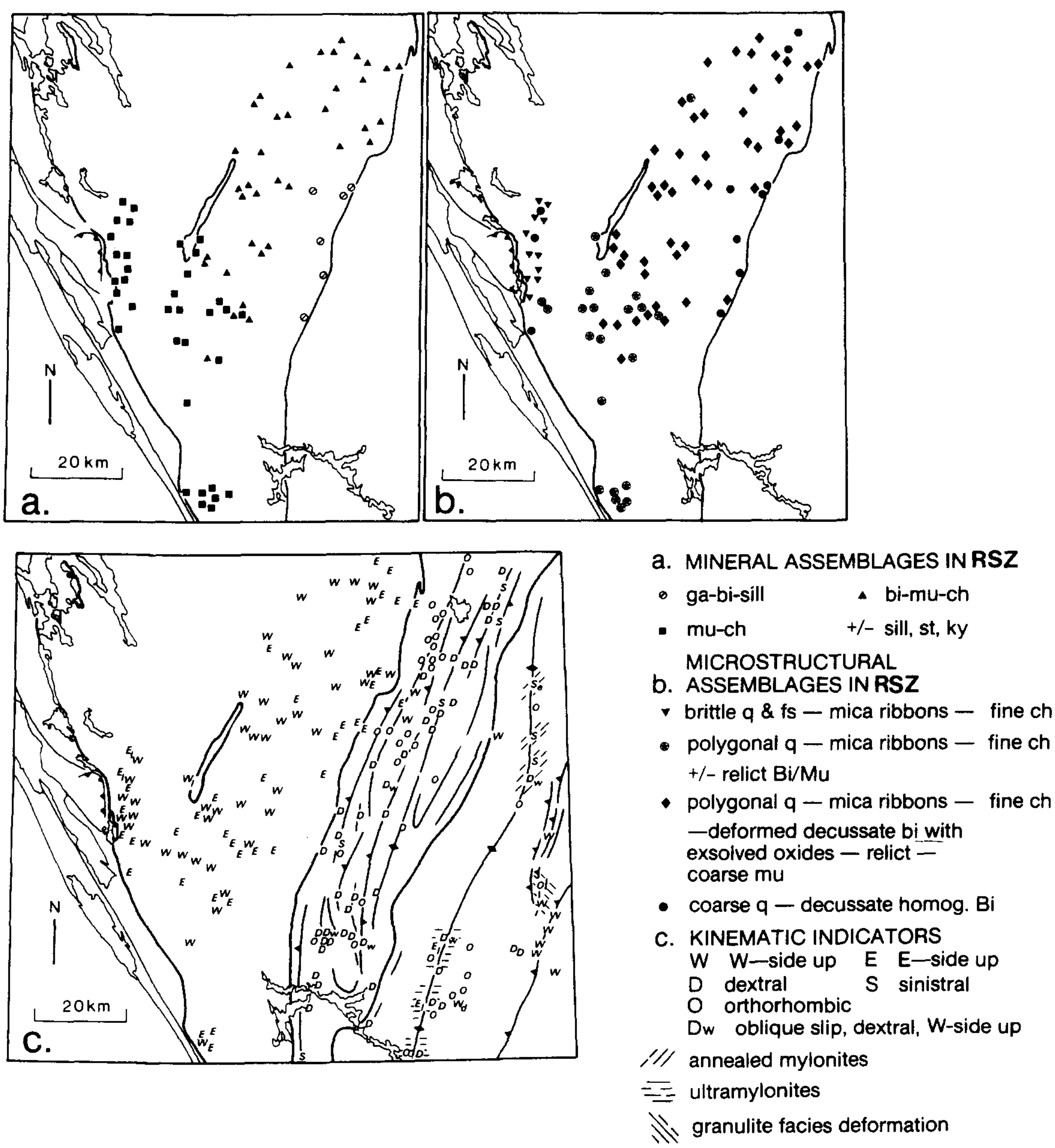


Fig. 4. Aspects of metamorphic and structural petrography of basement rocks in Thol map sheet. (a) Mineral assemblages in RSZ derived in Proterozoic from YkS. (b) Dominant microstructural assemblages in RSZ. (c) Microkinematic indicators. See text for details.

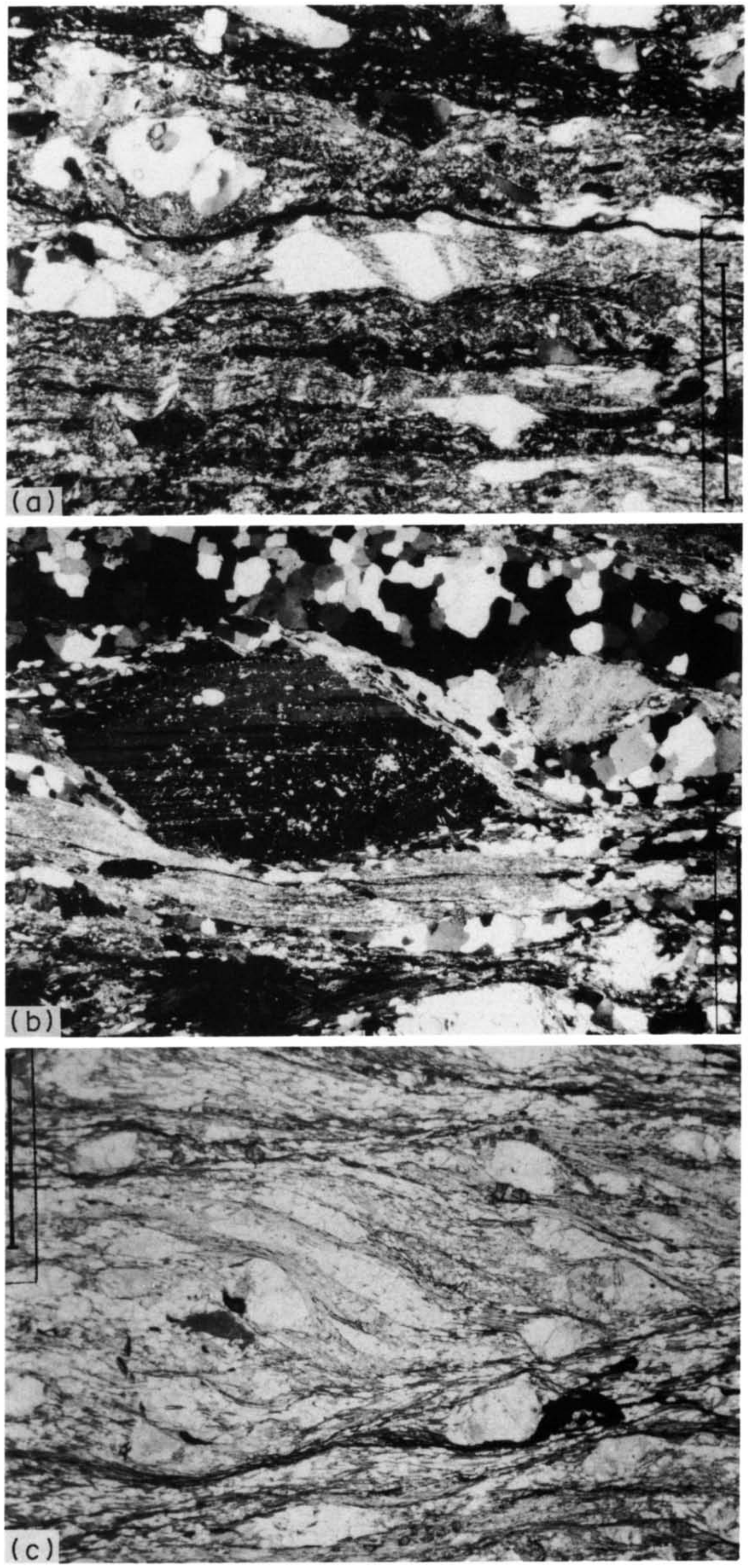


Fig. 5. Microstructure in Proterozoic tectonites. (a) Brittle deformation of quartz (pull-aparts) in muscovite–chlorite matrix; RSZ folation overprinted by crenulation (Fig. 4b); scale 1 mm; Kenyon Lake. (b) Asymmetric microstructure in RSZ defined by plagioclase porphyroclast and mica, set in foliation of polygonal quartz and mica ribbons, scale 2 mm; RSZ, east of Outlier No. 1 (YkS_2). (c) Asymmetric fabric in schist from Gg, defined by micas, ribbons of polygonal quartz and elongate feldspars; scale 2 mm.

