CHAPTER 6 STRUCTURE

6.0 Preamble

Several models have been proposed to explain the structure of the TNB (e.g., Fueten and Robin, 1989; Bleeker, 1990a; White et al., 1999). The main differences between the models are the relative weights given to the fold geometry of stratigraphic units *vs.* finite strain and kinematic analysis. Interpretations of superposed fold structures in terms of successive deformation phases has led to the development of a model involving early nappe tectonics followed by northeast-directed transpression (Bleeker, 1990a). However, strain and kinematic analysis has led to the development of a southeast-side-up kinematic model (Fueten and Robin, 1989). Both approaches are limited by the paucity of outcrop in the TNB.

Geochronological data available before the commencement of this project (Machado, 1990; unpubl. data) were not compatible with a simple nappe model, because the dispersion of ages (1836-1720 Ma) militated against a single major metamorphic-melting event of regional extent, as may be expected and has been observed in areas of known thrust tectonics. Nevertheless, a protracted history of polyphase deformation similar to that observed in the adjacent part of the Trans-Hudson Orogen, and characterized by more than one period of metamorphism related to multiple continental collisions, remains a viable tectonic model (Zwanzig, 1999b and references therein). Although an alternative, transpressional tectonic model, is easier to reconcile with the geochronological data, the model as proposed was too vague to be tested using high-resolution geochronological methods. Thus, one of the objectives of this project became to conduct simultaneous structural and geochronological studies in order to advance the understanding of the tectonic evolution of the TNB.

Given that the different models arise from the application of a different range of structural techniques, it was not possible to reach a consensus on the evolution of the TNB. Thus, Part I of this chapter presents a model of 'nappe tectonics' involving large-scale recumbent folding and subsequent upright folding, as modified from Bleeker (1990a) by Zwanzig, and Part II presents a transpressional model, as modified and refined by Potrel and Gapais.

PART I. MODIFIED NAPPE MODEL

6.1 Methods and Conventions

To minimize differences in terminology used in the structural history portion of this report and in previous work, the most prominent phase of deformation (D_3), which resulted in the NNE strike, steep easterly dip, and generally steep plunge of most units, is taken as a chronological reference period (Bleeker, 1990b). The entire period of late deformation during retrograde metamorphism is designated as D_4. In this analysis, structural elements that were interpreted to have been generated during a particular phase of deformation are assigned the same subscript number (e.g., S_2 foliation formed during D_2). Structural data that were recently acquired from the Setting and Mystery Lake areas are presented in a series of equal-area stereograms organized into subareas. Because of the similar character of the S_2 and S_3 foliations and the coplanar overprint of S_4, these elements are not always distinguishable in the diagrams.

The nomenclature of structural styles also follows Bleeker (1990b); a subhorizontal sheet-like (recumbent) fold with structural overlap >10 km is considered to be a fold nappe, even where such a structure has to be restored after upright folding and where the basal detachment zone acted in a ductile manner with no apparent loss of cohesion.

A detailed three-dimensional analysis of structural data from the Setting Lake area, which encompasses the southern third of the exposed TNB, and adjacent part of the Kisseynew Domain, is presented in the stereograms and also discussed in **Sections 6.2** and **6.4**. Mean planes and lines are calculated, where possible, using an eigenvector technique (provided in Pangeo Scientific™ SpheriStat 2®). Foliations plotted as lower-hemisphere poles that generally fall into great-circle girdles provide a mean hinge line for one or several major folds in each subarea. The orientation of such fold hinges and of the local minor folds, as well as various types of lineations, are tracked along the hinge zones to provide a three-dimensional picture of the structures. This work is still in progress and the results presented here are preliminary.

A preliminary structural synopsis that combines the new structural data with that of Bleeker (1990b) and applies it to the regional compilation map (TNB Geology Working Group, 2001) is used to summarise the major fold geometry of the TNB. This part of the work provides an important reference for tracking regional variations in the stratigraphy of the Ospwagan Group and of the ultramafic intrusions and known nickel deposits.

6.2 Structural History

6.2.1 Previous and Present Work

The history of Proterozoic deformation, modified from Bleeker (1990a and b) and consistent with Zwanzig (1998), was tentatively interpreted from large-scale domes and complex fabrics in the Archean basement gneiss, and from large- and small-scale folds in the Proterozoic supracrustal rocks. An important feature is the development of the basement domes and their internal fabrics during polyphase Proterozoic folding. This report also uses the age constraints provided by structures recognised in the relatively younger rocks of the Kisseynew Domain. Consequently, the history provided in this section (**Table 6.1**) differs somewhat from that of Bleeker (1990b). Deformation is interpreted to have occurred in four phases, lasting through high-grade and retrograde metamorphic conditions. The evolution path of basement and cover nappes is uncertain; the basement may not have been involved in the folding until partway into the progressive deformation history.

6.2.2 Basement Structures (Archean)

Many of the migmatitic gneisses that constitute the Archean basement to the Ospwagan Group are strongly layered (i.e., stromatic: Albino and Macek, 1981) and contain veins of pale grey to pink tonalitic or granodioritic leucosome that are interpreted to be Archean. The early age of this gneissic layering (S_A) is consistent with the gradational contact between the leucosome and the intermediate to mafic melanosome that constitutes the oldest component in the Archean gneiss. The early veins exhibit isoclinal folding that is commonly rootless and indicates high strain. Buff to pink granitoid veins with gradational to sharp contacts probably include Archean and Proterozoic leucosomes. The complex gneissic layering is locally truncated along the unconformable base of the Ospwagan Group (Bleeker, 1990a; Zwanzig,

Table 6.1 Summary of dominant TNB structure: comparison of Bleeker (1990b, shaded) and Zwanzig (this report, white background)

	Age	Folds	Faults/Shears	Kinematic Indicators	Schistosity	Lineations	Metamorphism	Interpretation
D_1	Pre-dates the mafic dikes in the Pipe Pit	Recumbent, isoclinal, in Ospwagan Group and basement rocks	Major movement zone at top of basement		S_1 schistosity and boudinage are sub-horizontal, layer parallel, axial planar to F_1 folds		Pro-grade, up to amphibolite facies	Nappe development, SE verging if Moak Lake structure is a syncline
D_1	Pre-dates the mafic dikes in the Pipe Pit	Original style unknown (probably upright), involves mainly Ospwagan Group	Inferred, but not directly observed, east-verging if present		Possible S_1 ENE-trending fracture cleavage in Bah Lake assemblage		Uncertain, probably low grade	Possible recumbent folds may be related to extensional tectonic, and/or upright folds leading to tectonic burial
D_2	Post-dates the mafic dikes in the Pipe Pit	Recumbent, tight to isoclinal; folded F_1 folds, mafic dikes, sillimanite lenses and earliest pegmatites	Shear zones mainly in metasedimentary rocks and adjacent basement	Intrafolial fold packets suggest non-coaxial strain	S_2 schistosity present in some fold hinges but coplanar with S_1 in fold limbs		Middle- to upper amphibolite	Continued recumbent deformation near peak metamorphism
D_2	Syn- and post-Kisseynew sedimentation, S_2 cut by >1818 Ma granite	Recumbent, D_2 has refolded and tightened F_1 folds and may have reoriented them from upright to recumbent	Superior Boundary fault zone, local SW-verging thrust faults along the boundary	Probably dextral, NE-over-SW rotation of early porphyroblasts	S_2 schistosity, gneissosity and boudinage are the regional foliation, subparallel to layering and Archean foliation	L_2 biotite crenulations have variable plunges	Middle- to upper amphibolite, possible lower granulite	Development of recumbent structure, SW thrusting of Ospwagan Group over Kisseynew gneisses, vergence changes to SW, possibly W
D_3	1770 Ma pegmatite coeval with F_3 folds	Main set of folds, NE trends, fold the peak metamorphic minerals, axial planes vertical to steeply SE dipping, axes plunge to S and NE	NE-trending mylonites (forming late D_3 and continuing through D_5)	Indications of mainly flattening, shear related to flexural slip	NE-trending fabric, S_3 absent or weakly developed as axial planar to F_3 folds	L_3 crenulation and intersection lineations, parallel to flexural-slip striations	Retrograde, amphibolite to greenschist facies	Strong NW-SE shortening with minor independent dip-slip components; left-stepping, NE-trending, en echelon folds indicate sinistral transpression.
D_3	As above	As above	Mylonites, NNE trending, steeply SE dipping. Conjugate faults, N to NNE and ENE	ESE-up shear bands with sinistral component. Sinistral and dextral faults	S_3 NE- trending, steeply SE dipping, best developed in tight F_3 fold hinges and shear zones	L_{3-4} is a weak down-dip stretching lineation, variable plunges in the southwest	?Granulite to greenschist facies	Mainly NW-SE shortening; regional, SE-side-up sinistral transpression, vertical stretching. Late-D_4 NW-SE compression with NE extension
D_4		As below					Greenschist facies	
D_3-D_4*		Minor NE-trending, sub-vertically plunging folds in F_3 fold limbs and mylonitic foliation (including sheath folds)	NE-trending low temperature mylonites and brittle faults; late SE-trending faults	Flattening and dip-slip, also sinistral shear zones in the west, but late (D_4) E-SE dextral slip	Mylonitic foliation overprinted on F_3 fold limbs	Weak down-dip stretching lineation; late horizontal striae	Retrograde greenschist facies	Modifies older structures, local E-SE dextral faults overprint NE sinistral faults

* F_4 and F_6 of Bleeker (1990b) are minor fold phases only.

