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[1] This paper presents a reappraisal of kinematics and tectonic history of the Thompson Nickel Belt, a major Paleoproterozoic deformation zone along the western boundary of the Archean Superior Province in Manitoba. The study, based on the analysis of foliation trajectory maps and associated shear zone arrays, emphasizes that the overall strain pattern results from transpression. Strains are large, marked by strong subvertical stretch and NW-SE subhorizontal shortening, combined with along-strike stretch. From these, we infer distributed crustal shortening, involving steeply plunging flow rather than large horizontal displacements, although kinematic indicators show that top-to-the-west motions were dominant. Along-strike shear indicators are poorly expressed but suggest a component of bulk dextral strike-slip. Synkinematic thermal indicators and new geochronological data indicate that transpression could have been a long-lasting, circa 100 Ma, event in the area. **Citation:** Gapais, D., A. Potrel, N. Machado, and E. Hallot (2005), Kinematics of long-lasting Paleoproterozoic transpression within the Thompson Nickel Belt, Manitoba, Canada, *Tectonics*, *24*, TC3002, doi:10.1029/2004TC001700.

## 1. Introduction

[2] The definition and evolution of Paleoproterozoic orogens are of significant interest to the understanding of early continental tectonic processes as they involve collage of Archean domains and further accretion of juvenile continental crust. Many of these orogens are associated with transpressive kinematics marked by large domains ductilely deformed under high thermal conditions [e.g., *Ehlers et al.*, 1993; *Holzer et al.*, 1999; *Caby et al.*, 2000; *Pelletier et al.*, 2002; *Vassallo and Wilson*, 2002]. In several examples, associated tectonic histories are interpreted as a result of large-scale piling up of compressive nappes progressively reworked by transpressive shear zones [e.g., *Bleeker*, 1990; *Vassallo and Wilson*, 2002]. In most of them, tectonic styles predating strain localization along transpressive zones are however poorly documented. Neither are the mechanisms by which transpressive motions and associated components of subvertical stretch are accommodated at crustal scale.

[3] The North American Trans-Hudson Orogen (THO) is one of the most thoroughly studied of such Paleoproterozoic orogenic systems. Although the main provinces involved in the orogen are well defined [*Hoffman*, 1990], the tectonic evolution of some boundary zones remains often subject to debate. This is particularly true for the Thompson Nickel Belt (TNB) [*Coats et al.*, 1972] that marks the boundary between the THO and the Archean Superior Province in Manitoba (Figure 1).

[4] Previous works have led to a general model involving (1) a major thrusting event, with emplacement of eastward verging nappes (between about 1880 and 1800 Ma), and (2) transpression combining top-to-the-west thrusting and sinistral strike-slip (1800–1720 Ma) [*Bleeker*, 1990; *White et al.*, 1999]. According to *Bleeker* [1990], a late event of dextral transpression occurred around 1700–1600 Ma. This scenario was largely based on the analysis and correlations of superposed folding events. The occurrence of strike-slip components is also suggested by continental scale reconstructions and magnetic and gravimetric data [*Lewry*, 1981; *Gibb*, 1983; *Green et al.*, 1985]. Constraints for an early history of eastward thrusting are rather poor. Thus *Fueten and Robin* [1989] noticed that most kinematic indicators (C-S fabrics, asymmetric folds, shadow zones around clasts. . . .) reflect top-to-the-west motions. In addition, deep seismic reflection data image east dipping reflectors consistent with top-to-the-west kinematics, without strong evidence for previous eastward verging thrust and nappe systems. Consequently, *White et al.* [1999] emphasized that most geophysical data are "in marked contrast to most of the tectonic models proposed for the zone" [*White et al.*,

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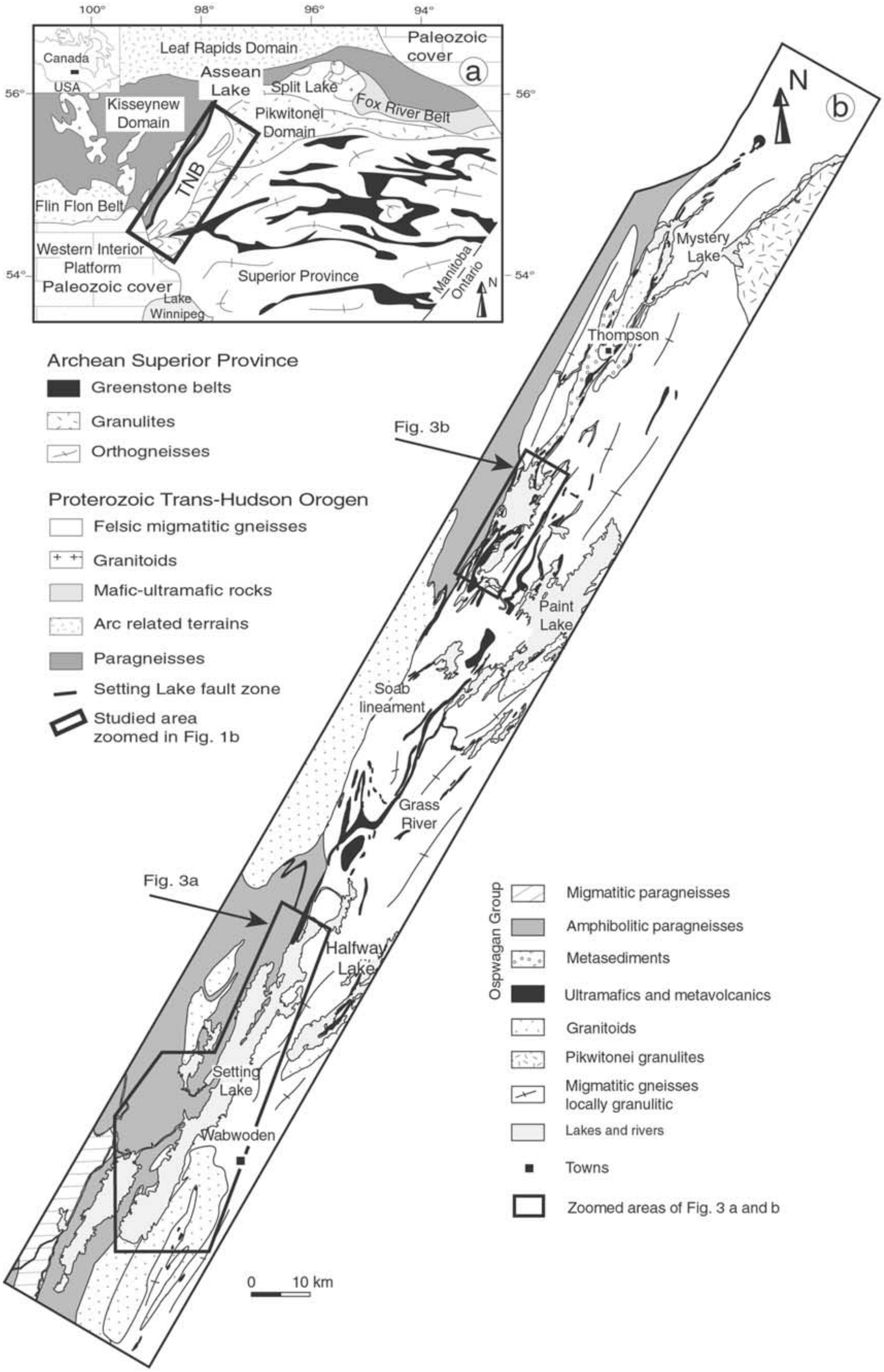
100°
98°
96°
94°
Leaf Rapids Domain
Paleozoic cover
Canada
USA
Assean Lake
Split Lake
Fox River Belt
a
56°
Kisseynew Domain
Pikwitonei Domain
TNB
Flin Flon Belt
Western Interior Platform
Paleozoic cover
Superior Province
Manitoba
Ontario
Lake Winnipeg
54°
N
Archean Superior Province
Greenstone belts
Granulites
Orthogneisses
Proterozoic Trans-Hudson Orogen
Felsic migmatitic gneisses
Granitoids
Mafic-ultramafic rocks
Arc related terrains
Paragneisses
Setting Lake fault zone
Studied area zoomed in Fig. 1b
b
Mystery Lake
Thompson
Fig. 3b
Paint Lake
Soab lineament
Grass River
Fig. 3a
Halfway Lake
Setting Lake
Wabwoden
0 10 km
Ospwagan Group
Migmatitic paragneisses
Amphibolitic paragneisses
Metasediments
Ultramafics and metavolcanics
Granitoids
Pikwitonei granulites
Migmatitic gneisses locally granulitic
Lakes and rivers
Towns
Zoomed areas of Fig. 3 a and b

**Figure 1**

1999, p. 446]. Furthermore, the distribution of available geochronological data for metamorphism and for felsic intrusions does not support large-scale thrusting. If this had been the case, a relatively narrow age range for HT regional metamorphism would be expected. In contrast, in the TNB ages of metamorphism and of felsic intrusions span a circa 100 m.y. interval (1850–1720 Ma) [*Machado et al.*, 1987, 1990; N. Machado et al., Timing of Trans-Hudson Orogen-Superior Province collision: constraints from U-Pb ages of granitoids emplaced during Paleoproterozoic transpression in the Thompson Nickel Belt (Manitoba, Canada), submitted to *Geological Society of America Bulletin*, 2004, hereinafter referred to as Machado et al., submitted manuscript, 2004] and appear randomly distributed throughout the belt.