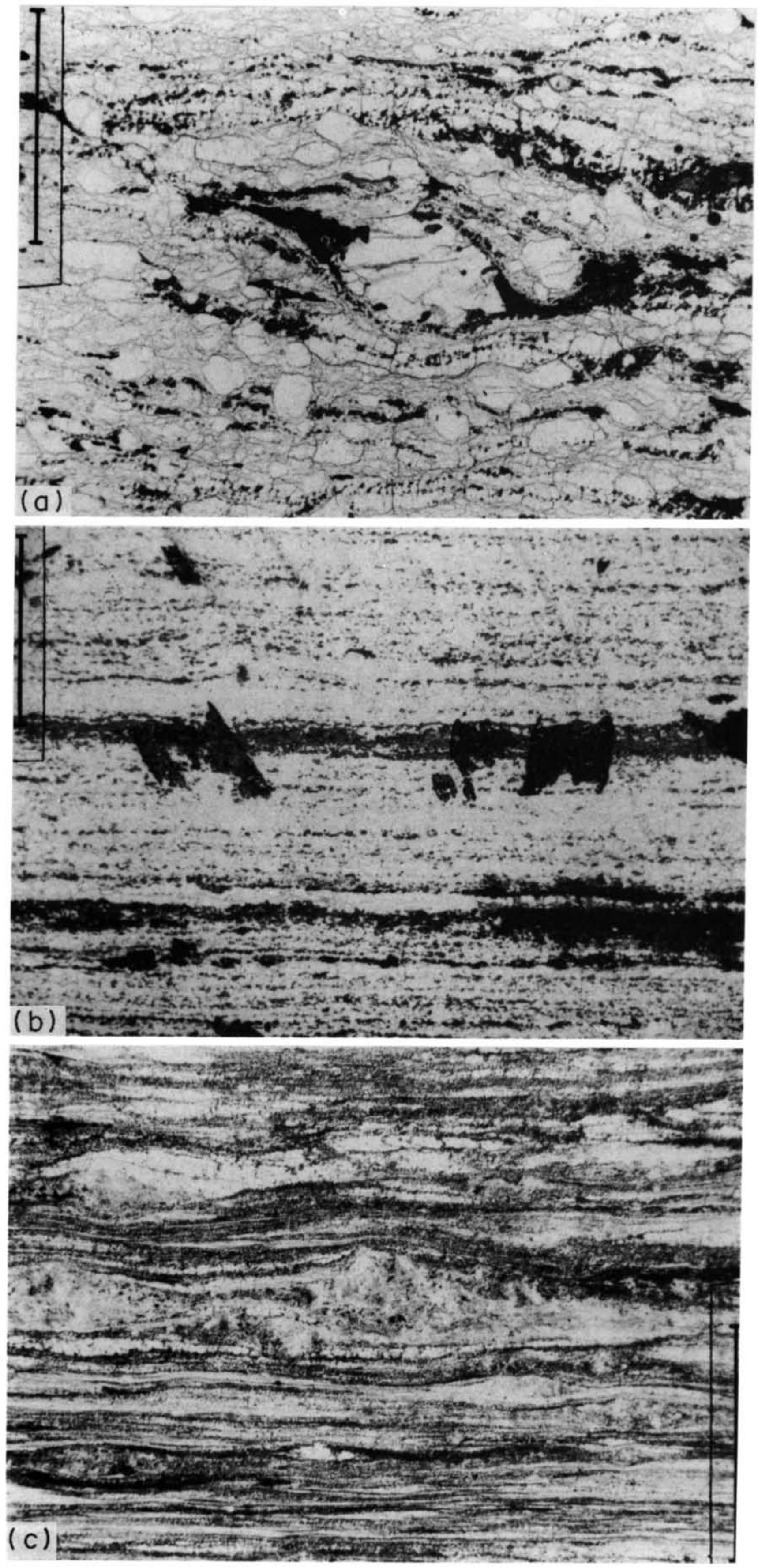


Fig. 6. Microstructure in Proterozoic tectonites. (a) Asymmetric pressure shadow (feldspar with opaque tail) in partly retrogressed granulite-facies gneiss. Porphyroclasts of feldspar lie in a matrix of dynamically recrystallized quartz ribbons, fine biotite, opaques and orthopyroxene (all dark). Scale 1 mm; southeast of Proterozoic granulites (Pga). (b) Foliation in annealed mylonite defined by epidote aggregates, set in granoblastic quartz–feldspar matrix, overgrown by cross-cutting dark amphibole. Scale 2 mm; north allochthon. (c) Foliation in ultramylonite, defined by dynamically recrystallized quartz and feldspar wrapping around feldspar augen seamed with new grains and sub-grains. Scale 1 mm; south allochthon.

assemblages are retrograde from granulite-facies assemblages.

Microstructure in the RSZ varies with grade (Fig. 4b). For example, with decreasing grade, decussate homogeneous biotite is replaced by kinked biotite, full of opaque inclusions. This fraction itself is replaced gradually as the proportion of chlorite-rich matrix increases to the southwest. In similar fashion quartz microstructure varies from coarse-grained ribbons at high grade through ribbons of finer, polygonal grains at medium grade to brittle deformation at the lowest grade within YkS_4 (Figs. 5a & b). The granitoid tectonites of the reworked craton edge and the allochthon display a wide range of progressive recrystallization of quartz and feldspar. They vary from ultramylonitic microstructure through fine-grained porphyroclastic mylonitic gneiss to statically annealed mylonitic microstructure (Figs. 6c & d).

In the RSZ asymmetric feldspar and mica fabrics are the primary kinematic indicators (Fig. 5b). Discrete shear bands are less common. Asymmetric fabrics in granitoids of both the reworked craton-edge and the allochthon are more varied. They include *S–C* type foliations, 'σ' porphyroclasts (Passchier & Simpson 1986), asymmetric pressure shadows (Fig. 6a), grain-shape preferred orientation within quartz ribbons, and shear bands. Schist fabrics resemble those in the YKS to the west (Fig. 5c). Orthorhombic fabrics are concentrated in the reworked craton edge.

MACROSCOPIC AND MESOSCOPIC STRUCTURE

Foreland

In the Bear Creek Hills, Tirrul (1985) described thin-skinned NW-directed transport above a décollement located within the Kimerot Platform of the Goulburn Supergroup. The evidence is a remnant of a fold and thrust belt preserved in a structural enclave formed by overprinting folds related to motion on the Bathurst Fault (Figs. 2 and 7). Tirrul related the thrust transport to NW-directed crustal shortening during formation of the TTZ (Tirrul 1985). This work was fundamental to our present understanding of the TTZ as an orogen. The detachment is present elsewhere in the stable foreland, outcropping further to the east in a tiny outlier preserved in a half-graben within undeformed basement of YkS_1 (Fig. 7). Its presence is also suspected further east in a synformal outlier (Outlier No. 1, Figs. 2 and 7) (J. Grotzinger personal communication 1985).