2000) and is cut at a low angle by Proterozoic mafic dikes. These dikes and the larger bodies of the Bah Lake assemblage volcanic rocks are highly sheared at their margins, but show evidence of only moderate to low strain in their cores. They contrast sharply with boudins of coarsely recrystallized amphibolite that are strongly foliated and locally invaded by the Archean leucosome. The early boudins are evidence of penetrative Archean deformation before the deposition of the Ospwagan Group.

The map-scale layering of the Archean gneiss is defined by aeromagnetic trends parallel to $S_{A,}$ which are generally subparallel to the Proterozoic NNE-trending structures that have transposed S_A. However, tight Archean folds, defined by elongate bodies of garnetiferous leucotonalite and magnetite-rich gneiss, trend 050° on Paint Lake (TNB Geology Working Group, 2001). Similar basement units extended obliquely across the TNB, providing an early anisotropy that was probably reactivated during the Proterozoic. The emplacement of plutons that may be Proterozoic, such as the K-rich intermediate intrusions extending in a northeast-trending chain south of Joey Lake, was probably guided by these structures. Other transverse fold trends in the basement gneiss occur between Manasan Quarry and Paint Lake and are oriented along a 340° trend. Some of the Archean structures may have had a role in basin development during the deposition of the Ospwagan Group and the intrusion of the ultramafic sills associated with the nickel deposits.

6.2.3 Pre-Grass River Group Proterozoic Structures (D_1)

F_1 folds have been interpreted to occur at the Pipe II pit (Bleeker, 1990b), where Proterozoic mafic dikes cut a limb and part of the hinge zone of two folds at a scale of tens of metres. They are interpreted to have formed before deposition of the Grass River Group, which is not intruded by such dikes and which contains younger detrital zircon grains than the youngest dated mafic dike in the TNB (**Section 10.3.2**). However, because of strong later deformation, the earliest Proterozoic structures are not preserved in their original orientation and probably not in their original style or degree of closure. The dikes generally have a small acute angle to the F_1 fold limbs and follow the variable trends produced during the subsequent folding.

Bleeker (1990a and b) has interpreted F_1 folds to be parasitic to a fold nappe that involved the basement gneiss, producing a locally inverted stratigraphic section that is refolded in the Thompson structure (**Figs. 6.1a** and **6.2a**; **Section 6.4.3**). The axial surface of the inferred nappe has been interpreted to underlie the Thompson structure and to emerge to the northwest in the Ospwagan Group, in the large D_3 syncline that extends from the Pipe II pit to Moak Lake. In this model, the axial surface of the complimentary anticlinal basement nappe would overlie the Thompson structure, the Pipe structure, and the large syncline to the northwest. Thus, the Pipe structure is interpreted to be part of the Thompson nappe and joined to the Thompson structure at depth. In contrast, Golightly and Lyons (1996) suggested that the axial surface of the basement core overlies the Thompson structure, but underlies the upright Pipe structure (**Figs. 6.1b** and **6.2b**). This interpretation is based on the observation that the magnetic signature of the Ospwagan Group in the northwest appears to be that of a simple syncline. It implies that the present enveloping surface of the nappe has an overall dip to the northwest, consistent with southeast-side-up movement during D_3 (**Section 6.2.5**). However, more recent mapping (TNB Geology Working Group, 2001) indicates that some of the magnetic features on which that interpretation is based may be due to the presence of an inverted section of the Ospwagan Group in a dome north of Nichols Lake. This would be more consistent with the model of Bleeker (1990a). The situation is further complicated by mapping at Setting Lake that raises questions about the age and sense of overturning (**Section 6.2.4**), and a finite strain analysis challenges the existence of any nappe in the TNB (**Section 6.10**).

Although Bleeker (1990b) concluded that F_1 folds have an axial planar S_1 high-temperature foliation, there is no evidence of early metamorphic zircon in the Proterozoic mafic dikes or monazite of the appropriate age in the felsic rocks of the TNB (i.e., >1.88 Ga; **Section 10.2**). However, an S_1 fracture cleavage may be preserved in the overlapping hinge zones of F_2 and F_3 folds in basalt with well-preserved primary structures east of Bah Lake. This ENE-striking cleavage (S_1) has poles distributed along a girdle with a subhorizontal axis (B_2 in **Figs. 6.4** and **6.5a**) and forms a low angle with fine-grained S_2 schistosity. The relationship suggests that the D_1 structures had an original ENE trend. The S_1 fabric is tentatively related to the development of a large syncline (Soab Creek structure in **Section 6.4.4**), which extends from Bah Lake northeast across the TNB near Soab Creek. This has been crossfolded by an F_3 fold along the Grass River (**Section 6.4.4**.). Based on similarities in structural style and attitude with the Thompson nappe, it is possible that the Soab Creek structure had the same history, initiating as a nappe. However, the size, age, vergence, and structural evolution of the nappe or nappes in the Soab area may differ from those suggested for the Thompson-Pipe area by Bleeker (1990b).

6.2.4 Early Synmetamorphic Structures (D_2)

A regional foliation (S_2) is developed in most rock types, including the Grass River Group (Zwanzig, 1998), and is interpreted to be much younger than the F_1 structures at the Pipe II pit. The S_2 foliation is interpreted to extend throughout the TNB, but is particularly well developed in the Kisseynew Domain to the west. Fine-grained hornblende generally forms a lineation (L_2) as part of a penetrative S-L fabric produced during D_2 deformation under conditions of medium- to high-grade metamorphism. Coarser blades of hornblende (<8 mm) have a planar alignment, locally with a weak lineation, or have a random orientation across S_2. These grains and late mica suggest that high-temperature mineral growth continued after the development of S_2. The age and distribution of metamorphic zircon and monazite in the Kisseynew Domain suggest that S_2 in that area coincided with peak metamorphism and migmatization at 1.80-1.82 Ga (Machado et al., 1999). S_2 in the TNB is interpreted to be coeval with S_2 in the Kisseynew Domain, but S_2 in the TNB has been overprinted by amphibolite- to granulite-facies metamorphism during D_3, which is interpreted to have occurred between 1.77 and 1.76 Ga. The early development of S_2 is best seen where S_2 and early quartz-feldspar veins are cut by S_3 that is axial planar to the main upright (F_3) folds.

In areas where the Ospwagan Group is well preserved and at its lowest metamorphic grade, early-aligned biotite and hornblende are fine- to medium-grained. Veins are thin (generally <1 cm), contain mainly quartz ± feldspar and were boudinaged during D_2. On the southeast corner of the largest island in Setting Lake (**Fig. 6.4**: area S4A), S_2 is axial planar to F_2 intermediate-scale reclined folds, even where these structures are refolded by later upright folds with a superimposed weak axial-planar S_3 foliation. The dip of the preserved S_2 foliation, the F_2 axial plane, and the plunge of the overprinting F_3 folds indicate that the D_2 plane of deformation probably dipped gently or moderately north (**Fig. 6.5b**) or, more generally, northwest (**Fig. 6.5d**) to recumbent (**Fig. 6.8e**).