[5] Because of the above uncertainties, we have reappraised the structures of the TNB through a detailed analysis of foliation and shear zone patterns. The analysis further allowed us to perform new U-Pb dating on synkinematic intrusions that are described in detail elsewhere (Machado et al., submitted manuscript, 2004). Consistently with the previous study of *Fueten and Robin* [1989], results show that top-to-the-west transpression is the only clearly constrained tectonic event of Paleoproterozoic age within the TNB. Furthermore, new syntranspression ages range from circa 1850 to 1750 Ma, suggesting that this event was a long-lasting one (Machado et al., submitted manuscript, 2004).

## 2. Geological Setting

[6] The TNB is a narrow NE trending belt (more than 100 km long and 5 to 30 km wide) on the western margin of the Archean Superior Province where it abuts the Paleoproterozoic THO (Figure 1a). Its western boundary, the Setting Lake fault zone (or Superior boundary fault) (Figure 1a), is rather sharp [*Zwanzig*, 1998] and has a steeply dipping geophysical signature down to about 15 km [*White et al.*, 1999]. Conversely, the eastern boundary of the belt is a more gradual transition where the E-W Archean structural trends are reworked into the NE-SW trend of the TNB (Figure 1). Reworking of Archean trends is accompanied by the retrogression of Archean granulite facies metamorphic assemblages of the Pikwitonei Domain (Figure 1a) to Proterozoic amphibolite facies [*Coats et al.*, 1972; *Russell*, 1981; *Paktunç and Baer*, 1986; *Fueten and Robin*, 1989; *Bleeker*, 1990]. The eastern extent of the Proterozoic overprint on the Archean basement is not precisely known. On the basis of lithological correlations, it has been proposed that the TNB turns east to the north, and extends into the Split Lake block and Fox River belt (Figure 1a). However, the recent discovery of Early Archean gneisses northwest of the inferred TNB boundary, in the Assean Lake area [*Böhm et al.*, 2000] (Figure 1) questions the location of the northeastern Superior/Trans-Hudson boundary. To the south, the belt disappears under the Paleozoic western Interior Platform.

[7] The TNB consists mainly of Archean gneisses that are variably migmatized and folded together with metasedimentary-metavolcanic units and associated ultramafic sills of the Ospwagan Group [*Coats et al.*, 1972] (Figure 1b). The age of deposition of the Ospwagan group is unknown. Several granitic bodies intrude both the Archean basement and the Ospwagan group. These intrusions underline two main structural trends: 030°–040° (parallel to the TNB) along the western boundary of the TNB (e.g., Setting Lake or Mystery Lake granitoids, Figure 1b), and 050°–070° in the eastern part of the belt (e.g., Halfway Lake area and southeast of Paint Lake, Figure 1b). The Mystery Lake granodiorite (Figure 1b) contains monazites of age 1836 ± 2 Ma and Archean zircons dated at circa 2.75 and 3.16 Ga [*Machado et al.*, 1987]. The Wintering Lake granodiorite (east of Paint Lake, not shown in Figure 1b) yielded a U-Pb age of 1822 ± 3 Ma, with both zircon and monazite; this granite also contains inherited zircons with estimated ages of 2.81 and 3.16 Ga [*Machado et al.*, 1987]. Granitic bodies cropping out in the Setting Lake area have yielded monazite ages ranging from 1818 ± 2 to 1797 ± 2 Ma (Machado et al., submitted manuscript, 2004).

[8] Available metamorphic data indicate that the TNB was affected by low pressure-high temperature amphibolite to granulite facies metamorphism (temperatures of 500°–700°C, for a mean pressure of 4.5 kbar [*Russell*, 1981; *Paktunç and Baer*, 1986]. However, *Bleeker* [1990] proposed higher (6–7 kbar) equilibration pressures for the peak metamorphic assemblages. The timing of the HT metamorphism is not well established, available U-Pb geochronological indicators ranging between circa 1786 Ma and 1720 Ma [*Machado et al.*, 1990].

## 3. Regional Strain Pattern

### 3.1. Foliations

[9] The TNB is characterized by a steeply dipping regional foliation associated with dome-shaped, doubly plunging NNE trending fold structures [*Fueten and Robin*, 1989; *Bleeker*, 1990].

[10] Folds at various scales have been mapped and studied in detail [*Bleeker*, 1990], but synthetic maps of associated strain trajectories had not yet been produced. Figure 2a shows a 1/250,000 synthetic foliation map obtained by averaging more than four thousand measurements of local fabrics. To obtain this map, the most detailed fabric maps available for the area (1/20,000, 1/25,000, 1/50,000 preliminary maps of the Manitoba Mineral Resources Division, listed in Figure 2a) were divided into one-kilometer square domains for which a calculated mean fabric was transferred to the corresponding square in the 1/250,000 topographic map. Only measurements of penetrative metamorphic fabrics (foliation and metamorphic layering) were considered. To escape problems attached to the averaging of directional data [see *Gumiaux et al.*, 2003], only the squares with regular,

**Figure 1.** (a) Simplified geology of the Trans-Hudson Orogen and location of the TNB (modified from *Weber* [1990]). (b) Simplified geological map of the TNB (modified from *Coats et al.* [1972]).

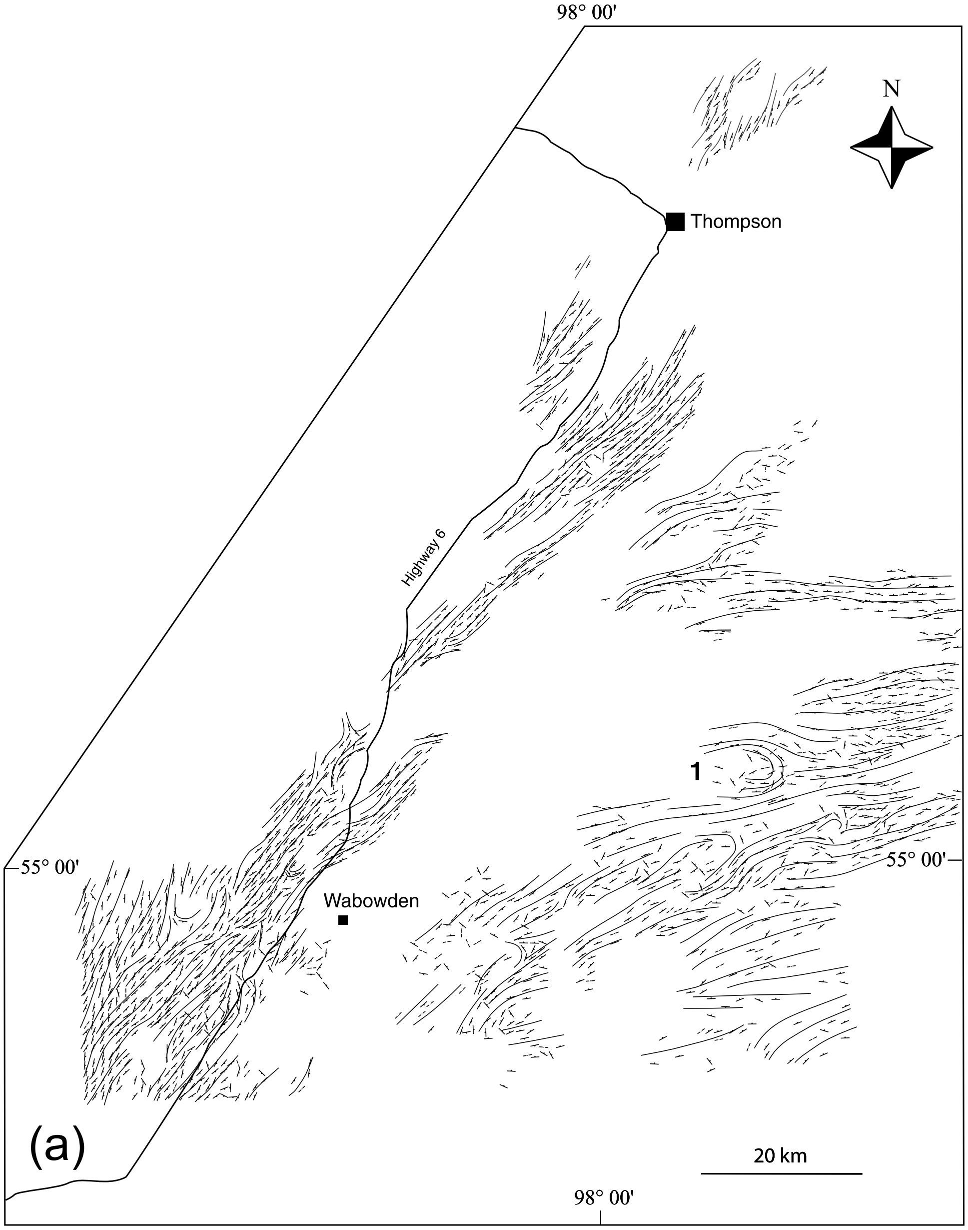


**Figure 2.** (a) Foliation trajectories in the TNB and adjacent Archean Superior Province in the Thompson area. Orientation data compiled from Preliminary Maps of the Manitoba Mines and Resources Division Geological Survey (1/20,000 maps 1977T-1, 1985T-1; 1/25 000 maps 1978T-1, 1979T-1, 1979T-2, 1980T-1, 1981T-1, 1981T-2; 1/50,000 maps 1969D-1, 1976T-1, 1978N-1, 1978N-2, 1978N-3, 1978N-4, 1978N-5, 1978N-6). Number 1 refers to particular zones discussed in the text. (b) Aeromagnetic map of the same area (reproduced after the Aeromagnetic map of Canada [*Viljoen et al.*, 1997]).

coherent directions were considered. Squares where the fabrics showed substantial directional variations were not taken into account.