Archean structural and metamorphic patterns (discussed by Culshaw & van Breemen in press) are outlined in Fig. 7, which shows a structural grain strongly discordant with that of the TTZ. Although there is evidently a long wavelength Proterozoic structure that tilts the unconformity, the Archean structural, metamorphic and plutonic pattern is preserved in great detail beneath the thin-skinned cover deformation. In the foreland basement, only low-grade minor shear zones in post-Archean mafic dykes and the metasedimentary rocks (Thompson *et al.* 1986), may be related to the Bathurst Fault.

Thick-skinned shortening in the craton-edge

In the sediments of the Yellowknife Supergroup, Proterozoic deformation is concentrated within metric to decametric zones of retrograde schist. A 25–30 km wide, TTZ-parallel belt of RSZ (YkS_2) lies between the eastern margin of the foreland and the granitoid gneisses (Figs. 2, 3 and 7). At Outlier No. 1, which lies along the western boundary of the zone, RSZ formed in the basement when the cover was folded. These are an analogue for RSZ formed elsewhere, where cover is absent.

The southern 5 km of Outlier No. 1 are illustrated in Fig. 8. The dominant structures are subhorizontal, upright to overturned basement-involved folds. Along the southeast side of the outlier the unconformity is vertical and truncates basement layering. Northward, the YkS at the unconformity is transformed to steeply dipping chloritic RSZ that locally cut out the basal conglomerate. Similarly, an anticlinal culmination of basement within the outlier has a steeply lineated schistosity which is continuous with the cleavage in the basal conglomerate above. The west margin of the outlier is a SE-directed overthrust of Archean migmatites, bounded by several metres of chloritic schist and overlying overturned basal conglomerates (Fig. 8).

Within the cover, intensely lineated schistosity is common both in the dolomitic member and meta-argillites. It occurs on the limbs of the overturned synform, beneath the thrust in the west, with lineations in the thrust transport direction. It is also present along the steep limbs of the main synform where it may represent the folded thin-skinned detachment, since it strongly resembles and occurs at the same stratigraphic horizon as the detachment at Bear Creek Hills (J. Grotzinger personal communication 1985). If this correlation is true it would be natural to suggest that the detachment roots further east, beyond its present exposure, at the proposed cryptic suture (Hoffman *et al.* personal communication 1986–1989).

A gently dipping crenulation cleavage overprints the schistosity in both retrograded basement and cover. In the latter, crenulations grade into reclined folds that are most common north of the fault (Fig. 8, and beyond to the north). These may have formed after basement overthrusting of rocks containing the steeply dipping schistosity.

The basement domain east of Outlier No. 1 (YkS_2, Figs. 2 and 3) consists of steeply dipping metric to decametric RSZ comparable to those at the outlier. They separate wide areas in which Archean structures (Fig. 3, YkS_{2a}, pre-RSZ) and metamorphism are preserved. Although somewhat irregular, the RSZ predominantly dip steeply NW (Fig. 3) and form a network with an overall NW dip. Microkinematic analysis shows that the RSZ in YkS_2 are ductile shear zones with a

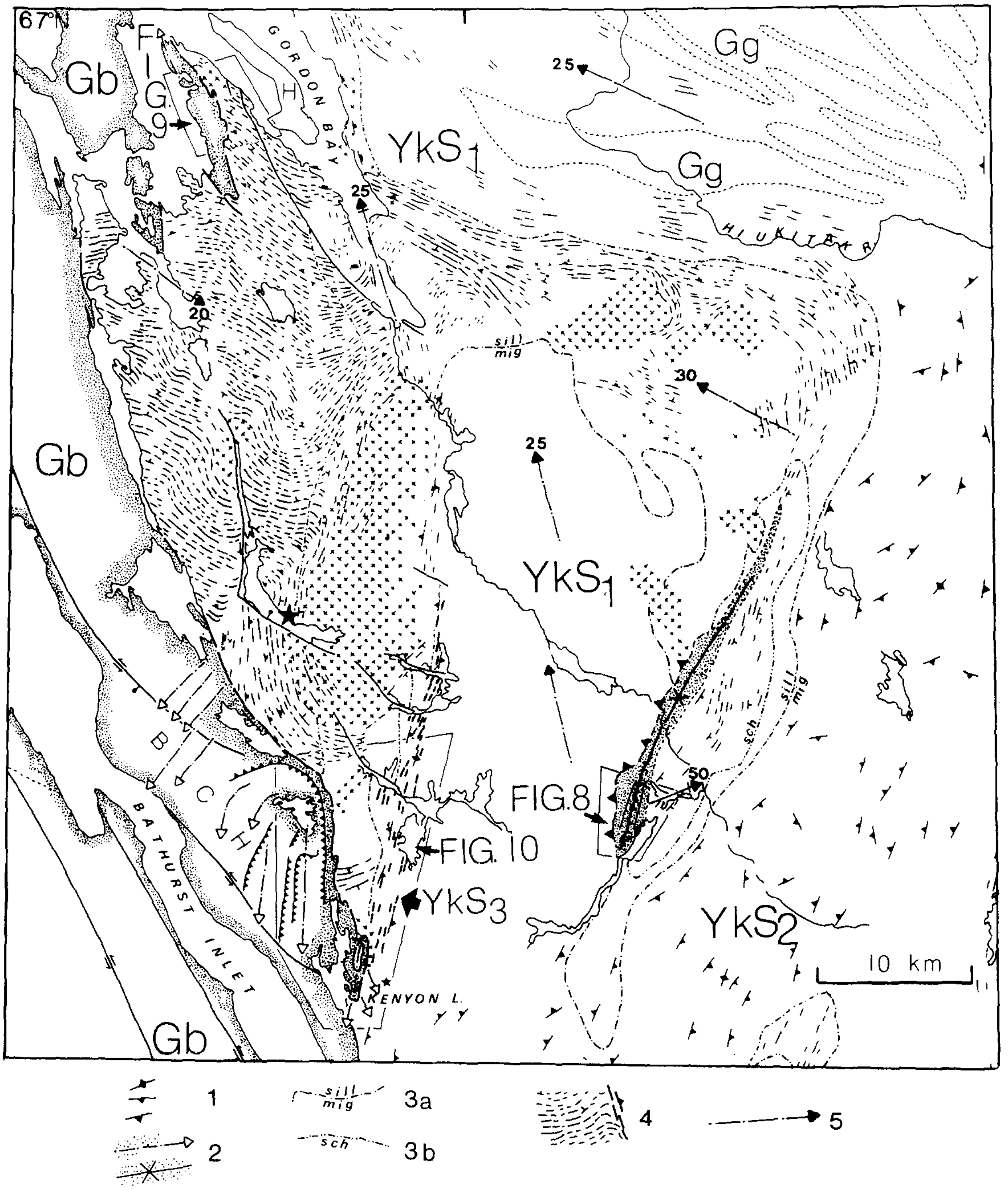


Fig. 7. Geology of foreland (location, Fig. 2), illustrating preservation of Archean structures and metamorphic patterns and their relationship to Proterozoic strain in the stable craton. The thin-skinned detachment is exposed in Bear Creek Hills (BCH) and in half-graben (star). Sources, as Fig. 2. Key: 1, Proterozoic retrograde shear zones (RSZ); 2, Proterozoic folds in cover; 3a, Archean isograd, sillimanite schist (sill) to migmatite (mig); 3b, andalusite–cordierite schist (sch) to sillimanite schist; 4, light strike-lines for sub-migmatite grade YkS, bold, Proterozoic RSZ; 5, Archean fold hinges inferred from π-diagrams. Also shown, Proterozoic faults, solid line with shear-couple or ball on down-side; thrusts, toothed line. *Lithologies:* letter symbols as Fig. 2; ornament in Gb changed; crosses, Archean two-mica granite. H, Hadrynian.

variable shear-sense parallel to the scattered but dominantly steeply plunging lineation (Figs. 3 and 4c).