In most areas, the late folding is tight and S_2 is not distinguished from the overprinting S_3 foliation, or is recognised only in the late fold hinges where it has a moderate to shallow dip (**Fig. 6.5d**). However, a D_2 age for foliation development is evident from its regional F_3 folding to produce a great-circle distribution of poles to S_2 (with girdle axis B in **Figs. 6.5** to **6.8** and B_3 in **Fig. 6.5a**). Because of this folding, much of S_2 lies in the steeply dipping, NNE-trending D_3 plane of deformation that produces the strong pole maxima (S or S_3 in **Figs. 6.5** to **6.8**).

In an area northwest of Setting Lake, the grain sizes of the minerals that define the S_2 fabric coarsen westward and quartz-rich veins acquire granitic margins. Quartz-sillimanite knots (faserkiesel) are developed in the arkosic (upper) formation of the Grass River Group in the west. Within the main part of the Kisseynew Domain, the dominant foliation comprises migmatitic layering and gneissosity that are most prominent in the Burntwood Group. This gneissosity is interpreted as mainly S_2; it shows the same geometry, with preferred ENE strike, steep dip, and girdle distributions of poles that have axes that vary between moderately south plunging, subvertical, and gently northeast plunging, as in the TNB (**Figs. 6.7a** and **6.7b**). However, shallow-plunging hinge lines extend over wider areas (**Fig. 6.7c**) and linear structures generally have a shallow to moderate northeast or southwest plunge (**Figs. 6.7a** to **6.7d**). This is consistent with a weaker development of later strain than in the TNB and suggests that the L_2 stretching direction was northerly, similar to stretching lineations in the basement saddle at Sasagiu Rapids, where later upright structures are weakly developed (**Fig. 6.8e**).

The F_2 minor folds in the Kisseynew Domain are interpreted to be coeval with migmatite development because some folded leucosomes have offshoots along the axial plane. The F_2 folds are only locally recognised where they are cross-folded by F_3 structures or the axial surfaces have an unusually moderate dip (**Fig. 6.7d**). (Where no relative age criteria exist, the minor folds were designated as F_3 on the stereograms.) Monazite from granite that is interpreted to be coeval with D_2 migmatite leucosome yielded an age (~1.82 Ga) typical of early high-grade metamorphism elsewhere in the Kisseynew Domain (**Section 10.3.2**).

Major F_2 folds on the margin of the Kisseynew Domain are attenuated, isoclinal (sheet-like), and have a strong S_2 axial-planar foliation. At the north end of Setting Lake, F_2 folds are interpreted to define an anticline-syncline pair in the Grass River Group and a structurally overlying anticline in the Bah Lake assemblage volcanic rocks. These are refolded in the Setting Lake antiform such that their original orientations and vergence are uncertain. A preliminary structural model suggested a southwest vergence of recumbent or moderately inclined F_2 folds (**Fig. 6.10a** in **Section 6.4.5**; Zwanzig, 1998). Poorly preserved rotated porphyroblasts in pre-1.82 Ga quartz syenite on southwest Setting Lake and southeast Pakwa Lake also suggest NE-over-SW or dextral rotation whereas younger sinistral shear zones in the same rocks are interpreted to have formed during D_3.

Although a Proterozoic schistosity overprints the Archean gneissosity in the basement rocks, the younger aligned biotite, hornblende, and muscovite are generally coplanar with S_A, such that S_A, S_2, and S_3 are indistinguishable. However, the Proterozoic schistosity curves over domes in the basement (**Figs. 6.8a, 6.8b,** and **6.4c**), under basins in the Ospwagan Group (**Figs. 6.6d, 6.6e,** and **6.8d**), and locally exhibits a shallow dip in saddles between the domes (**Fig. 6.8e**). This indicates strong development of schistosity in the basement gneiss during D_2. Rare recumbent F_2 minor folds with variably trending axes occur in the saddle at Sasagiu

Rapids. They are isoclinal and show very open F_3 cross-folds. The F_2 folds and shallow-dipping S_2 foliation and boudins occur directly below the unconformity at the subhorizontal base of the Ospwagan Group, where they provide evidence for early recumbent folding and horizontal flattening.

A mafic dike in Thompson South Pit, which has yielded a 1855 Ma minimum age of crystallization (**Section 10.2.4**), cross-cuts the basal unconformity and the Ospwagan Group stratigraphy at a low angle. Layering in the dike has been interpreted to represent an S_1 fabric, suggesting that D_1 is younger than ~1855 Ma and that the overturning of the Thompson structure occurred during D_2. This dike is younger than "typical" Molson-type dikes (1880-1890 Ma: **Section 10.2**), such as those that have been interpreted to cut F_1 folds at the Pipe II pit. Thus, D_2 is interpreted to represent the earliest phase of deformation that involved basement and large-scale recumbent folding in the TNB (cf. **Table 6.1** and Bleeker 1990a).

6.2.5 Late Peak-Metamorphic Structures (D_3)

From Setting Lake westward, the dominant folds are characterized by folded S_2 foliation, bedding, and veins, but with a local axial-planar schistosity (S_3) that is best developed in tight hinges. These folds are therefore interpreted as F_3. Quartz-sillimanite knots (faserkiesel) are flattened in S_3 with little retrogression, indicating that conditions of high-grade metamorphism were maintained during D_3. Large and small folds mapped in the Setting Formation on islands in northern Setting Lake are interpreted to be D_3 structures (**Fig. 6.5b**; Ducharme and Zwanzig, 1999). In areas where F_3 folding is tight, S_2 biotite foliation and veins are folded or transposed by a strong S_3 foliation with rare parallel veins. Local F_2 intermediate-scale folds are refolded by F_3 structures in which a weak axial-planar S_3 foliation is locally developed. Major F_2 folds are refolded in a large antiform (Setting antiform; **Fig. 6.10b** and **Section 6.4.5**). Toward the west, in the Kisseynew Domain, domes and synforms in the younger gneissic units are less tightly apressed and show a girdle distribution of poles with variably plunging axes lying in the northeast-striking plane of D_3 deformation (**Fig. 6.7**).

The Archean basement gneiss and the folded Ospwagan Group cover form chains of elongate northeast-trending domes overturned toward the northwest (**Figs. 6.8a, 6.8b,** and **6.8c**; Zwanzig, 1998). Although the doming process was protracted (D_2 to D_4), the dominant strain that controls these structures throughout the TNB, and in the adjacent part of the Kisseynew Domain, occurred during D_3 (Bleeker, 1990b; Zwanzig, 1998) and under high-temperature conditions. The Ospwagan Group occurs in double-plunging or canoe-shaped folds, mainly narrow synclines produced or transposed during D_3. These structures locally plunge subvertically (**Figs. 6.6d** and **6.6e**).

A penetrative hornblende and stretching lineation, which lies close to the L_3 direction of elongation of the domes and basins (**Fig. 6.8**), generally plunges steeply east or southeast in steeply dipping schistosity that is transposed into S_3 or folded around the domes. Rotated early hornblende and younger oriented hornblende that formed during D_3 are generally not distinguishable. Grass River Group conglomerates on the limbs of large F_3 structures contain clasts with elongated oblate (oval pancake) shapes with dimension ratios >3 on horizontal outcrops, ratios ≥ 1 in the foliation, and with long axes that define a subvertical stretching lineation (L in **Figs. 6.6b** and **6.6d**). Pillows and pebbles in the F_3 fold hinges are prolate (cigar-shaped) spheroids with low dimension ratios on joint faces perpendicular to L, but higher stretching along L, which is subparallel to the moderately plunging F_3 fold axis (B_3 and B in **Figs. 6.5a** and **6.5c**). This relationship is explained most simply by D_2 flattening in a gently northerly dipping plane (S_2) and superposed flattening in a steeply ESE-dipping plane (S_3) with subvertical stretching (L_3).

Folds are rotated toward the steep L_3 stretching lineation in double-plunging structures. The separation angle between northeast-plunging S-folds and south-plunging Z-folds is occupied by steep stretching lineations (**Fig. 6.5e**). The relationships are the same as in arrays of progressively developed flexure folds during a transition to sheath folds (Zwanzig, 1973). They suggest that the folds were rotated progressively in a regime of vertical stretching and southeast-side-up slip. This pattern is weakly developed in the Kisseynew Domain, is more prominent along the TNB boundary, and is strongly developed in sheath-like basement domes in the TNB. The systematic transition from variable plunges in the Kisseynew Domain to generally steep plunges in the late metamorphic core zone of the TNB is consistent with increased D_3 strain in the TNB.