[11] The map (Figure 2a) underlines that the foliation in the Archean Superior Province shows a dominant E-W trend. The Archean foliation has a variable dip, often higher than 45°. Complex patterns are locally observed, with crosscutting fabric directions (e.g., zone 1, Figure 2a). To the east, the Archean Superior Province is marked by an overall E-W trend of folded greenstone belts (Figure 1a). Consequently, we tentatively interpret the local occurrence of variable fabric attitudes (like in zone 1, Figure 2a) as reflecting superimposed fabrics, with remnants of a folded metamorphic layering showing E-W to NE-SW axial-plane foliations, parallel to the regional Archean trend. Toward the west, the Archean trend is reworked, taking a NNE-SSW attitude in the vicinity of the eastern TNB boundary. In the TNB itself, the foliation strikes mainly 030°–040°,


**Figure 2.** (continued)

subparallel to the belt [*Fueten and Robin*, 1989; *Bleeker*, 1990]. Locally, 050°–070° trends are observed (e.g., west of Wabowden, Figure 2a). A good overall correspondence is observed between regional foliation trajectories and the structural grain observed on the aeromagnetic map of the area (Figure 2b). This emphasizes an overall consistency between trends of regional foliations and lithologies.

[12] More detailed foliation trajectory maps have been made within the TNB, in the Setting Lake and Ospwagan areas (Figure 3). These maps were obtained by interpolation of more than seven hundred measurements of foliation and schistosity [*Stephenson*, 1974; *Macek and Russell*, 1978; this work].

[13] Trajectories highlight several heterogeneities in the strain pattern, as follows:

[14] 1. Fabric trajectories appear locally folded (e.g., area 1, Figure 3a). In the field, the metamorphic layering is commonly affected by tight folds with steeply dipping NNE axial planes, parallel to the regional foliation [*Bleeker*, 1990]. Crosscutting relationships between the metamorphic layering and the regional foliation are well preserved in fold hinges of dome-shaped structures [*Bleeker*, 1990]. We therefore interpret the locally folded trajectories (e.g., area 1, Figure 3a) as reflecting preserved early fabrics, folded and wrapped by the regional foliation.

[15] 2. In the Setting Lake area, foliation trajectories tend to define triple points at the edge of some granitic bodies (e.g., areas 2a and 2b, Figure 3a). This is particularly clear for a small granite located in the SW edge of the lake (area 2b, Figure 3a), between Setting and Pakwa lakes.

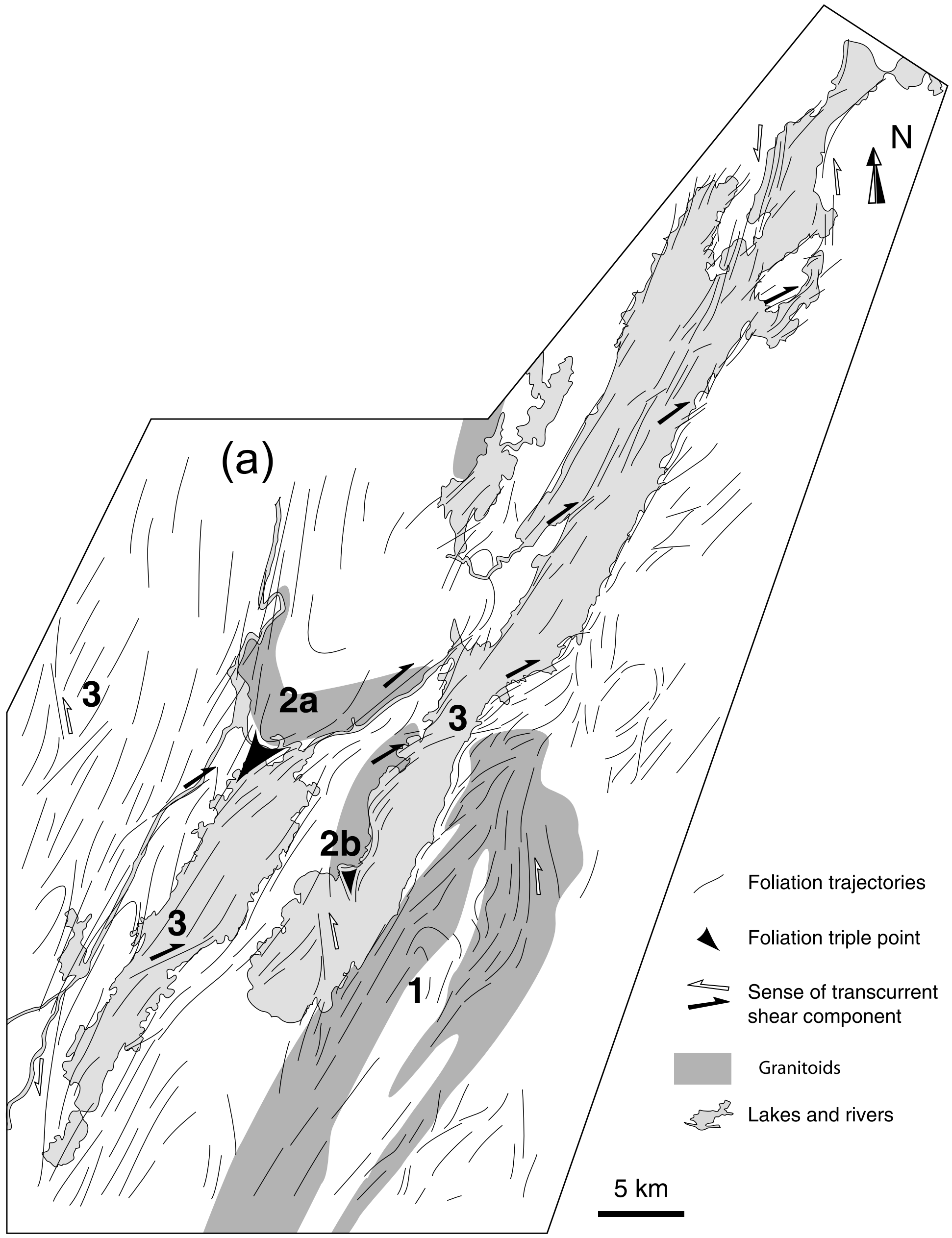


**Figure 3.** (a) Foliation trajectories in the Setting Lake area. (b) Foliation trajectories and lineations in the Ospwagan Lake area. Numbers refer to particular zones discussed in the text.

[16] 3. Locally, the foliation has a 050°–070° strike, oblique to the main structural trend. NNW to NS strikes are also observed. On the foliation maps, these two sets of orientations locally define ENE and SSE elongate bands. Because foliation trajectories converge toward these bands, we interpret them as the trace of map-scale shear zones (e.g., areas 3, Figure 3a). ENE and SSE striking zones are conjugate, with dextral and sinistral horizontal shear components, respectively (Figures 3a and 3b). The location of major shear zones appears partly controlled by lithological heterogeneities. This is for example suggested by the location of an ENE striking zone, at the southeastern termination of a large pluton on the Setting Lake map (area 2a, Figure 3a).