Along the eastern margin of the metasediments, YkS_2, high-grade rocks are in probable thrust contact with granite gneiss. At the southern end, the boundary is overprinted by a zone of dextral strike-slip displacement, associated with folding (Fig. 3, YkS_{2b}), which occurred at low grade (Thompson 1987).

Upright folds of the cover in the northern part of the map area (Gordon Bay, Figs. 7 and 9), display the characteristic pattern of thick-skinned deformation, like that at Outlier No. 1, in which a vertical unconformity truncates basement layering. Although lacking RSZ, it also illustrates a heterogeneous pattern of basement deformation. This occurred at low metamorphic grade and may be related either to deformation along TTZ or to late faulting.

At the southern end of the synform illustrated in Fig. 9, the folded subvertical unconformity truncates NW-striking basement layering. The basement here has rare narrow zones of retrograde schistosity, but more numerous, variably oriented, slickenlined quartz veins (Fig. 9, 1 and 2). Kinematic analysis (Arthaud 1969) indicates that the vein system could have accommodated E–W shortening by shear along the veins in the slickenline direction (Fig. 9). These structures are inferred to be in the hangingwall of a blind thrust that crops out further north. The thrust cuts up-section, carrying both unfoliated basement granite and lowermost cover members, including the vertical unconformity (Fig. 9). Hangingwall structures at both locations are parallel, for example the N–S-trending fold axes and eastwardly inclined cleavage and transposed foliation. Cleavage in footwall argillite also strikes N–S (Fig. 9). Stretching lineations and shear bands at the thrust, and slickenlines in footwall quartz shear veins, however, demonstrate a NW transport direction. The orientation of fold axes in a small quartzite horse is similar, probably resulting from reorientation into the transport direction during thrust motion (Fig. 9). The N–S-trending structures are interpreted to be formed during E–W shortening occurring as the NW-directed thrust propagated along strike.

Orogen-parallel deformation in the craton-edge

Proterozoic deformation occurred in an approximately 20 km wide zone, which is made up of belts of mylonitic gneiss and lesser mylonite derived at medium and low grade, predominantly from migmatitic Archean granite gneisses (Gg, Figs. 2 and 3). The zone tapers dramatically to *ca* 5 km width in the south. Individual belts vary in width from several hundred metres to over 1 km and separate lensoid zones of less strongly foliated migmatitic granite gneiss. Foliation in both generally

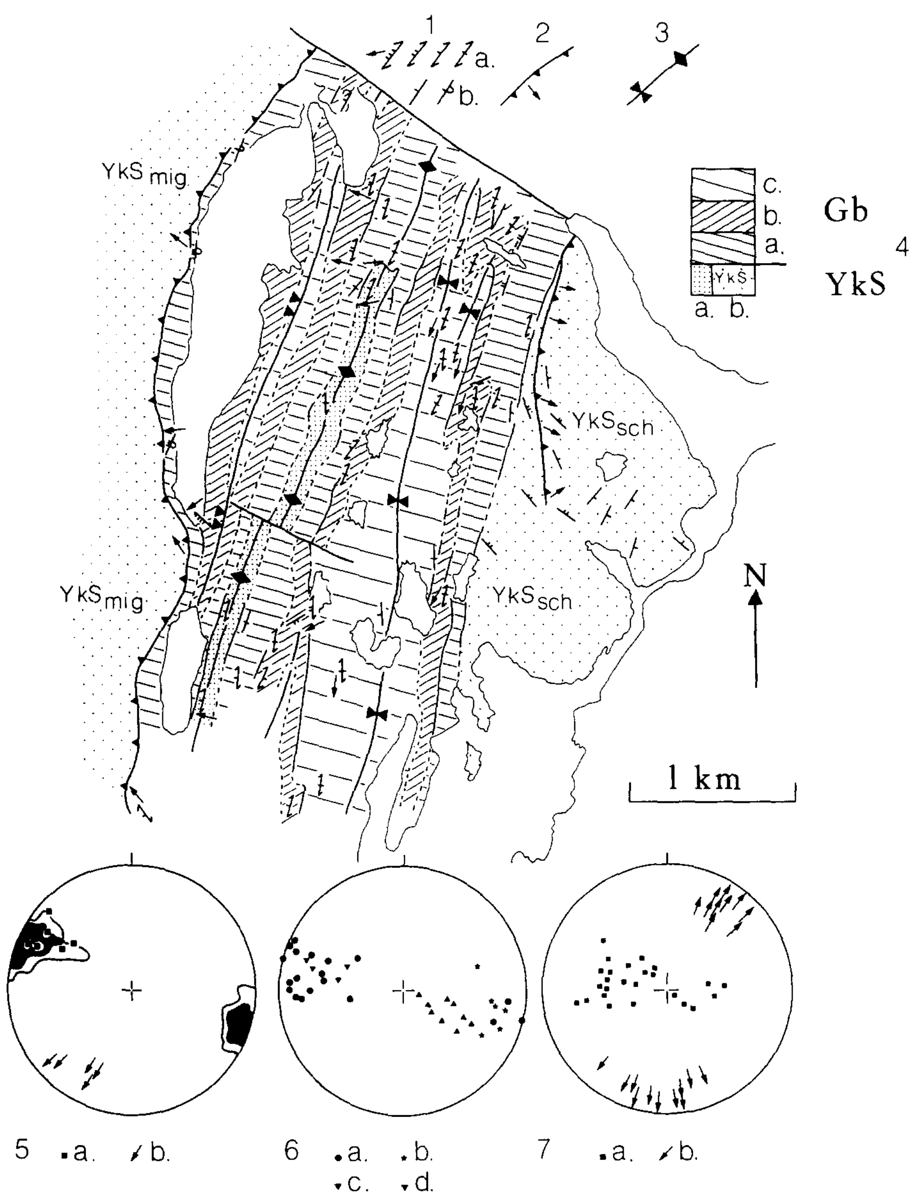


Fig. 8. Map of part of Outlier No. 1, showing basement–cover relations (location, Fig. 7). *Lithologies:* Archean Yellowknife Supergroup, YkS: a, retrograde inlier; b, migmatite (YkS_{mig}) and schist (YkS_{sch}) Proterozoic Goulburn Supergroup, Gb: a, conglomerate and quartzite; b, dolomite; c, argillite. *Map symbols:* 1, Foliations, a, cleavage, shallow, moderate, steep and very steep; b, upright and overturned layering. 2, Thrust, with lineation. 3, Fold-axial trace. *Stereonet symbols.* 5, Contoured poles to layering and transposed layering (including folded detachment?); a, axial planar cleavage; b, axes of early folds. 6, Retrograded basement foliations at, a, east boundary, b, basement inlier, c, west thrust, d, east thrust. 7, Crenulations and crenulation-folds, a, axial planes, b, axes.