Shear fabrics in mylonite zones, which appear to have been active during D_3, suggest that the D_3 flattening, vertical stretching, and southeast-side-up flow had a sinistral component, likely partitioned into the high strain zones (**Section 6.5**).

6.2.6 Post–Peak Metamorphic Structures (D_4)

The F_2 and F_3 structures were further tightened during the development of a greenschist-facies S_4 foliation in zones where retrograde metamorphism has occurred. These are particularly well developed in major fault zones and in the basement gneisses directly below the Ospwagan Group unconformity. Microfabrics indicate that S_2 and S_3 were overprinted by a subparallel spaced (strain-slip) cleavage in which the high-grade mineral assemblages were retrogressed to greenschist facies, with chlorite, fine-grained white mica, and epidote coating paper-thin surfaces. The S_4 foliation ranges from a coarse (up to 8 cm) spaced cleavage to penetrative conjugate microshears. It occurs in all components of the reworked Archean gneiss and the Proterozoic rocks, including younger pegmatites that cut F_3 folds. Quartz veins cutting F_3 folds have been subsequently folded by small upright F_4 folds. A fine striation (L_4), occurring locally on the limbs of these folds, is oblique or perpendicular to the hinges. The style of open to tight, moderately plunging folds without any axial-planar cleavage is consistent with flexural slip along L_4 during D_4.

A NNE-trending cataclastic foliation (S_4), which grades into bands of mylonite (S_M), is a locally dominant structural feature in the gneisses near the contact with the Ospwagan Group (e.g., along promontories on the southeast shores of Mystery, Brostrom, and Setting Lakes). Dips range from vertical to 55°SE and indicate that the unconformity between the basement and the Ospwagan Group has been sheared and overturned toward the northwest. High-grade annealed tectonite units along strike from the late mylonite units indicate a long history for these high-strain zones. Sheets of leucogranodiorite, which preferentially intrude the basement contact, commonly contain a S_4 retrograde cataclastic fabric. Quartz occurs as long sigmoidal aggregates in the sheared granite, feldspar is altered and broken, and chlorite is the only mafic mineral. Whereas kinematic indicators in the shear zones indicate a consistent southeast-side-up sense of slip in most areas, the southeast side is locally downthrown. Horizontal displacement can be dextral, but is more generally sinistral.

A major Z-shaped fold pair with a steeply southward plunge (Kiski Creek fold in **Figs. 6.3** and **6.6d** and **Section 6.4.8**) extends northward across the southern end of Setting Lake. Retrogression to greenschist-facies assemblages along major folded contacts and an association with late faults suggest that it formed as a fault-propagation fold during D_4. Where minor F_4 folds are well developed (e.g., on the south shore of Brostrom Lake), they are Z-shaped, axial surfaces strike north, hinges plunge steeply south, and lineations are subvertical (**Fig. 6.8c**).

On islands in Setting Lake where the effect of D_4 is strong, a mylonitic foliation forms high-strain zones more than 30 m in width with abundant south-plunging, Z-shaped intrafolial folds and steeply southward-plunging stretching lineations. Small oval structures with indeterminate plunges are interpreted to be sheath folds. Ductile D_4 structures may have formed during the early stage of D_4. Most appear to have had southeast-side-up slip and a component of sinistral slip (**Fig. 6.9b, 6.9c,** and **6.9d**). Younger discrete shear zones and late brittle faults, for example minor faults in the Setting Lake fault zone (**Fig. 6.9e** and **Section 6.5.3**), contain pseudotachylite and abundant fabrics that suggest east-side-up displacement with either dextral or sinistral components.

6.3 Structural Geometry and Strain Patterns

Structural trends in the TNB are uniformly NNE, parallel to the boundaries of the belt and to the transition between middle amphibolite metamorphic mineral assemblages along the northwestern margin and upper amphibolite to granulite assemblages in the core zone. The structures in the adjacent part of the Kisseynew Domain have similar trends, as does the gradient from an early metamorphic stage, in which grade increased toward the northwest. Although this structural pattern is dominated by tight folds, which occur at all scales and indicate strong WNW-directed compression, there are important north- to northeast-trending ductile high-strain zones and faults indicative of non-coaxial strain that may have been produced in a long-lived regime of transpression. All of these structures are subparallel to, and dominated by, the Superior Boundary Fault Zone (SBFZ), a crustal-scale discontinuity located along the TNB–Kisseynew Domain boundary.

The dominant folds in the TNB are isoclinal and some are over 100 km long. They and the adjoining high-strain zones strike 025-030° and dip 75-85°SE. Flattened domes are common in the Archean basement gneiss. An analysis of the structural history of the area has shown that these ubiquitous NNE-trending folds formed during advanced stages of deformation (D_3 and D_4) that occurred during and after peak metamorphism in the TNB, but after high-grade metamorphism in the Kisseynew Domain (**Section 6.2**).

Fundamental changes in the origins of the rocks across the SBFZ (**Sections 10.1** and **10.2**) suggest that this structural break had an early history as a plate boundary. Changes in the structural style of the dominant folds extending across the SBFZ indicate that it served as a ductile zone of detachment in the TNB during progressive deformation. The boundary has an overall NNE trend that is slightly more northerly than that of the main structures in the TNB. Consequently, Archean and Ospwagan Group units are interleaved with Kisseynew units west of Mystery Lake and the Grass River Group is folded into the TNB basement south of Setting Lake. This relationship is well displayed in the Setting Lake Fault, which cuts across the SBFZ at a low angle during the main and late stages of deformation in the TNB.

6.4 Folds

This section describes the three-dimensional geometry of major and minor fold structures, mainly from the southern half of the exposed TNB, where new structural mapping was carried out (Zwanzig, 1998). Large, doubly plunging, northeast-trending folds in that area dominate both sides of the TNB-Kisseynew Domain boundary and are used to interpret the structural relationships within and between these tectonic domains. Large important folds are described in detail and are used to interpret the regional structure of the TNB. The fold geometry in the northern part of the TNB is summarised from the compilation map (TNB Geology Working Group, 2001) and from previous work (Bleeker, 1990b).

The main structural control on the geometry of the formations in the Ospwagan Group and associated ultramafic sills are large and small NNE-trending folds. Such folds were analyzed in the Setting Lake–Brostrom Lake area (Zwanzig, 1998, 1999a; Ducharme and Zwanzig, 1999) where they have been interpreted as D_3 structures (**Section 6.2.5**). They appear to be comparable to folds in the northern part of the TNB, which are reported to have had a long complex history (Bleeker, 1990a). Large-scale stratigraphic repetitions refolded in the main northeast-trending structures have been reported in the Pipe II and Thompson structures (Bleeker, 1990a; Kraus et al., 1998). Large-scale stratigraphic repetition in recumbent folds and early thrust faults also occur along the SBFZ (Zwanzig, 1999a).

6.4.1 Archean Basement Structures

A distinctive unit of anomalously magnetite-rich Archean basement gneiss occurs on Paint Lake, apparently in isoclinal northeast-trending folds with limbs over 15 km long. The unit reappears farther southwest along strike, in oval basement structures between Joey and Soab Lakes. These structures are cut at a low angle (<10°) by the Grass River lineament (**Section 6.5.1**) and by the main NNE-trending folds in the Ospwagan Group, but without significant offset in either the basement or the Ospwagan Group. They are therefore interpreted to be Archean structures that were only partly transposed during the Proterozoic deformation.

6.4.2 Basement Domes and Basins

Three large areas of Archean basement gneiss that occur between tight synclines in the Ospwagan Group occupy chains of domes or elongate, double-plunging anticlines (**Fig. 6.3**). Early folds and the regional Proterozoic foliation (S_2-S_3 in **Sections 6.2.4** and **6.2.5**) are folded over the domes, which therefore likely formed relatively late in the Proterozoic deformation of the TNB. NNE-trending chains of closely spaced domes up to 75 km long occur in several areas, including: 1) along Highway 6 southeast of Setting Lake, Bah Lake, and Soab Lake (Zwanzig, 1998, 1999a); 2) between Nichols Lake and Thompson, providing one of the keys to the structure of the TNB; and 3) in a smaller domal area north of Joey Lake. The latter structure is poorly defined, but the basement gneiss within it extends along much of the northeast margin of the TNB, it is probably also continuous with the southern chain of domes (1, above), and it forms the lower storey to the TNB.