### 3.2. Lineations

[17] The stretching lineation is marked by preferred orientations of elongate minerals and objects (e.g., xenoliths) within the foliation plane. It is generally steeply plunging (Figures 3b and 4) [*Fueten and Robin*, 1989]. Nevertheless, data are scattered on a great circle outlining the average regional foliation plane (Figure 4). Most fold axes show comparable distributions [*Fueten and Robin*,

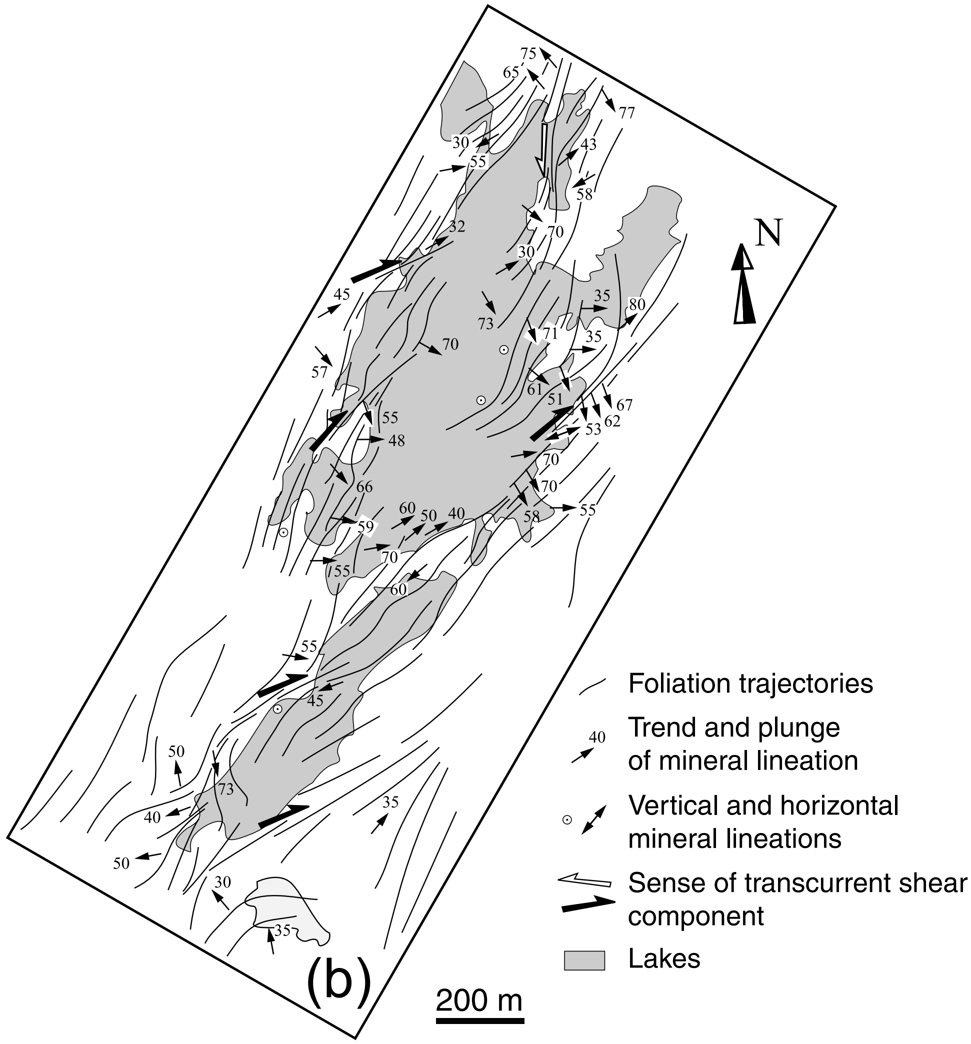


**Figure 3.** (continued)

1989; *Bleeker*, 1990]. The scattering of lineations and fold axes along the regional foliation trend could be related to the dome shape of regional-scale folds and reflect variations in the degree of reorientation of linear features toward the overall stretching direction, to local variations in relative amounts of thrusting and wrenching components, and/or to deviations around mechanical heterogeneities.

### 3.3. Finite Strains

[18] Most outcrops show evidence for horizontal stretching (boudins, tension gashes, shear zones with horizontal shear component, flattened xenoliths and sillimanite patches). Furthermore, chocolate-tablet boudinage is locally observed, indicating flattening finite strains. However, L-tectonites occur locally. In particular, pencil-shaped fabrics due to local interference between regional foliation and metamorphic layering can be observed in preserved fold hinges.

[19] At all scales, structures indicate rather large strains. These are in particular outlined by the occurrence of rolling

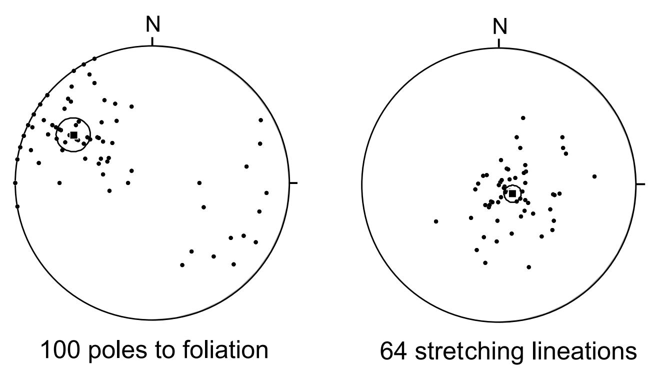


**Figure 4.** Stereograms (equal angle, lower hemisphere) showing distribution of foliation poles and stretching lineations in the studied part of the TNB. Mean foliation pole (square) plunges 22.4° in the N301.4° direction (95% confidence cone angle is 9.8°). Mean lineation (square) plunges 76.5° in the N122.4° direction (95% confidence cone angle is 7.1°).

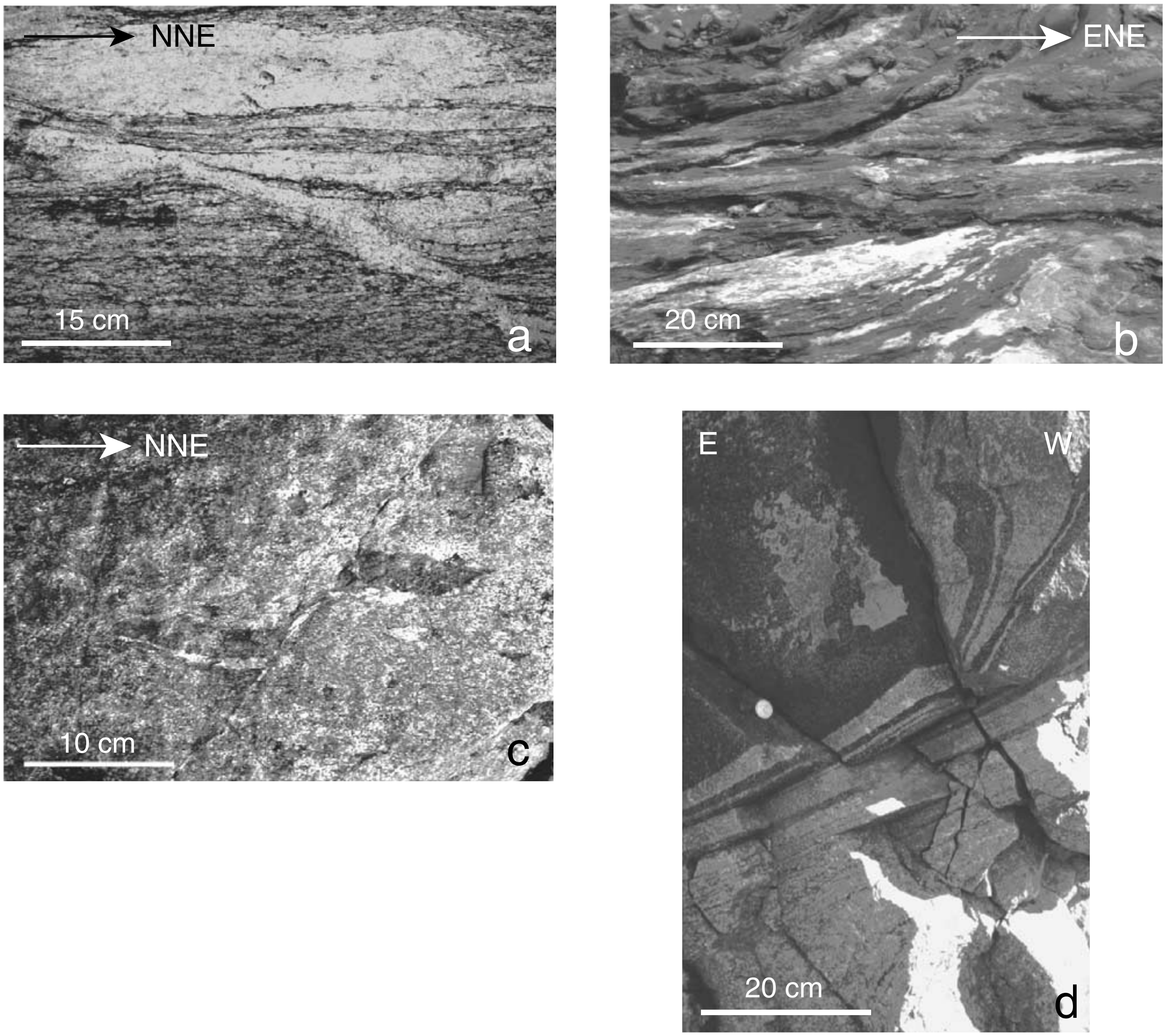


**Figure 5.** Examples of outcrop-scale shear bands. (a) Melt-bearing NE-SW shear band with dextral strike-slip component (horizontal view) (Thompson Pit area). (b) Sulphide-bearing, ENE-WSW shear band with dextral strike-slip component (horizontal view) (Thompson Pit area). (c) Discrete NNW-SSE fault with sinistral strike-slip component (horizontal view) (Burntwood River). Offset of xenolith underlines 10-cm-scale horizontal displacement. (d) Amphibolite facies shear band with top-to-the-west thrust component (vertical view) (South Jonas road).

structures, of C/S/C′ mylonites, by the reorientation of fold axes in the foliation plane, with locally sheath-like folds [*Fueten and Robin*, 1989; *Bleeker*, 1990], and by the overall parallelism between lithological contacts, belt boundaries and planar fabrics.