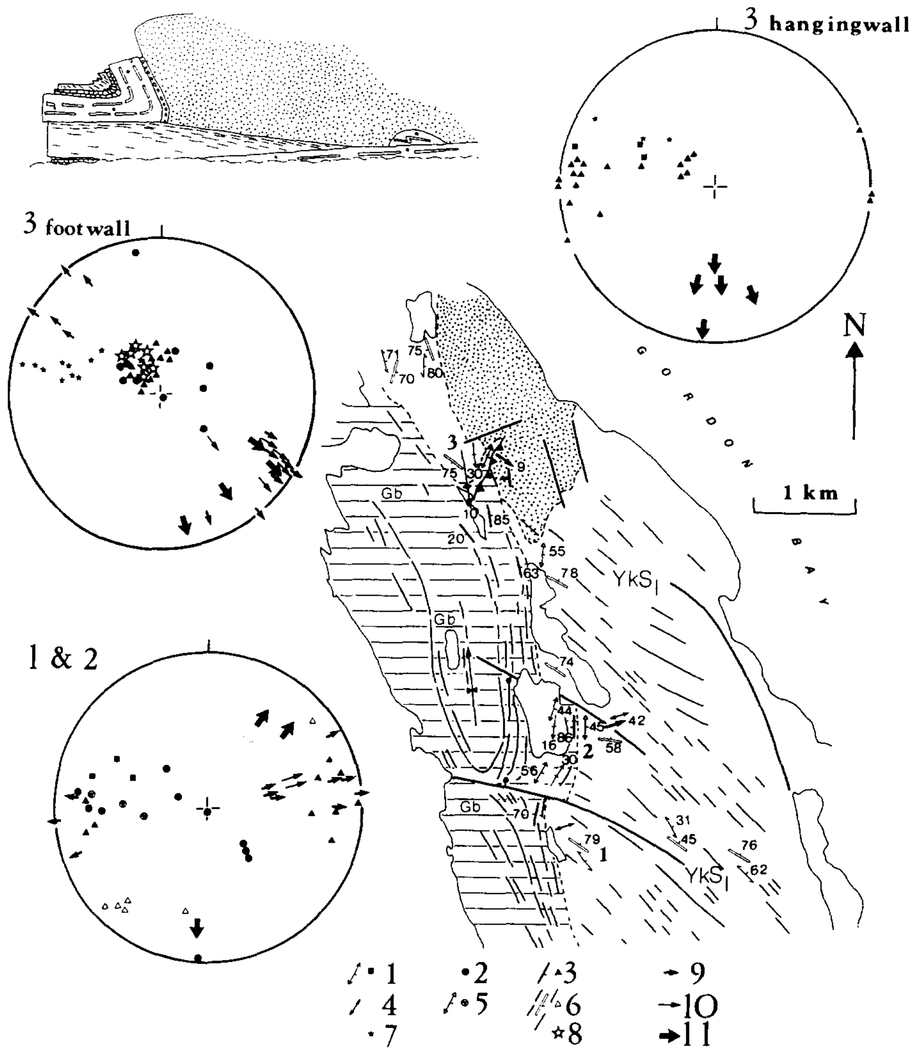


Fig. 9. Basement–cover relations at Gordon Bay between Proterozoic Goulburn Group (Gb), Archean Yellowknife Supergroup (YkS_1) and two-mica granite (stippled) (Fig. 7 for location). Stereonets are keyed to locations 1, 2 and 3. Inset shows diagram (looking north, east end of section is indicated) of thrust at location 3, showing hangingwall of Archean two-mica granite (overlying a horse of quartzite) and lowermost cover sequence (conglomerate, quartzite, dolomite, argillite) with truncation of unconformity; footwall of quartzite, argillite and minor dolomite. *Symbols:* 1, Axial plane in cover; 2, quartz vein; 3, layering in cover; 4, shortening direction in basement inferred from Arthaud (1969) analysis of slickenlined quartz veins; 5, retrograde schist in basement; 6, layering in basement; 7, cleavage in cover; 8, thrust phyllite; 9, quartz-vein slickenlines; 10, lineation in basement, thrust phyllite, retrograde schist; 11, fold axes in cover (including horse at 3).

dips steeply west, parallel to the overall attitude of the RSZ in the Yellowknife Supergroup to the west (Fig. 3). With a few exceptions, lineations are generally gently plunging, in contrast to those in the YkS_2 (Fig. 3). They are most commonly mica and amphibole lineations in schistose and mafic rocks, linear shape fabrics in granitoid gneisses being noteably poorly developed. The micro- and macroscopic fabric is that of a dextral transcurrent shear zone (Fig. 4c) (also Thompson 1987).

Deformation of granites and granulites in the allochthon

The lithological break defining the allochthon boundary is the western-limit of Proterozoic plutons and granulites, and the eastern limit of numerous metadiabase bodies and rocks directly traceable to the Slave Province (Fig. 2). It also marks a west to east change from subdued to pronounced magnetic patterns. The juxtaposition of the granulites against rocks of the Slave Province was the result of NW-directed thrusting (Thompson 1987, Hoffman 1987, Thompson 1988), similar to that along the TTZ south of Bathurst fault (Thompson & Henderson 1983, James 1986, Thompson *et al.* 1987). This took place before crustal shortening along structures with steep NW dips (Fig. 3). However, in the south, close to the granulite boundary, SE dips are preserved (Fig. 3, Pgl_2).

The granulites have an irregular (Pg_a, Fig. 3) or layered structure (Pgl, Fig. 3). After their emplacement belts of strike-slip and thrust-sense were formed at medium to low grade. A prominent retrograde zone of *LS* fabric, mylonite and ultramylonite occurs in the south (Figs. 4c and 6c). Further north, this zone gives way to a narrow belt of annealed and granoblastic, mylonitic gneisses (Figs. 4c and 6b). In the south foliations are subvertical and lineations are gently plunging. In the northern annealed mylonitic gneisses the lineation has a variable plunge within steep foliation (Figs. 2

and 3, $GtSZ_1$). Kinematic indicators at all scales show dextral shear for the southern part of the zone, but varied shear-sense in the north (Fig. 4c).

In the extreme east of the map area, beyond the second belt of granulites, there are zones of mylonitic gneiss and mylonite flanking a granitoid pluton (Fig. 3, $GtSZ_2$) and within the layered granulites (Pgl, Fig. 3). Foliations dip west with a down-dip lineation (Fig. 3) and microkinematic analysis indicates an eastward thrust sense (Fig. 4c).

Deformation parallel to the Bathurst Fault

The Bathurst Fault cuts obliquely across the foreland and the reworked craton-edge. Basement deformation close to the fault in the foreland (Kenyon Lake, YkS_3, Figs. 2, 3 and 10) is different in overall style from that in the reworked craton-edge (YkS_4, Figs. 2, 3 and 11), although both have heterogeneous deformation.

In the foreland, at Kenyon Lake, the unconformity beneath the Bear Creek Hills detachment was folded during motion on the Bathurst Fault (Tirrul 1985). The basement is heterogeneously deformed with styles varying with lithology. The most prominent element is a network of NNE-striking RSZ formed from Archean migmatites (Fig. 10). Shear-sense was parallel to the lineation, which is spread within the steep foliation (Fig. 10), and was either west- or east-side-up oblique-slip (Fig. 4c). Gently dipping RSZ zones are east-side-up thrusts (Fig. 4c) but no kinematic information is avail-