These composite domal areas are flanked by long narrow keels and inverted folds of Ospwagan Group rocks. The domal areas are separated at the ends by transverse structures in the Ospwagan Group with variable plunges. The fold style is related to fold interference and to the ductility contrast between the Ospwagan Group and the stiffer basement rocks. A preliminary structural analysis suggests that the Archean basement rocks occur at two or more structural levels that overlap from east to west. The infolded Ospwagan Group is interpreted to be part of the Thompson nappe (Bleeker, 1990a) and its probable southern extension, the Soab Creek structure (**Section 6.4.4**).

Three complexly shaped areas of basement gneiss, each about 10 km long and up to 5 km wide, occupy basinal structures: 1) between Hambone Lake and Max Lake, 2) at Mid Lake, and 3) between Manasan Quarry and the southern outskirts of Thompson. The Archean rocks in the basinal areas are interpreted to be structurally underlain by the Ospwagan Group (Bleeker, 1990b; Golightly and Lyons, 1996). The minimum overlap onto the basement rocks is therefore interpreted to be of the order of 10 km toward the southwest and 5 km toward the northwest, but narrower corridors of basement connecting the basinal areas suggest that a single sheet extends from Moak Lake 90 km southwest to Hambone Lake and forms a basement nappe. Depending on vergence and the method of early fold restoration, the total overlap may have been originally east over west and no more than 10 km (however, see Bleeker, 1990a.)

A chain of elongated basement-cored domes with mantles of Ospwagan Group occurs south of Soab Creek (**Fig. 6.4**). The Pollog dome, west of Brostrom Lake, features steeply outward dipping strata on its margins, subvertical in the north, east and west, and southerly dipping in the south. Pole girdles indicate that the strongly curved margin in the northeast plunges steeply NE (B^P in **Fig. 6.8a**) and southerly in the south (B in **Fig. 6.8b**). The diverging plunge indicates that the structure is a doubly plunging antiform with a strongly curved hinge line similar to a sheath fold. Subvertical lineations indicate stretching parallel to the core of the dome. Preliminary work on the Sasagiu dome, south of the rapids, indicates that it has the same structural style with only a small angle between the NE plunge on the north side and the subvertical plunge on the southwest (**Fig. 6.3**, and B^N and B^{SW} in **Fig. 6.8d**). An east-trending belt of Ospwagan Group in the saddle between the Pollog dome and the dome near the Soab South mine site also features steeply dipping strata with subvertical lineations. All of these structures have a sheath-like geometry that reflects the vertical stretching in the central part of the TNB.

The orientation of minor fold hinges and lineations in the large doubly plunging Highway 6 anticline north of Wabowden also illustrates the vertical stretching. The steeply southeast-plunging stretching lineation occupies the separation angle between fold hinges, some of which are interpreted to have been rotated during the strain. Nevertheless, the enveloping surfaces of the Ospwagan Group unconformity and of the parallel S_2 foliation is subhorizontal or very gently east dipping, a geometry that is more consistent with doming by fold interference than by regional SE-side-up shear. High coaxial strain with vertical stretching producing WNW shortening oblique to earlier folds is consistent with the geometry of the domes. A smaller non-coaxial component of strain is apparent in anastomosing high-strain zones on the flattened margins of the domes and in the limbs of the doubly plunging folds (**Section 6.5**).

The Sasagiu saddle structure, which connects the domes north and south of the rapids, has shallow north- and south-plunging stretching lineations and small recumbent folds like those in the Five Mile synform in the Kisseynew Domain. The orientations of the minor structures in the Sasagiu saddle are unusual for the TNB and are interpreted to be preserved early structures (**Figs. 6.3** and **6.8e**; **Section 6.2.4**).

Four domes have been delineated in the northern part of the TNB (**Fig. 6.4**; TNB Geology Working Group, 2001), including the Nichols Lake dome and Owl Lake dome (Golightly and Lyons, 1996). In these domes, the cores form windows into the basement structurally below the Ospwagan Group and the caps form the basement gneiss that surrounds the domes. The Ospwagan Group mantles the core gneiss. The lower formations (Manasan and Thompson Formations) face upward at the lower contact and downward where they extend around the dome at the upper (inverted) contact. The central layer of the mantle is the Pipe formation and defines the hinge zone of a refolded sheet-like syncline (Thompson nappe). The double dome of the Thompson structure to the north exposes only an inverted section of the Ospwagan Group, but is inferred to be cored with basement gneiss at depth (Bleeker, 1990b). The doming is thus interpreted to be superposed on the early sheet-like structures i.e. on nappes or large recumbent folds.

Oval structures with very thin (~100 m) mantles of Ospwagan Group occur southeast of the Grass River at Phillips Lake and Halfway Lake. These mantles locally feature a recognizable stratigraphy with the Manasan Formation at the margin and Pipe Formation in the centre. They are interpreted to be more highly attenuated versions of the dome and basin mantles, the early sheet-like folds found elsewhere in the TNB. Similar oval ring-shaped structures, interpreted from geophysical data and drilling results, occur west of Thompson (TNB Geology Working Group, 2001) and north beyond the airport (MEL zone). The abundance of thinly mantled structures in a predominantly basement terrane in the east, and wider belts of the Ospwagan Group close to the Kisseynew Domain boundary, in the west, suggest that the enveloping surface of the early synclines dips gently east and that the vergence during recumbent folding may have been westerly.

6.4.3 Thompson Nappe

The large syncline extending from Moak Lake southwest to the Pipe II pit has been interpreted as a late fold in which the upward-facing limb of the synclinal 'Thompson nappe' was preserved (**Fig. 6.1** and **6.2**; Bleeker, 1990b). However, the magnetic signature of iron-formation and ultramafic rocks in the fold has been used to interpret it as downward closing and unconnected with structures to the southeast (Golightly and Lyons, 1996). Nevertheless, the transverse structures at Thompson, between Manasan Quarry and Owl Lake and between the Pipe II pit and Liz Lake, provide clear evidence that the Ospwagan Group in the syncline becomes shallow dipping at depth and extends over 10 km farther east, mainly in the subsurface, in the Thompson nappe. The transverse structure extending to Liz Lake plunges consistently northeast and suggests that the basement gneiss to the northeast overlies the downward-facing limb in the Ospwagan Group. This relationship is confirmed in the domes north of Nichols Lake and at Owl Lake, in which the cores form windows into the basement below the nappe and the attenuated Thompson nappe mantles the domes. The Owl Lake dome plunges northeast toward the domal Thompson structure, which is reconnected to the main syncline in the northwest across the Burntwood mylonite zone. The analysis of the mylonite lends little support for a break between these structures, but provides evidence for mainly flattening without detachment (**Section 6.5.2**; Golightly and Lyons, 1996). Consequently, the compilation (TNB Geology Working Group, 2001) supports the original thesis that the Ospwagan Group occupies a synclinal isoclinal recumbent fold (Bleeker, 1990a). However, the enveloping surface of this early structure dips east or northeast (**Fig. 6.2a**) and suggests a westerly vergence.

The compilation also indicates that the belt of Ospwagan Group defining the nappe extends an additional 15 km southwest to Kay Lake. Primarily basement rocks are exposed west of a line between Kay Lake and the Pipe II pit. The Ospwagan Group rocks defining the nappe may have been eroded in that area and farther west or they may plunge back into the subsurface. If the gneissic units between Max Lake and Hambone Lake represent the inverted basement rocks in the upper limb of the synclinal (Ospwagan) nappe, as is suggested by their continuity to the northeast, then the anticlinal (basement) nappe extends for 90 km further to the northeast. Structural mapping is required southwest of Joey Lake to test this structural model.