## 4. Shear Zones and Shear Bands

[20] Ductile shear bands and shear zones are observed at all scales throughout the belt (Figures 2, 3, and 5). In plane view, NE and NNW striking shear bands show components of dextral and sinistral strike slip, respectively (Figures 3, 5a, 5b, and 5c). When observed on subvertical surfaces, most show reverse shear components (Figure 5d). Shear bands have developed under various thermal conditions, from partial melting (Figure 5a) to lower temperatures indicated by discrete narrow fault-like zones (Figure 5c). In granitic rocks, some of these are marked by crystallization of epidote, which attests to rather low metamorphic grade. Thus shear bands appear to have formed and acted successively during progressive cooling of the area.

[21] In the TNB, assessing the shear direction along individual shear zones is not easy because (1) regional distributed strains are large and differ from simple shear,

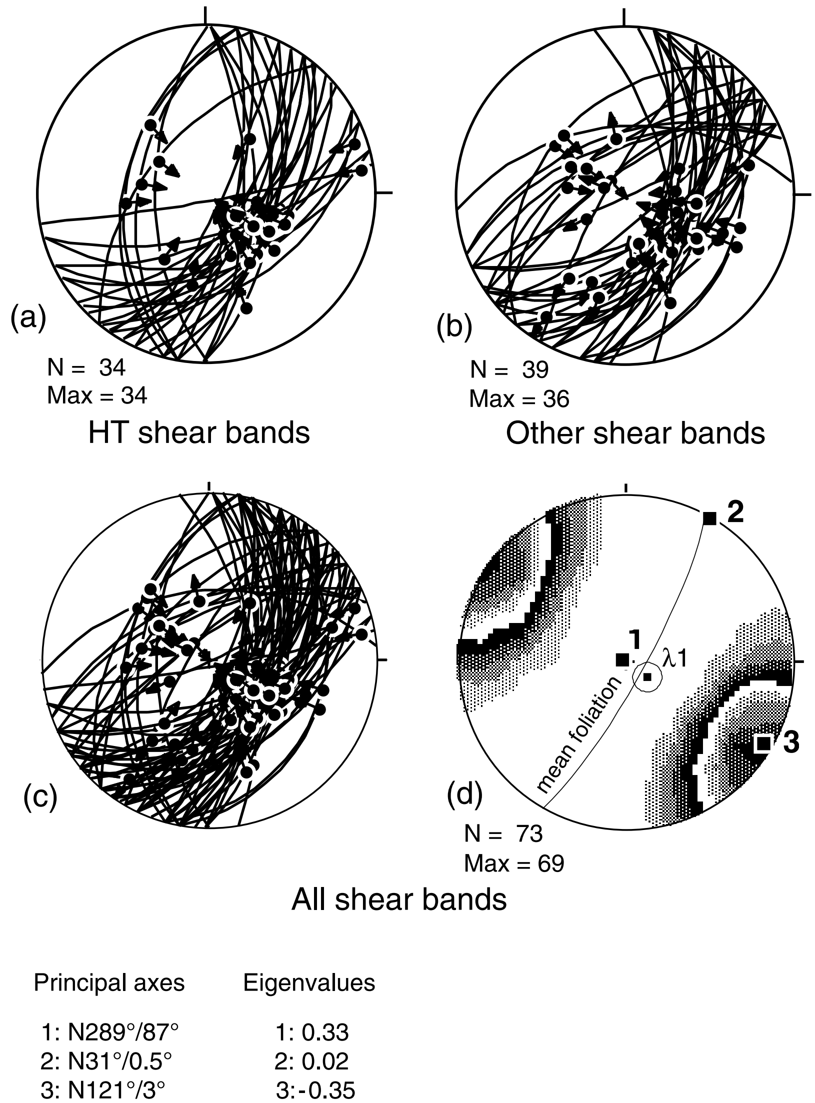


**Figure 6.** Statistical analysis of shear bands using the right-dihedra method [*Angelier and Mechler*, 1979]. Both (a) HT shear bands, many melt-bearing, and (b) other shear bands show similar distributions and associated bulk kinematics. Calculated principal axes for (c and d) all shear bands outline an overall orthorhombic symmetry, with subvertical principal stretch and subhorizontal principal shortening. A good consistency is found between principal directions deduced from shear band population (axes 1, 2, and 3) and those indicated by mean regional foliation and lineation ($\lambda 1$). Two eigenvalues are above zero, indicating flattening.

(2) many shear zones contain synkinematic magmas that have accumulated much less solid-state strains than the surrounding rocks (Figure 5a), and (3) outcrops are generally 2-D. Nevertheless, we could make estimates of shear directions along several decimeter-scale to meter-scale shear bands. Estimates are based on the inference that preferred orientations of shear zones with respect to the bulk finite strain field are generally those that tend to maximize the amount of parallel shear and to minimize the amount of parallel stretch [*Gapais et al.*, 1987, 1991]. In other words, an efficient shear zone is not expected to strongly deviate from a zone of finite simple shear, irrespective of the type of bulk finite strain field. It follows that the mineral preferred orientation within an individual shear plane constitutes a satisfying approximation of the local shear direction.

[22] Stereograms of measured shear planes and attached shear direction and shear sense show the following features (Figure 6a):

[23] 1. With respect to the mean regional foliation, two main groups of conjugate shear bands are observed: SE dipping and NW dipping zones, both with dominant reverse shear component. This emphasizes that the shear zone array contributes to the principal subvertical stretching.

[24] 2. Reverse shear zones with top-to-NW motion are dominant with respect to their conjugate with top-to-SE motion (Figures 6a and 6b). This is consistent with the study

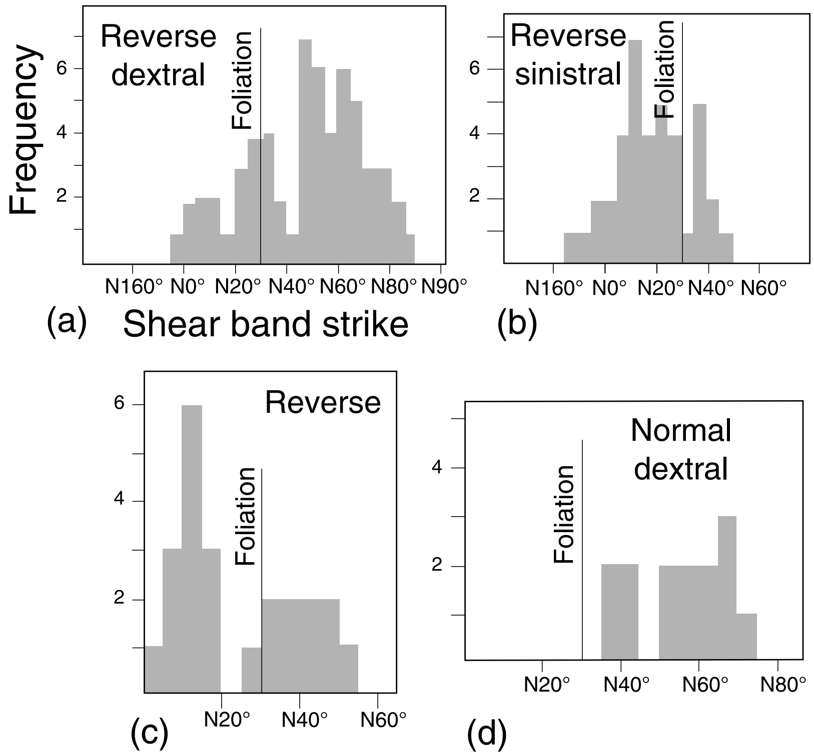


**Figure 7.** Diagrams showing frequency versus strike of shear bands with different kinematics. See text for further explanations.

of *Fueten and Robin* [1989] and with models proposed for late stages of the evolution of the TNB [*Bleeker*, 1990; *White et al.*, 1999].

[25] 3. SE dipping shear zones show substantial scattering in shear directions, from dominantly dip slip to shallowly plunging. Thus the pattern combines sets of bands with dominant reverse components, and less developed bands with dominant strike-slip components. This pattern implies outcrop-scale components of finite stretch along the intermediate subhorizontal strain axis ($\lambda 2$), and is therefore consistent with bulk flattening strains.

[26] 4. Figures 6a and 6b show distributions of shear bands associated with amphibolite facies metamorphic conditions, many being melt-bearing, and other shear bands, respectively. Both show quite similar patterns. Provided the orientation, the shear direction and the shear sense are known for individual shear zones within a shear zone array, data can be analyzed using kinematic methods, like the right-dihedra method [*Angelier and Mechler*, 1979], in a similar way as classically done for fault slip data [*Cobbold et al.*, 1991]. The analysis made on the whole set of data emphasizes the following points (Figure 6c).

[27] 5. Most shear bands have compatible infinitesimal kinematic stretching and shortening fields (69 shear bands among 73). This emphasizes that the shear bands reflect similar bulk kinematics irrespective of thermal conditions.

[28] 6. The shear zone pattern is compatible with subvertical principal stretching and SE-directed sub-horizontal principal shortening. This is consistent with the general strain pattern defined by regional foliation and lineation. Consistently, eigenvectors describing the distribution have quite similar attitudes than those of the mean principal strain axes deduced from regional foliation and lineation (Figure 6c).