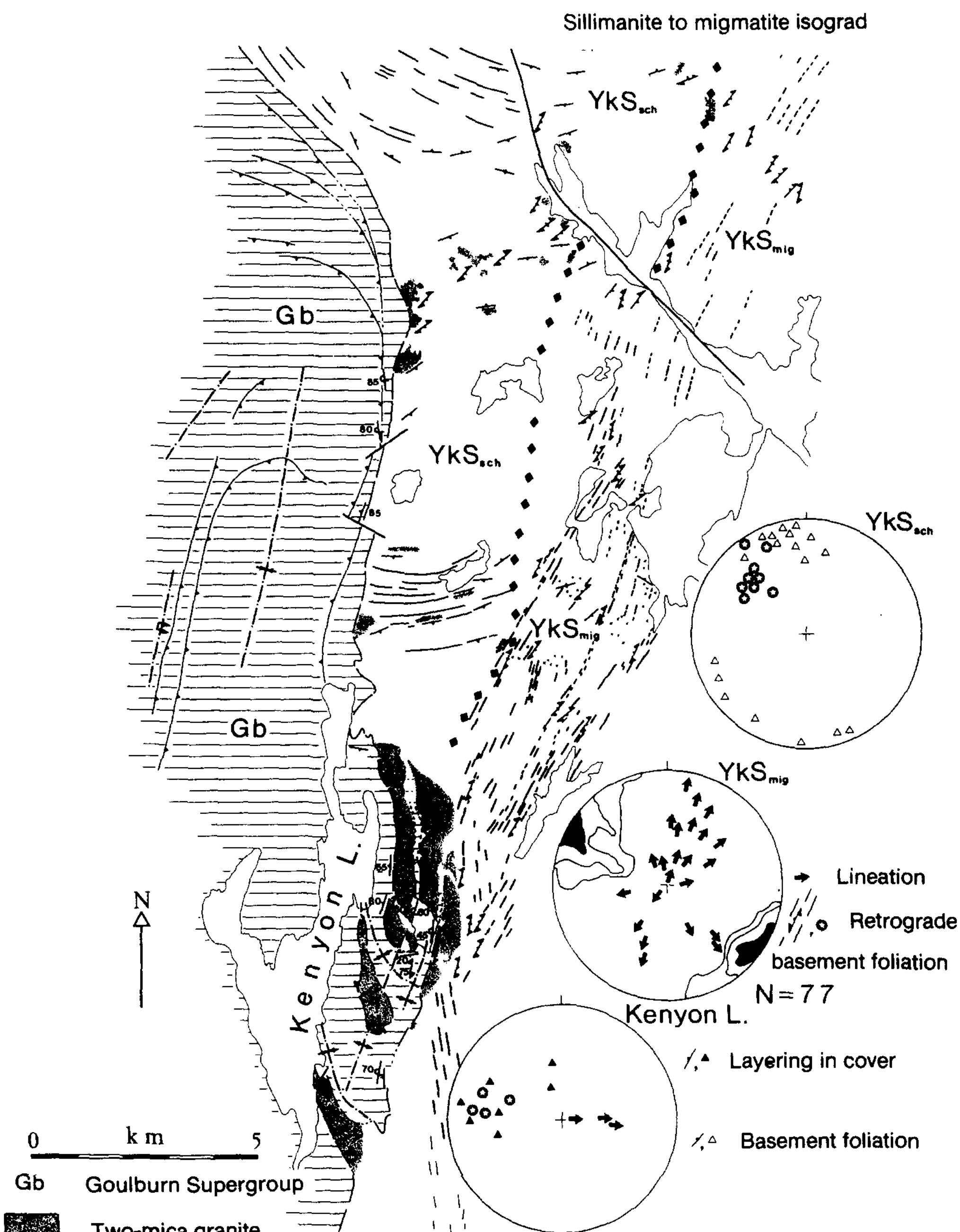


Fig. 10. Basement structure and basement–cover relations at Kenyon Lake (Fig. 7 for location). RSZ (heavy dashes) in YkS_{mig} lie to the east of migmatite isograd (diamonds) and sillimanite schist (YkS_{sch}), which contains Archean two-mica granites (stippled). Stereonets show retrograde basement fabrics and some basement–cover layering. Sources, Thompson & Ashton (1984) and Tirrul (1985) (structure in Goulburn, Gb, and SE Kenyon Lake), and structural mapping by author.

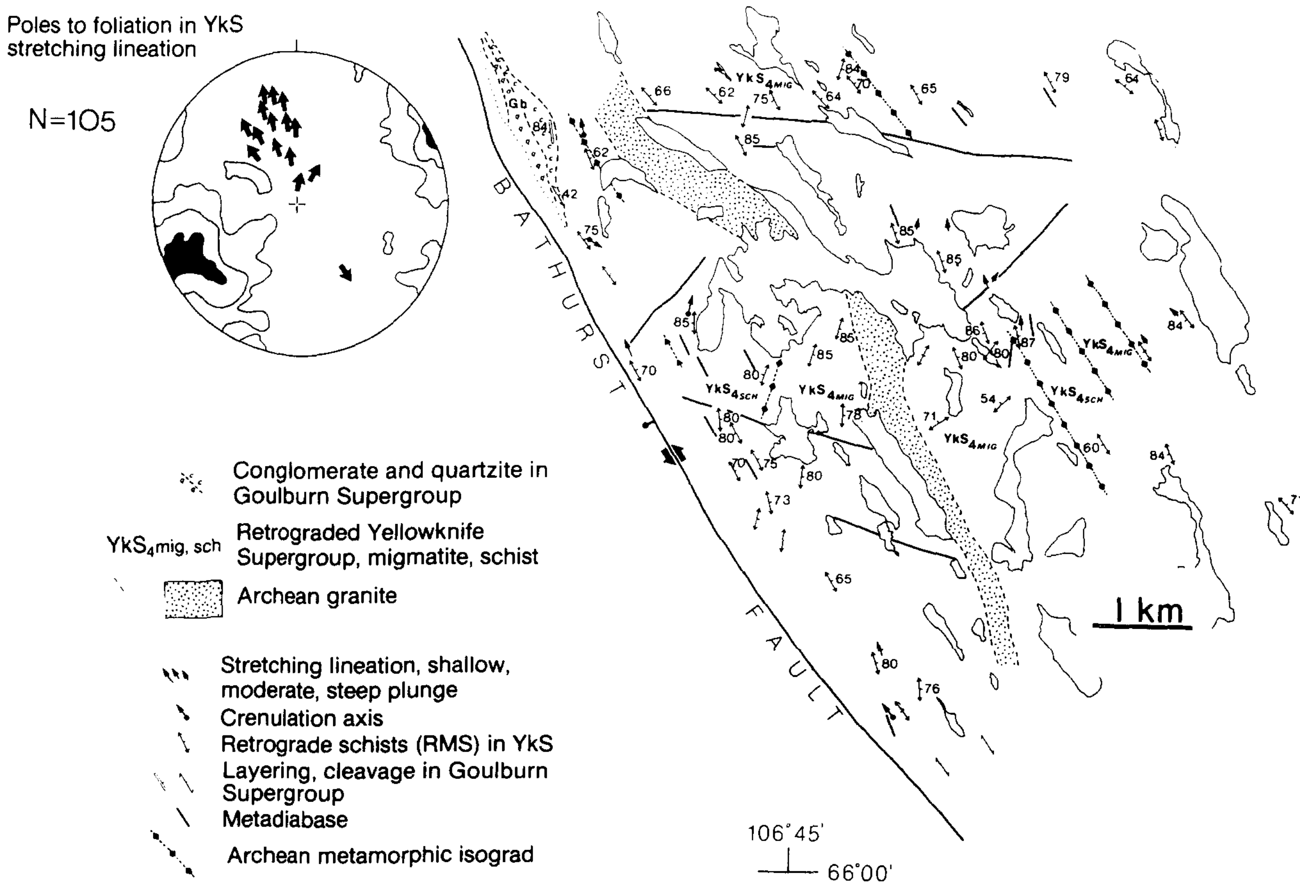


Fig. 11. Proterozoic reworking of Archean basement close to Bathurst Fault, southeast of Bathurst Inlet (location, Fig. 2). $YkS_{4mig/sch}$ retrograde schists (RSZ) and less deformed retrograde rocks derived in the Proterozoic from migmatites and schists (andalusite–sillimanite) of the Yellowknife Supergroup.

able for retrograde schistosity west of the migmatite isograd. Within the intrusive Archean granite at the southwest end of the RSZ zone there are successive NW- and NNE- to N-trending folds of basement and cover (Fig. 10) (Tirrul 1985). The latter are associated with steeply E- to SE-dipping shear zones within the granite which are parallel to cleavage in the cover, and which have locally resulted in a complete interleaving of basement and cover (Fig. 10). All these structures were formed at low grade (Fig. 4a), compatible with the occurrence of brittle microstructures in quartz (Figs. 4b and 5a) and low temperatures in the cover (Thompson & Frey 1984).