East of the line extending from Liz Lake to the north end of Ospwagan Lake, Bah Lake assemblage volcanic rocks are missing from the core of the nappe, but the Manasan and Thompson Formations are relatively thicker. This geometry can also be explained by a westward vergence such that the upper formations are progressively closed and the lower formations dominate closer to a closure in the Ospwagan Group in east. The geometry is consistent with the gradual rise in the enveloping surface of the nappe that lies deepest in the Thompson structure and highest between Joey Lake and Ospwagan Lake (**Fig. 6.2**). This model suggests that the overall trend of the hinge line is northward and that the Archean basement rocks were transported westward or southwestward over the Ospwagan Group. The model is consistent with a D_2 age for recumbent folding and nappe emplacement directed toward the Kisseynew Domain, as indicated at Setting Lake (**Fig. 6.10**) and suggested by the LITHOPROBE high-resolution seismic profile (White et al., 1999). The model is consistent with that of Bleeker (1990a) in that early sheet-like folds are considered to be refolded into dome and basin structures. However, it differs in the relative age of the recumbent folding (D_2 rather than D_1) and in the vergence, i.e. west or southwest rather than southeast (**Table 6.1)**

6.4.4 Soab Creek Structure

The Soab Creek structure is a giant synclinal structure that may extend southwest from a probable root zone at Nichols Lake for a distance of 110 km to Kiski Lake. It may be the southwestern extension of the Thompson nappe or a separate, partly underlying nappe. Soab Creek structure is characterized by regional variations in the relative thickness of the various formations in the Ospwagan Group and by the presence of relatively small ultramafic bodies. The long narrow synclinal keels and antiformal ridges that were developed in the structure during advanced stages of folding (D_3 and D_4 in **Section 6.2**) trend NNE along the TNB, parallel to the Grass River lineament. Other arms of the Soab Creek structure form narrow folds that extend north to Matte Lake (TNB Geology Working Group, 2001). The change from upright synclines in the southwest to synclinal antiforms in the northeast is a key to the early geometry of the Soab Creek structure.

In the southwest, much of the Soab Creek structure forms a folded upright sequence. It occurs in a tightly apressed syncline (Brostrom syncline), but this fold is draped over the chain of basement domes to the west (**Section 6.4.2**) and joins a northwest-facing homocline in Setting Lake. At Brostrom Lake, the syncline is a typical late fold (F_3-F_4 in **Section 6.2**) developed in the upright limb of the Soab Creek structure. Brostrom Lake is underlain by steeply east-dipping sedimentary rocks of the Ospwagan Group, exposed on several headlands. Archean basement gneiss occurs on much of the east and west shores and forms the outcrops on the adjacent high ground. The gneiss is stratigraphically overlain by the lower part of the Ospwagan Group (mainly Manasan Formation quartzite [member Om1] and semipelite [member Om2] and Pipe Formation semipelite [member Op2] plus iron formation occur in the core). The upper formations in the Ospwagan Group (Setting quartzite with thin pelite [member Os1] and Bah Lake mafic flows and sills [member Ob2]) occur in the highly apressed, northern part of the synclinal core, above Pisew Falls (Zwanzig, 1999a). Stratigraphic younging is toward the centre of the lake and thus defines the northeast-plunging Brostrom syncline. This is consistent with the northerly plunge observed east of Sasagiu Rapids.

North of the synclinal core at Pisew Falls, the Brostrom Lake syncline joins the main Soab Creek structure. At the mouth of the creek, the structure becomes downward facing and closes upward between the basinal area of basement gneiss south of Max Lake and the root zone of that inverted basement sheet to the east. The highly apressed northeast arm of the Soab Creek structure is therefore a synclinal antiform that joins the Nichols Lake dome. If it also joins the Owl Lake dome and the Thompson structure to the north (TNB Geology Working Group, 2001), it is part of the Thompson nappe. However, if the Soab Creek structure is disconnected from the northern domes, it is a separate nappe.

The Bah Lake assemblage volcanic rocks in the Soab Creek structure extend southeast into the large body of volcanic rocks and gabbro at Bah Lake that have been interpreted to occur within an F_1 syncline. The structural analysis of cleavage east of Bah Lake (**Fig. 6.5a**; **Section 6.2.3**) suggests that a large upright syncline (Soab Creek structure) lies structurally above the Bah Lake anticline. This represents the stratigraphically highest part of the Soab Creek structure. A change in major- and trace-element geochemistry at this level, from unfractionated to slightly more fractionated and weakly contaminated (CAMIRO TNB Research Group, 1999) and the southeast continuation of the basaltic rocks above the SBFZ to Fish Lake are key elements in the tectonic interpretation of the west margin of the TNB. The changes in chemistry may reflect unmapped early (F_1) thrusting that carried basalt that originally lay outboard of the TNB over the main part of the Bah Lake assemblage volcanic rocks (CAMIRO TNB Research Group, 1998) or upward stratigraphic evolution of the basaltic section (CAMIRO TNB Research Group, 1999). Systematic sampling and reconsideration of existing data from areas at the Pipe II pit, Liz Lake, and Ospwagan Lakes will be required to test these hypotheses.

At Bah Lake and on Setting Lake, the Ospwagan Group in the Soab Creek structure is truncated in the west along the contact with the Kisseynew Domain by a series of faults that makes up the SBFZ (**Section 6.5**). Only a thin, discontinuous layer of basalt is preserved along the Setting Lake Fault and along the sheared unconformity below the Grass River Group (**Section 5.2.3**).

Thin sheets of Ospwagan Group, probably forming the root of the Soab Creek structure east of the Grass River lineament, are interpreted to be draped over basement domes at Phillips Lake and Tracy Lake. They line up *en échelon* with the 060° trend of the early part of the Soab Creek structure, parallel to the interpreted S_1 cleavage near Bah Lake where the structure opens as an upright syncline. Consequently, the ENE trend of that part of the fold may be primary. The early trend was predicted by Bleeker (1990b).

6.4.5 Setting Antiform

One of the largest folds along the TNB–SBFZ is a double-plunging antiform in the Setting Lake area (Setting antiform). It extends NNE from Pakwa Lake to the north end of Setting Lake, is cored by granodioritic orthogneiss (Albino and Macek, 1981) that extends for nearly 50 km, and is surrounded by previously folded supracrustal rocks (**Figs. 6.3, 6.4** and **6.6**; Zwanzig, 1998). The northwest limb dips moderately northwest in the north, but is overturned and dips steeply southeast where the fold is isoclinal in the south (around Pakwa Lake). The steeply southeast-dipping limb is truncated along the Setting Lake Fault (**Section 6.5.3**). The core gneiss pinches and swells along strike, partly as a result of the changing plunge of the hinge line. Where the Bah Lake assemblage volcanic rocks and Grass River Group close over the fold in the north, the plunge is moderate and the hinge line trends northeast (B_3 and B in **Fig. 6.5a** and **6.5c**, respectively). Further south, the plunge is shallower (**Fig. 6.5d**) and becomes subhorizontal in the central part of Setting Lake (**Fig. 6.2a**). The hinge line continues to curve and finally plunges SSW at Pakwa Lake (**Fig. 6.2b**). Minor folds generally reverse their asymmetry with the reversal in plunge, from S-shaped in the north to Z-shaped in the south, because most occur on the southeast limb of the antiform and are parasitic to it (**Fig. 6.5e, 6.6b**). The northern hinge zone has preserved depositional and early deformation structures (D_1 and D_2), whereas, in the overturned isoclinal part of the fold at Pakwa Lake, minor fold hinges generally dip steeply south, nearly parallel to the subvertical stretching and mineral lineation. This geometry is interpreted to result from hinge rotation during initial tightening and subsequent inhomogeneous compression of the Setting antiform.

6.4.6 Bah and Fish Lakes Anticlines

Based on the above analysis, the northern part of the Setting antiform can be unfolded to depict the possible geometry of the earlier structure (**Fig. 6.10**; Zwanzig, 1998). An original large anticline (Bah Lake anticline) is interpreted to have had a relatively shallow north-dipping axial surface and a southwest vergence. The unconformity at the base of the Grass River Group was overturned in the sheared, highly attenuated lower limb of the Bah Lake anticline. A major syncline-anticline pair was developed in the part of the Grass River Group that the Bah Lake anticline overrode. The synclinal core of the Soab Creek structure occurs above it.

West of Setting Lake, the ‘Fish Lake antiform’ appears to be equivalent to the Bah Lake anticline, but its core is developed in Burntwood Group paragneiss heavily intruded by leucogranodiorite. These rocks are interpreted to lie structurally below or west of a narrow slice of Bah Lake assemblage volcanic rocks. They are separated from the volcanic rocks by the SBFZ, which is folded by the Fish Lake antiform with younger rocks (Burntwood Group) in its core. The antiform is a tight, early fold with a northwest-dipping axial surface and a shallow NNE-plunging hinge line (B in **Fig. 6.7d**). It is interpreted to be rooted in the north at August Lake and refolded in the Five Mile synform. The unusual northwest dip of the isoclinal fold limbs is therefore considered to be a result of their position on the common limb between the Setting antiform and the Five Mile synform.