[29] 7. Eigenvalues describing the distribution indicate some stretching along the intermediate axis (intermediate eigenvalue > 0), which is consistent with bulk flattening.

[30] The geometry of the shear zone array is further illustrated by frequency histograms distinguishing shear zones according to their strike and the type of their shear component (Figure 7). Most faults are reverse faults, with subsidiary component of strike slip. Reverse-dextral bands show a peak around 045°–070°N (Figure 7a), conjugate reverse-sinistral around 005°–040°N (Figure 7b). The overall trend of the regional foliation lies in between these two sets. A few bands with pure reverse shear component (pitch of shear direction higher than 85°) have also been measured (Figure 7c), as well as a few dextral shear bands with a normal shear component and striking 035°–075°N (Figure 7d).

[31] From the above analysis, we conclude that (1) shear bands and regional fabric (foliation and lineation) are kinematically compatible, mainly indicating subhorizontal flattening and subvertical stretching throughout the TNB, (2) most bands attest to dominant top-to-the-west motions, (3) in the horizontal plane, perpendicular to the principal stretch, the pattern is rather symmetric, and (4) the shear band pattern indicates that comparable

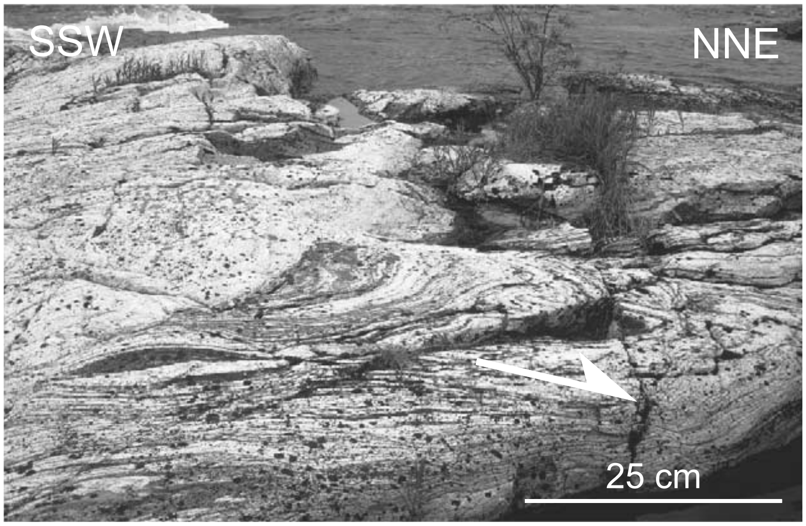


**Figure 8.** Example of high-grade flat-lying foliation within the TNB. Associated shear bands (arrow) are consistent with subvertical shortening (Sassagiu Rapids area).

kinematics has affected the belt during its HT and retrogressive histories.

## 5. Earlier Deformations

[32] Throughout the TNB, a very common outcrop-scale structure consists of boudins of amphibolite dykes or quartz and pegmatite veins that have been subsequently folded, a feature attesting to superposed deformation events. Field relationships indicate that the regional foliation results from reworking and folding of an initially shallowly dipping metamorphic and lithological layering transposed along fold limbs associated with subsequent subhorizontal shortening [*Bleeker*, 1990; *Zwanzig*, 1998; see also *White et al.*, 1999]. Kinematics associated with the early events is difficult to assess. However, where flat-lying fabrics occur, one can observe mineral lineations that strike north to NE, at low angle to the TNB. The attitude of associated shear bands appears consistent with subvertical shortening (Figure 8).

## 6. Discussion

### 6.1. Deformation History

[33] Within the TNB, the strain pattern is marked by a steeply ESE dipping penetrative foliation, a steeply plunging stretching lineation (downdip on average), and very large strains leading to sheath fold development [*Fueten and Robin*, 1989; *Bleeker*, 1990]. Our analysis illustrates the consistency of the deformation pattern at regional scale, and shows that the development of the regional fabric involved some strain localization along shear zones at various scales. The regionally steeply dipping principal stretch, the associated shear zone pattern and the evidence for horizontal flattening finite strains are consistent with an overall transpressive tectonic setting [e.g., *Merle and Gapais*, 1997; *Dewey et al.*, 1998; *Fossen and Tikoff*, 1998; *Lin et al.*, 1998], as previously argued for the area [*Fueten and Robin*, 1989; *Bleeker*, 1990]. Associated deformations can be correlated with the phases F3 to F7 of *Bleeker* [1990], and our structural analysis suggests that these different phases should be grouped in a single progressive deformation event. The general pattern proposed (Figure 9) is consistent with the observations made by *Fueten and Robin* [1989]. As underlined by *White et al.* [1999], the dominantly steep fabrics exposed throughout the TNB may appear difficult to correlate with seismic reflection data that mainly image overall east dipping reflectors at crustal scale. However, the interpretation of high-resolution seismic data is consistent with the occurrence of steep, dominantly east dipping deformation zones that rework and fold an earlier fabric [*White et al.*, 1999, Figure 7]. According to field data [*Bleeker*, 1990; *Zwanzig*, 1998], the folded fabric imaged by seismics should mainly correspond to the primary metamorphic and lithological layering [*White et al.*, 1999].

[34] Field data indicate that strains accumulated during high-grade metamorphic conditions, involving partial melting, and during subsequent retrogression. Thus, at least most of the LP-HT clockwise retrogressive path recorded in the area [*Russell*, 1981; *Paktunç and Baer*, 1986; *Bleeker*, 1990] appears characterized by comparable kinematics. A rather long-lasting event of transpression is confirmed by new geochronological U-Pb data obtained on synkinematic granitic and pegmatitic intrusions (Machado et al., submitted manuscript, 2004) (Figure 10). Undeformed or weakly deformed granitic intrusions have yielded rather old U-Pb ages around 1850–1840 Ma on partially recrystallized inherited Archean zircons (Figure 10). Pegmatites and granitic veins, undeformed or affected by top-to-the-west shearing, have yielded emplacement ages between 1820 and 1750 Ma (Figure 10). Thus both structures and U-Pb data indicate that the TNB has been a long-lasting deformation zone. Youngest ages appear concentrated in the

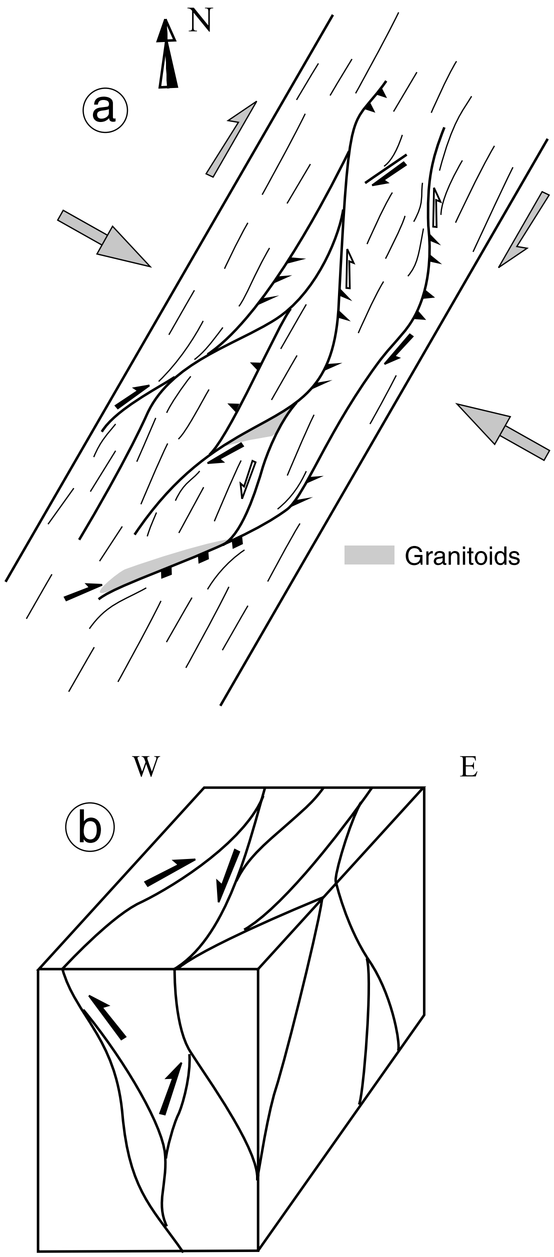


**Figure 9.** Sketch summarizing the transpressive structural pattern of the TNB in (a) map view and (b) block diagram. See text for further explanations.

western part of the belt (Figure 10), marked by NNE-SSW alignments of major nickel-bearing occurrences. Strain localization in the western part of the belt during retrogression could account for a more intense ore remobilization and increase in ore concentration along retrogressive shear zones in this area.

[35] In the eastern part of the belt, a pegmatite intruding Archean gneisses has yielded a minimum zircon age of 2656 ± 2 Ma, monazites pointing to some minor Proterozoic reworking at about 1.9 Ga. In contrast, zircon overgrowths within an Archean gneiss of the TNB have yielded ages around 1802 Ma (Figure 10). These data are consistent with limited Paleoproterozoic tectonic and metamorphic reworking of the Archean basement toward the east, where Archean structural trends are preserved.