Southeast of the Bathurst Inlet, within a corridor of earlier deformation parallel to the Bathurst Fault, the style is pervasively ductile. Archean lithological boundaries, isograds and small remnants of Proterozoic cover lie parallel to the fault within a zone more than 7 km wide (YkS_4, Figs. 2, 3 and 11). Northeast of the zone, structures trend N–S, departing from the main trend of the TTZ, and curve into the zone (Figs. 2 and 3). In addition to the RSZ, areas of Archean textural preservation are retrogressed (Fig. 4a), although ductile quartz microstructures suggest more elevated temperatures (greenschist facies) than at Kenyon Lake (Fig. 4a). Most foliations dip steeply NE except for local TTZ-parallel deviations. The few microkinematic analyses show a dominance of east-side-up (dextral) oblique-slip parallel to the moderately NW-plunging lineation (Fig. 4c). In the small cover remnant close to the fault trace the SW-dipping bedding is overprinted by a single NE-dipping cleavage, parallel to that in the basement (Fig. 11).

DISCUSSION

Thick-skinned deformation—cover synforms

At Outlier No. 1, shortening perpendicular to the TTZ was by upright folding of the cover, and heterogeneous shortening and SE-directed thrusting in the basement. This resulted in the characteristic elongate synforms of cover. Similar cusp-like synforms occur in other Proterozoic orogens (e.g. Tirrul 1983, Harris *et al.* 1987), in the external Alpine massifs (Ramsay 1967), and in basement–cover thrust sheets in the Moine thrust system (Coward & Kim 1981). Pinched synclines are suggested to have resulted from: (a) folding of an interface separating materials of strongly contrasting viscosities (Ramsay 1967, Smith 1979, Hoffman *et al.* 1984); or (b) from deformation of horizontal cover above steep basement faults (Gratier & Vialon 1980, Coward & Kim 1981, Tricart & Lemoine 1986). Hoffman *et al.* (1988) present evidence that folding of basement and cover typically follows thin-skinned deformation in early Proterozoic orogens and is preferred over thrusting as the mode of thick-skinned deformation in these orogens. These authors note the presence of ductile basement shear zones in one of the examples they cited.

In Thol, similar RSZ occur in the Yellowknife metasediments in both the reworked craton edge and the foreland. Accompanying cover synclines are preserved where erosion was not too deep. Thus, it can be argued that the RSZ, east of Outlier No. 1, where there is no shortened cover, accommodated shortening transverse to the TTZ. The combination of variable attitude of RSZ in YkS_{2a}, relatively dispersed lineations (Fig. 3), and varied shear sense on the RSZ (Fig. 4c) can be explained as a system of shear zones that accommodated a bulk coaxial shortening (vertical extension) perpendicular to the TTZ (Gapais *et al.* 1987, Ramsay & Huber 1987). The clustered orientation of the lineations in YkS_2 indicate a plane bulk strain (Fig. 3) (Gapais *et al.* 1987). This may have accompanied SE-directed thrusting along the east side of the metasediments, analogous to that at Outlier No. 1. This would be compatible with the overall NW dip of RSZ, and the increase of metamorphic grade within the RSZ towards the TTZ.

The model of heterogeneous basement deformation also applies to basement structures along the Bathurst Fault and at Gordon Bay as well as to shortening perpendicular to the orogen. In the latter case, continuity between undeformed foreland and the reworked craton-edge can be maintained.

Post-collisional transpression

As outlined above, RSZ in the Yellowknife metasediments of the craton-edge were formed during shortening perpendicular to the TTZ. Further east within the craton-edge, the late dextral strike-slip at medium and low grade was concentrated into the granitoid gneisses (Ggm, Fig. 4c) rather than the metasedimentary Yellowknife Supergroup. This is interpreted as an essentially simultaneous deformation occurring during transpression. The correlation is made primarily on the basis of similarity of grade. Also it is unlikely that these granitoid tectonites formed during an early stage since they pinch out southward. This feature, as argued below, is related to a regional late vergence switch. The partitioning could be because the metasediments were detached from the underlying granitoid gneisses during transpression. In the granitoid gneisses, where true transpression took place, oblate finite strains would be expected (Sanderson & Marchini 1984), thus explaining the dearth of linear shape fabrics, the monoclinic microfabrics (Fig. 4c), and their detachment from the overlying metasediments.

In the allochthon, various structures were formed at medium to low grade, retrogressing the granulites. Southeast-directed thrusting post-dated the youngest Proterozoic granite (1.908 Ga) in the east and occurred at similar grade to dextral strike-slip in the central zone (Fig. 4c). Since these are structures formed during shortening perpendicular to the orogen and strike-slip parallel to it, they are also interpreted to have been formed during transpression, like those in the reworked Slave craton to the west. The most notable difference between the two areas is that in the east, shortening structures are separated from strike-slip structures by relatively hard granulites (Fig. 12). The presence of undeformable walls would have allowed simple shear within individual belts (as in Gg), and the absence of oblate fabrics.

The post-collisional architecture of Thol is therefore a system of deformation belts that accommodated oblique convergence in a transpressional orogen. Transpression is accommodated in two ways, either as a single zone in which shortening is spread-out over a much greater width than strike-slip (craton-edge) (cf. England *et al.* 1985), or as several non-overlapping zones, separated by undeformable walls (allochthon) (Fig. 12).

The amount of obliquity of the post-collisional oblique convergence (Culshaw 1986, Hoffman 1987) can be judged from Fig. 1, if the correlative Great Slave Lake shear zone (Hanmer & Connelly 1986, Hanmer 1988) was a continental transform (Hoffman 1987) and contained the displacement vector. Partitioning of the shortening and strike slip components of oblique convergence into separate orogen-parallel and transverse structures analogous to those outlined here has been known for some time at ocean–continent margins (Fitch 1972, Beck 1983). In the continental setting, the struc-

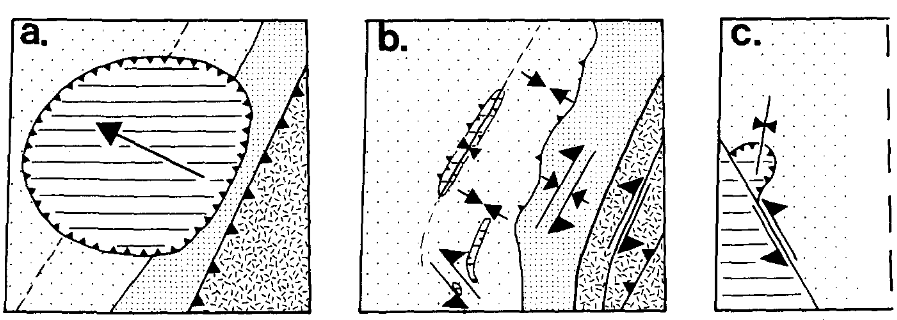


Fig. 12. Cartoon of development of structures and zoning of TTZ within Thol map-sheet. Lithological symbols as in Fig. 2. (a) Early collisional stage with NW-verging thrust of Proterozoic granulites and granitoids onto the Archean Slave craton margin. Thin-skinned thrusting occurs above the edge of the Slave craton. (b) Post-collisional oblique convergence, deformation migrated into Slave craton-edge, vergence of shortening structures changed and the ductile Bathurst zone developed. In reworked craton-edge, transpression is partitioned into a zone of shortening perpendicular to orogen and a zone of mixed shortening and strike-slip; in allochthon, distinct strike-slip and thrust belts are separated by hard granulites. (c) Motion on brittle Bathurst Fault accompanied tectonic escape of northern TTZ segment; heterogeneous basement deformation and folding of cover resulted in preservation of fold–thrust belt remnant.

tural record in orogens of oblique convergence is probably more common than generally recognized (Ellis 1986, Gates *et al.* 1986, Woodcock 1986). This is probably because the strike-slip belts will be much narrower than thickening structures (England *et al.* 1985), as is observed here.