6.4.7 Five Mile Synform

The Five Mile synform is a large late structure (D_3 in **Section 6.2.5**) with a highly variable plunge (**Figs. 6.7a, 6.7b** and **6.7c**) like the adjacent Setting antiform. It appears to represent a complex saddle structure, probably developed from an early recumbent fold in the stratigraphic succession of the Kisseynew Domain. The core of the synform between the Setting antiform and the area underlain by the Burntwood Group northwest of August Lake contains mainly gneiss of unit Gb in the Grass River Group. The linear structures within the Five Mile synform have a shallow northeast or southwest plunge (**Fig. 6.7c**; **Section 6.2.4**), found elsewhere only in saddles between basement domes in the TNB to the east. The sinuous northeast-trending belt of steeply dipping and plunging rocks that contain member Ob4 of the Bah Lake assemblage and the Burntwood Group is tentatively interpreted as the closure of the older recumbent structure (**Fig. 6.4**, area F2). This requires further analysis.

6.4.8 Kiski Creek Fold

The structure at the south end of Setting Lake is interpreted to be dominated by a large, asymmetric, Z-shaped fold with a subvertical plunge (Kiski Creek fold in **Fig. 6.4**). The fold extends northward across the lake with an axial surface trending 010°. Retrogression to greenschist-facies assemblages suggests that it formed relatively late (D_4 in **Section 6.2.6**). The Setting Lake fault probably served as detachment zone during folding. Early thrust faults along the southwest and southeast shores of Setting Lake, which juxtapose the Setting Formation with the Grass River Group and with a sliver of Bah Lake assemblage volcanic rocks (**Section 6.4.8**), are interpreted to be deformed in the Kiski Creek fold. The fold is cut by a late northerly trending fault that is interpreted mainly from geophysical data. On the north and south sides, the plunge is steeply south (**Fig. 6.6d**) to vertical (**Fig. 6.6e**) and parallel to lineations in the area. Stratigraphic younging in the Ospwagan Group is northwest across the fold. The Kiski Creek structure is therefore interpreted to be a late "neutral" fold (neither synform nor antiform).

The Kiski Creek fold is important because it is best interpreted as a fault-propagation fold developed at the south tip of the main strand of the Setting Lake Fault and parallel to the late crosscutting fault. Sinistral displacement on the northeast-trending Setting Lake Fault (**Section 6.5.3**) and dextral movement on the northerly trending fault are also interpreted to have accompanied development of the Kiski Creek fold.

6.5 Faults and Shear Zones

Brittle faults and ductile high-strain zones to discrete shear zones occur at all scales. Their development during the later stages of the structural evolution of the TNB is shown by various degrees of alteration to retrograde greenschist-facies mineral assemblages. They provide important information for the non-coaxial component of strain and for the movement pattern of structural blocks and sheets in the TNB and the adjacent Kisseynew Domain. Their location and the directions of displacement are important for tracing formations in the Ospwagan Group and the ultramafic intrusions that they host. Some ductile zones of mylonite occur as annealed tectonite units or 'straight gneiss'. These have recrystallized under high-temperature metamorphic conditions and must have formed during earlier stages of deformation, particularly along the SBFZ and the Grass River lineament. The earliest faults, which predate the annealed tectonite units, probably controlled subtle variations in the

Ospwagan Group stratigraphy and may have been important in focusing the emplacement of the ultramafic bodies.

The largest and most important structural breaks include:

1) Grass River lineament (near the southeast margin of exposed Ospwagan Group),
2) Burntwood mylonite zone (which occurs northwest of the Grass River lineament),
3) Setting Lake fault,
4) Superior-Boundary fault zone (which together with the Setting Lake fault lies along the northwest margin of the TNB) and
5) Fish Creek-Pakwa Lake zones (in the adjacent part of the Kisseynew Domain).

6.5.1 Grass River Lineament

The high-strain zone along the Grass River is a long-lived structure that marks the eastern limit of the largest belts of Ospwagan Group. It extends from the south shore of Brostrom Lake NNE for at least 50 km along a series of exceptionally straight contacts between the basement gneiss and the Ospwagan Group. The lineament is slightly sinuous, but exhibits an average trend of 030°. It locally cuts and is deflected by more northerly trending basement structures, such as at Pisew Falls and east of Brostrom Lake (TNB Geology Working Group, 2001).

The Grass River lineament was not remapped, but was examined at Pisew Falls, where it forms a mylonite zone in the Pipe Formation semipelite (member Op2) that contains no easily identified kinematic indicators. The southern termination of the mylonite zone at Brostrom Lake and the continuity of some basement structures across the zone without significant offset indicate that the Grass River lineament is not a simple crosscutting fault. Because the Ospwagan Group in this area is confined to narrow, oval, ring-shaped structures (possibly refolded recumbent synclines of the Soab Creek structure), interpreted to have formed at a low structural level in the southeast, the basement rocks southeast of the lineament were probably uplifted. Such displacement can be demonstrated to have occurred during the advanced stages of deformation at the south end of Brostrom Lake, where south-plunging Z-shaped F_4 minor folds and steep lineations (**Fig. 6.8d**) indicate east-side-up displacement or development of an antiform southwest of the Grass River lineament. The minor folds are interpreted to be parasitic on a small, partly developed satellite dome north of the Sasagiu dome. If these structures were linked to the southward propagation of the Grass River lineament, they establish a link between doming and shear zone development, a conclusion that is consistent with the sheath-like shape of the domes. Alternatively, the Grass River lineament may represent a reactivated early normal fault related to extensional tectonic activity in the TNB, as shown by the Molson dike swarm, which is parallel to the lineament.

A highly banded, intermediate-mafic straight gneiss along the southeast shore of Brostrom Lake is annealed and predates the high-grade metamorphism in the area. It is interpreted to be part of the lineament and to demonstrate its protracted history, but needs further investigation to establish its origin.

6.5.2 Burntwood Mylonite Zone

The Burntwood mylonite zone (Bleeker, 1990b) extends for more than 20 km through Thompson along a trend of 030° to Moak Lake, where the structural trend changes to 060°. Mylonite is developed in the basement rocks that separate the Thompson structure from the Ospwagan Group and Mystery Lake granodiorite to the northwest, particularly in strongly retrogressed schistose stromatic gneiss along the shore of Mystery Lake. The zone was re-examined for kinematic indicators, which are prominent in granite augen gneiss east of Mystery Lake (Zwanzig, 2000).

All planar fabrics in the Burntwood mylonite zone are vertical or have a steep southeasterly dip; they contain subvertical to south-plunging stretching and mineral lineations and moderately plunging crenulations (**Fig. 6.9a**). Further study is required to determine whether these crenulations represent ridge-in-groove striations (Lin and Williams, 1992). In any case, the strong planar fabric and the generally poor development of asymmetric shear-sense indicators suggest that the Burntwood mylonite zone experienced strong northwest compression and vertical stretching.

Microfabrics include strained, elongated to ribbon-shaped quartz aggregates, and broken to mortar-textured, variably cloudy feldspar grains. Biotite is partly shredded or retrogressed to chlorite + muscovite or epidote. Strong fabrics with little retrogression extend beyond the mylonite zone across a locally preserved unconformity (Zwanzig, 2000) into the Ospwagan Group. Well-developed micro-shear bands in vertical sections indicate a southeast-side-up sense of displacement. Horizontal sections show an anastomosing symmetrical fabric or weak sinistral asymmetry. This fabric is interpreted as having formed during D_3 (**Section 6.2.5**) and to indicate predominately southeast-side up, weakly sinistral transpression.