[36] Thus major outcomes of our study compared with previous models [*Bleeker*, 1990; *White et al.*, 1999] are the importance and the duration of the transpressive event. In our model (Figure 9), individual shear zones can initiate, propagate, and eventually become inactive at various times during progressive deformation. This means that ductile shear deformations and associated synkinematic mineral recrystallizations can reflect different time spans from one zone to another. Such a model can thus account for the substantial scatter in U-Pb metamorphic ages throughout the belt.

### 6.2. Transpressive Kinematics

[37] A major feature of the strain pattern within the TNB is its rather orthorhombic character. In particular, the pitch of the principal stretch direction deduced from both mineral lineations and shear zone patterns, is close to 90° (Figure 6c). This has implications on both thrusting and strike-slip components, as follows.

#### 6.2.1. Thrusting Components

[38] The overall pattern of reverse shears is not strongly asymmetric; however, top-to-the-east shear bands are clearly dominant throughout the studied area (Figure 6). On the other hand, the overall subvertical attitude of both foliation and principal stretch, combined with the overall large strains, are not in favor of major horizontal displacements associated with thrusting. These characteristics are rather compatible with pervasive shortening involving substantial steeply dipping stretching [e.g., *Fossen and Tikoff*, 1998; *Lin et al.*, 1998, *Robin and Cruden*, 1994]. Consistently, neither metamorphic zonations, nor deep seismic data [*White et al.*, 1999] provide clear arguments for a late tilting of initially less dipping fabrics.

#### 6.2.2. Strike-Slip Components

[39] *Bleeker* [1990] has proposed that two successive strike slip components, first sinistral and then dextral, occurred along the TNB. On the other hand, *Fueten and Robin* [1989] concluded that the deformation was basically associated with reverse-type motions. Our observations emphasize that the assessment of a dominant component of strike slip is indeed not straightforward.

[40] The mean value of about 90° for the pitch of the principal stretch does not point to a dominant sense of strike-slip component. This might be due to a change of shear sense with time [*Bleeker*, 1990], but this is not suggested by the shear zone pattern that does not show major differences according to metamorphic conditions (Figure 6). Furthermore, no particular crosscutting relationships between sets of shear zones have been observed in the field. Difficulties in assessing a sense of strike-slip component in natural transpressive zones are suggested by theoretical models [e.g., *Fossen and Tikoff*, 1998] and analogue experiments [*Casas Sainz et al.*, 2001] of oblique convergence. These have emphasized that the principal stretch direction can switch from subhorizontal for convergence angles between 0° (pure strike slip) and 20° to subvertical for higher convergence angles. Thus compressive systems

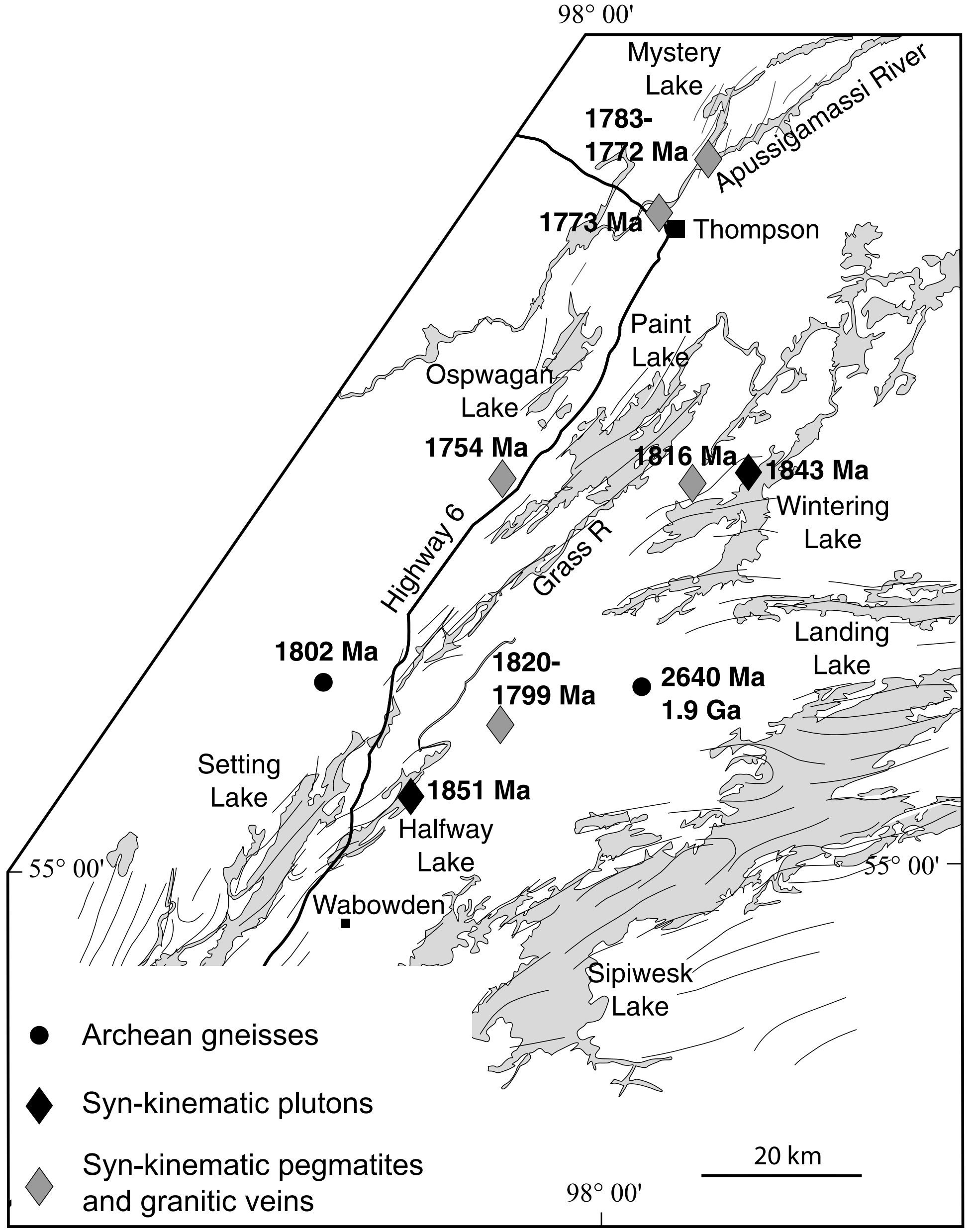


**Figure 10.** U-Pb geochronological data recently obtained within the TNB on metamorphism within Archean gneisses (circles), and emplacement of syntranspression plutons (solid diamonds) and pegmatitic and granitic dykes (shaded diamonds) (detailed description given by Machado et al., submitted manuscript, 2004).

of comparable thrust geometries, both on maps and on cross sections, have been obtained experimentally for variable convergence angles between 90° (pure thrusting) and about 20° [*Casas Sainz et al.*, 2001].

[41] In map view, foliation trajectories and magnetic data (Figure 2) suggest counterclockwise reorientation of the EW Archean trends toward the TNB. The curvature of the magnetic grain has thus been used as an argument for sinistral strike slip [e.g., *Lewry and Collerson*, 1990]. However, because the deformation involves vertical stretching, the curvature of structural trends on the map cannot be straightforward used to demonstrate a regional sense of strike slip. As underlined by *Fueten and Robin* [1989], such a pattern on map view can simply result from the reorientation and/or transposition of E-W striking Archean structures during dominant dip-parallel shearing along a steeply dipping NE-SW shearing plane. On the other hand, some features suggesting a bulk dextral strike-slip component can be found in the shear zone pattern. First, NE striking shear zones with dextral horizontal component are more developed than the NNW striking set with horizontal sinistral component. This is observed for outcrop-scale shear bands (Figures 6 and 7) and map-scale shear zones (Figure 3). Second, we have observed a few SE dipping and