Deformation parallel to the Bathurst Fault

At Kenyon Lake, the N-trending folds of cover, detachment and unconformity were formed during left-lateral motion on the Bathurst Fault (Tirrul 1985), with orientations appropriate for a wrenching environment (Wilcox *et al.* 1973). The basement structures were formed along RSZ within the cool, low-grade foreland. The classic explanation for the brittle episode along the Bathurst Fault is that it took place during tectonic escape (Burke & Sengor 1986) of a crustal wedge occurring late in the orogeny (Gibb *et al.* 1983, Hoffman *et al.* 1988). According to Hoffman (1988) it was accommodated by the Bathurst Fault and Ellice Fault, a high-level fault that lies to the east of the map area.

Wall rock deformation southeast of Bathurst Inlet (YkS_4), however, is concentrated in a wide ductile zone that continues southeast of Thol further into the TTZ (Frith 1982), in which most planar elements are parallel to the fault. Fabrics demonstrate non-coaxial strain along the zone (Fig. 4c), with, perhaps, orthogonal shortening, to explain NE-dipping foliations (Fig. 11). Metamorphic grade, microstructure and structural level (marked by preservation of the unconformity) is similar to that in basement at the south end of Outlier No. 1 (Figs. 4a & b), implying that some of the deformation here overlapped that in RSZ parallel to the TTZ. Accordingly, ductile deformation parallel to the Bathurst Fault must have formed while the deformed craton-edge was still warm, and more deeply buried than the foreland further northwest, but before the formation of the brittle Bathurst Fault.

The presence of ductile structures was predicted by Tirrul (1985) (cf. Frith 1982). He reasoned that since the estimated brittle displacement (>48 km, Thomas *et al.* 1976) cannot account for the more than 100 km left-lateral separation required to remove the Bear Creek Hills fold and thrust belt from the southern side of the fault, the remainder must have been taken up along ductile structures that were then unrecognized and not necessarily coeval. The ductile structures may have originated as a response to an original irregularity in the hangingwall or footwall of the collision, and their significance is tied-up in the history of the TTZ as a whole.

The late history of the TTZ

The transpressive structures discussed above verge SE. This is opposite to the transport direction of the thin-skinned thrusting (Tirrul 1985) and the direction of emplacement of the granulite allochthon. The SE-verging structures, therefore, overprinted the northwestward, and, as argued above, were essentially

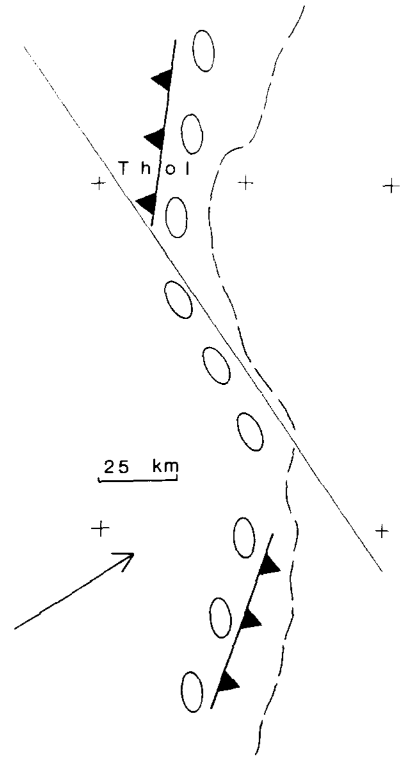


Fig. 13. Regional setting of the second stage of deformation along TTZ. A zone of ductile deformation along brittle Bathurst Fault (to be), shown linking transpressive zones with same sense of strike-slip but opposite vergence of shortening. Incremental strain ellipses and inferred displacement vector are shown. Dashed strike-line based on aeromagnetic pattern (GSC map NQ 12-13-14-AM).

synchronous with formation of the ductile Bathurst structure.

The simultaneous formation of SE-verging transpressive structures and the ductile Bathurst structure after NW shortening, explains several features in Thol. In this interpretation, the second stage saw NW migration of SE-verging ductile thick-skinned structures, perhaps triggered by footwall heating in the toe of the orogen. These remobilized the foreland, folding the cover and the thin-skinned detachment (as suggested by J. Grotzinger personal communication 1985). The strike-slip belt in the east of the craton-edge narrows as it dies out close to the ductile Bathurst structure, which was active at the same time. Likewise, reorientation of the granulite thrust resulted in its NW dip everywhere except near the ductile Bathurst structure, where the effects of the second deformation were absent (Pgl_2, Fig. 3). Annealed mylonites, close to the fault trace (Fig. 4c), may have been related to the NW-thrusting or to pre-collisional strike-slip. The static grain-growth (Fig. 6b) would have occurred after thrusting, and their varied lineation plunge (Fig. 3) would have been imposed in the second deformation.

A key feature of the regional geology of the TTZ north and south of the ductile Bathurst structure is that it links dextral transpressional zones with oppositely verging zones of contraction (Fig. 13) (cf. thrust reversals across Precambrian shear belts in Zambia and Zimbabwe, Coward & Daly 1984). Perhaps such a switch of vergence had to occur in order to allow migration of the northern locus of transpression towards the southeast, so that the transpressive TTZ, as a whole, remained as short, straight and as soft as possible. The obvious suggestion is that map patterns of transpressive zones may change in a fashion analogous to transient reconfigurations in cross-sections of orogenic wedges (cf. Davis *et al.* 1983).

This episode of opposing vergence either side of the zone may explain other features. For example, continued NW thrusting south of the fault would have resulted in a concentration of crustal loading, which could explain the paired gravity anomalies (Henderson *et al.* 1987, Thompson *et al.* 1987), which are absent in the north. Isostatic uplift and erosion would have been greater there, compared to the north, resulting in the disappearance of the foredeep and thin-skinned belt.

CONCLUSIONS

(1) Collision, preceded by convergence with the formation of an early Proterozoic magmatic arc and granulites, was initiated with NW overthrusting of the granulites onto the Slave Province accompanied by thin-skinned shortening of the Proterozoic cover in the west.

(2) During transpression, shortening structures assumed a SE-, rather than NW-, vergence; a deformation front migrated westward into the Slave craton-edge, causing folding of the cover, probably including the detachment; transpression was now zonally partitioned, within both the reworked craton-edge and the allochthon, into zones of shortening, shortening + strike-slip, and strike-slip.

(3) A zone of ductile structure, possibly transpressive, occurred at this time along the trace of the Bathurst Fault; it links dextral transpressive zones, in which the shortening structures had opposite vergence (SE in Thol, north of the fault, and NW in the south).

(4) The last espisode of convergence, tectonic escape, may have been accomplished by brittle deformation on the Bathurst Fault.

(5) In the foreland and the reworked craton-edge, the role of heterogeneous basement deformation is very important. The basement had a complex Archean structure, which was overprinted by systems of Proterozoic shear zones. The bulk strains accomplished by these are expressed as upright folds in the stratiform cover.

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