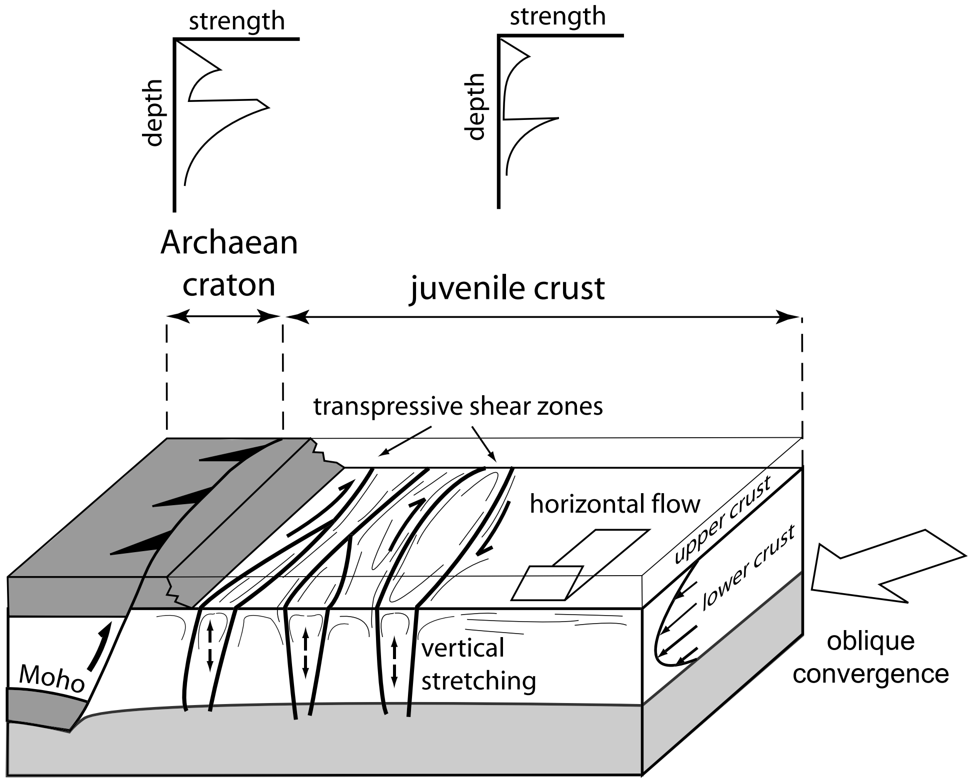


**Figure 11.** Sketch illustrating a possible framework for the behavior of a weak, hot and buoyant Proterozoic juvenile lithosphere during convergence toward an Archean craton. The component of horizontal flow and/or lateral extrusion parallel to the deformation belt can result from oblique convergence and/or from particular boundary conditions allowing for lateral escape.

NE striking shear bands showing dextral horizontal component and southward plunging displacement directions. These bands can be described as normal-dextral shear bands (Figure 7d) indicating local extension along a NW horizontal direction. Extension along such direction is difficult to explain in a context of NNE-SSW sinistral strike slip where the NW direction should be in the shortening field.

### 6.3. Relationships Between Deformation and Granitic Intrusions

[42] Several lines of evidence suggest close relationships between shear zone development and channeling and emplacement of melts. At outcrop-scale, synkinematic melting is shown by melt concentrations along shear bands (Figure 5a), as well as by the occurrence of leucosomes parallel to the axial plane of folds. Several granitoid outcrops show penetrative C-S fabrics, as classically developed during synshearing cooling from HT conditions [*Gapais*, 1989]. For example, the northern part of Setting Lake is marked by granitoids affected by penetrative top-to-the-west C-S fabrics. The rather simple structure of these outcrops, compared with the more complex shear band array commonly observed throughout the TNB, suggests syntectonic emplacement. Foliation triple points occur around granitic bodies (e.g., zone 2b, Figure 3a). These can result either from foliation wrapping around resistant bodies or from interference between tectonics and pluton ballooning [e.g., *Brun and Pons*, 1981]. Because of the overall HT regional metamorphic conditions, limited strength contrasts between granitoids and surrounding gneisses (most being orthogneisses) are expected. We therefore tentatively interpret local foliation triple points as associated with the emplacement of syntectonic plutons. In addition, some granitoids show isotropic textures or rather weak magmatic fabrics underlined by schlieren (Machado et al., submitted manuscript, 2004). Again, because of the overall HT metamorphic conditions, the preservation of weakly deformed granitoids within a strongly deformed tectonic belt is rather unlikely. Two weakly deformed granitoids have been consistently dated around 1850 Ma (Figure 10) (Machado et al., submitted manuscript, 2004), i.e., relatively early in the tectonic history of the belt. Their low strain compared with the strongly deformed country rocks, as well as their elongate shape along NE-SW directions (e.g., granitoid located south of Paint Lake, Figure 1), suggest that they could have preferentially emplaced along dextral extensional zones (Figure 9).

### 6.4. Crustal-Scale Mechanisms

[43] Transpressive zones implying distributed horizontal shortening and important subvertical stretching are common

in Archean and Proterozoic convergence zones. This is for example observed in Archean Greenstone belts of North Minnesota [*Hudleston et al.*, 1988], in the Finnish Svecofenides [*Ehlers et al.*, 1993; *Lonka et al.*, 1998], along the western boundary of the Gawler Craton (SE Australia) [*Vassallo and Wilson*, 2002], or in the Paleoproterozoic of Terre Adélie (Eastern Antarctica) [*Pelletier et al.*, 2002]. Boundary conditions and crustal rheology allowing for such deformation style are still unclear. Recent analogue experiments have shown that compression of hot and therefore weak lithospheres was accommodated by distributed penetrative thickening combined with localization along subvertical shear zones [*Cagnard et al.*, 2004; *Cruden et al.*, 2004]. Experiments further show that subvertical shear zones are marked by combined local uplifts of ductile crust and burial of pop-downs of upper crustal material [*Cagnard et al.*, 2004] attesting to large strains involving intense bulk vertical stretching and associated vertical flow. In these experiments involving a ductile lithospheric mantle and a rather thin brittle upper crust, crustal-scale shallowly dipping thrust systems did not develop. Large strains involving important vertical stretch (sheath folds, C-S fabrics, boudinage...) are a characteristic of the TNB [*Fueten and Robin*, 1989; this study]. In a study of Archean granulites from northern China, *Dirks et al.* [1997] proposed that subvertical crustal flow could be accommodated upward within domains of horizontal spreading, below the brittle-ductile transition. Indeed, in their study area, steeply dipping transpressive shear zones coexist with domains of less-dipping or flat-lying foliations. Such coexistence in space is in fact frequent [e.g., *Ehlers et al.*, 1993; *Choukroune et al.*, 1997; *Pelletier et al.*, 2002; *Vassallo and Wilson*, 2002]. In most examples, transpressive shear zones appear to expand at the expense of domains of flat-lying fabrics, the latter being often interpreted as related to early thrusts or nappes [e.g., *Ehlers et al.*, 1993; *Choukroune et al.*, 1997; *Vassallo and Wilson*, 2002]. However, in these examples, radiometric data suggest some chronological overlap between the two types of structures [e.g., *Ehlers et al.*, 1993; *Pelletier et al.*, 2002; *Vassallo and Wilson*, 2002]. Furthermore, both show similar HT conditions, and geometric evidence for large-scale early thrusting is not so clear. Thus, in some examples, stretching lineations associated with flat-lying fabrics are subparallel to the transpressive zones [*Caby et al.*, 2000; *Pelletier et al.*, 2002; *Vassallo and Wilson*, 2002; *Davies and Maidens*, 2003]. As these are expected to be significantly oblique to the convergence direction, such attitudes of stretching lineations do not easily support crustal-scale thrusts.

[44] Combined development of transpressive shear zones and lateral extrusion and/or horizontal flow of hot, weak, and buoyant juvenile crust at the margin of a stable craton acting as a buttress could provide some explanation to the observed deformation style [*Pelletier et al.*, 2002; *Cruden et al.*, 2004] (Figure 11). Few constraints exist to date in the TNB area to discuss mechanical models. There are nevertheless zones of flat-lying fabrics (Figure 8) that show comparable ages and metamorphic conditions than the steeply dipping transpressive fabrics (e.g., Sassagiu Rapids area [*Machado et al.*, 1990].) There, stretching lineations appear to strike dominantly NNE, at low angle to the TNB, and shear band attitudes are consistent with components of vertical shortening (Figure 8). Similar trends of lineation, dominantly N-NE at high angle to the expected compression direction and associated with gently dipping metamorphic fabrics, are observed at regional-scale west of the TNB, within the juvenile Kisseynew domain (Figure 1a) [see *Zwanzig*, 1999, Figure 9b]. In this domain, available metamorphic ages range between 1820 Ma and 1770 Ma [*Machado et al.*, 1999], which shows that associated deformations are in part coeval with the transpression recorded in the TNB.

## 7. Conclusions

[45] The following points summarize our conclusions.

[46] 1. In the Thompson Nickel Belt, the development of the steeply dipping, NNE-SSW regional foliation was associated with the development of an array of ductile shear zones, from outcrop-scale to map scale.

[47] 2. Structures, principal strain directions, and shear zone patterns indicate subvertical principal stretching in a transpressional regime, with NW-SE subhorizontal shortening and top-to-the-west thrust motion.

[48] 3. The overall strain pattern suggests that transpression was accommodated by distributed shortening, without evidence for extensive thrust motions.

[49] 4. Shear zone patterns indicate similar kinematics during the retrograde history, from early HT conditions marked by partial melting. This, and new geochronological data, suggest that top-to-the-west transpression could have been a long-lasting event of progressive deformation, of the order of 100 Ma (Machado et al., submitted manuscript, 2004).

[50] 5. Horizontal motions are difficult to document, and a sense of regional strike-slip is difficult to assess. Nevertheless, along-strike dextral motions are suggested by (1) NE-SW shear zones with dextral horizontal motions that dominate over their sinistral conjugate set, (2) the occurrence of some NE-SW to ENE-WSW shear zones with both dextral and normal components, and (3) the occurrence of weakly deformed granitic bodies elongate along the NE-SW direction.

[51] 6. Structures observed in the TNB area might be related to convergence between two thermally different lithospheres, a weak and hot juvenile crust and an Archean craton acting as a buttress.

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