The outcrop-scale mylonitic fabrics in the Burntwood mylonite zone generally exhibit discrete shear bands that display mainly sinistral and southeast-side-up displacement (D_4 in **Section 6.2.6**) and probably formed during progressive deformation (Hanmer and Passchier, 1991). Retrogression to lower greenschist-facies minerals is complete in the shear bands, indicating that they are late features. Orientation measurements of associated shear bands (C_4) and mylonitic foliations (S_M) were used to estimate the direction of late shear strain (calculated slip line) from the pole to their intersections with the plane of the mylonitic foliation (Zwanzig, 2000). These lines plunge SSW at about 30°, indicating late sinistral slip with a smaller southeast-side-up component (**Fig. 6.8b**). A dispersion of stretching lineations may be related to local variations in ductility and reflect the partitioning of the simple shear component of strain into narrow zones in which the stretching lineations approach the slip line (Lin et al., 1998; Zwanzig, 2000). Shear bands indicating a dextral component of slip are present, but not abundant. The dextral shear bands strike northeast, whereas the latest sinistral shear zones contain pseudotachylite and strike north (**Fig. 6.8b**). The structures demonstrate variations in displacement direction with time, but indicate an overall northeast-side-up, weakly sinistral transpression directly after peak metamorphism in the TNB.

6.5.3 Setting Lake Fault

The Setting Lake fault extends along the northwest shore of the large peninsulas in central Setting Lake (**Figs. 6.3** and **6.4**) and is manifested as a zone of greenschist-facies retrogression with mylonitic foliation to structureless cataclasite with abundant small faults.

The affected zone is up to 400m wide, slightly sinuous in form, and includes splays that curve around blocks of less deformed well-preserved rocks in the hanging wall to the southeast, abundant boudinaged and folded quartz veins, and dismembered mafic to felsic dikes. The most prominent alteration and metamorphic retrogression is in the steep footwall to the northwest. Elongate bodies of leucogranite, ranging from massive to strongly mylonitic, occur all along the fault in the hanging wall.

The fault forms much of the contact between the Grass River Group and the Bah Lake assemblage volcanic rocks. It cuts off a nearly complete northwest-younging sequence of the Ospwagan Group. The adjacent structure to the northwest (Setting antiform in **Section 6.4.5**) contains only the uppermost unit in the Ospwagan Group (Bah Lake assemblage volcanic rocks) and younger sedimentary rocks belonging to the Kisseynew Domain. Consequently, the Setting Lake Fault is considered to be part of a wider zone (Zwanzig, 1998), now included in the SBFZ (**Section 6.5.4**).

Mylonitic foliation (S_M) occurs in lenses along the fault and is closely associated with alteration and retrogression. S_M forms a penetrative cleavage of microshears containing strained quartz aggregates, broken and mortar-textured to turbid feldspar, and fine-grained chlorite, epidote, calcite, or white mica. The presence of these greenschist-facies minerals is typical of late structures (D_4 in **Section 6.2.6**). The most highly retrogressed cataclasite contains up to 35% epidote and up to 50% chlorite as ~0.1 mm-long grains. Microshears also contain hematite and pyrite, the latter appearing to be plastically deformed. Most of the cataclastic rocks appear to have been derived from Grass River Group sandstone with significant loss of quartz, but volcanic rocks, containing carbonate minerals and veins, also occur in the fault zone. The mylonitic cleavage locally separates microlithons that are rarely thicker than 2 to 4 mm, but contain an upper-amphibolite facies mineral assemblage that defines an anastomosing early foliation (S). The angle of S to S_M and curved trails of S locally indicate a sense of east-side-up, sinistral shear in these rocks.

The 032° trend and 85°SE dip of the Setting Lake Fault is precisely parallel to other major shear zones in the TNB and to the overall trend of the TNB (**Fig. 6.9d**). Mylonitic foliations dip ~80°, suggesting reverse displacement. Abundant shear bands (C_4) and small discrete shear zones strike slightly more northerly (~020°) and dip slightly less steeply (~70°SE). They show kinematic indications of sinistral displacement on horizontal outcrops and reverse displacement on vertical faces. The normal to the intersection of the S_M and C_4 fabrics plunges gently south. Moreover, the subvertical mean direction of stretching and mineral lineations that occur over a wider area than the fault zone indicates that the regional strain occurred in a regime of transpression, identical to that observed in the Mystery Lake mylonite zone and elsewhere in the TNB (cf. **Fig. 6.9b** and **6.9d**). Some groups of variably trending shear bands suggest a dextral sense of displacement, but these are considered to be antithetic (Hippertt, 1999) or subordinate to the sinistral shears.

Small F_4 folds, which have intrafolial, rootless, and locally sheath-fold characteristics, are interpreted to have formed during shearing and retrogression. An equivalent large structure developed at the south tip of the main part of the Setting Lake fault (Kiski Creek fold in **Section 6.4.8**). The south-plunging folds are Z-shaped and exhibit a southeast-side-up slip sense of displacement, apparently parasitic to the Setting antiform to the northwest (e.g., **Fig. 6.5b**). The fold axes were probably rotated into the stretching direction during shear.

However, the fold axial surfaces are vertical and cut the steep, northeast-trending D_3 structures, thus producing the southeast-plunging Z-folds.

Small faults with cm- to m-scale separation on bedding or veins are abundant near the Setting Lake fault. Many of these faults are purely brittle and contain pseudotachylite coatings and lenses. Others show brittle-ductile behaviour. They form a steeply dipping conjugate set of predominantly sinistral, NNE-striking faults and predominantly dextral, ENE-striking faults (**Fig. 6.9e**). They indicate late northwest compression and northeast extension in the area of the Setting Lake fault. Rare related subhorizontal striations were found, but the largest faults are not exposed. Large late faults, interpreted mainly from geophysical data (TNB Geology Working Group, 2001), produce a prominent map-scale discontinuity along the entire length of Setting Lake, but are particularly evident in the southwest part of the lake.

6.5.4 Superior Boundary Fault Zone

The contact of the Ospwagan Group with younger rocks of the Kisseynew Domain to the west is generally sharp and interpreted to be a fault zone (SBFZ: Bleeker, 1990b). Although the boundary has been studied in detail only in the Setting Lake area, this work and the regional compilation map indicate that the SBFZ separates cordierite-garnet-biotite gneisses of the Burntwood Group and largely coeval metasandstones of the Grass River Group from metasedimentary rocks of the Ospwagan Group and orthogneisses of the Archean basement. Most faults in the zone are not exposed, but have been interpreted from the regional geology and geophysical data. Contacts in drill core are locally sharp and may represent early brittle faults, unconformities, or intrusive contacts with amphibolite of unknown origin. A prominent exception occurs in the footwall of the Setting Lake Fault, where the Grass River Group has been interpreted to lie unconformably on the Ospwagan Group.

The fault zone is interpreted to represent the main suture between the internal (Reindeer) zone of the Trans-Hudson Orogen and the TNB. It is marked by an abrupt change in the age of detrital zircons in the Ospwagan Group relative to those in the Grass River Group (**Section 10.3.2**) and the Burntwood Group (Machado et al., 1999). Because all of the known Ni-Cu-(PGE) deposits in the TNB occur within the Pipe Formation of the Ospwagan Group, the location and 3D geometry of TNB-Kisseynew boundary limits the area available to contain Thompson-type Ni-Cu-(PGE) deposits. Thus, the nature and origin of this boundary and the structural interleaving of the TNB and the Kisseynew Domain along it are considered to be important guides in nickel exploration.

The suture zone is interpreted to represent an ancient plate boundary and is consequently a crustal-scale feature. LITHOPROBE seismic profiles indicate steep structures extending into the middle crust at Thompson, but only to a depth of about 15 km near Setting Lake. Below that, the dips are moderately east or northeast. Reflectors in the internal zone dip eastward and are truncated along the Moho below the eastern limit of the TNB (**Fig. 6.12**). Accordingly, the southern exposed part of the TNB is interpreted to be underlain by a wedge of juvenile rocks of the Trans-Hudson Orogen. This implies that the SBFZ is probably a reverse fault at depth. The steeper reflection-free zone along the boundary in the upper crust may image a transpressional fault zone underlain by rocks of the Reindeer Zone, but only in the lower crust in the vicinity of Thompson (Lucas et al., 1996; White et al., 1999). This crustal architecture is consistent with the seismically determined northeast dip at the north margin of the Kisseynew Domain (White et al., 1999). However, the history of displacement is poorly known. Following peak metamorphism in the TNB, there appears to have been a sinistral component of slip, but there may have been a dextral component during earlier high-grade metamorphism, for which kinematic indicators were not generally preserved in the Kisseynew Domain. Still earlier (i.e., before deposition of the Grass River Group), eastward-directed thrusting may have occurred in the upper part of the Bah Lake assemblage volcanic rocks, as suggested by changes in geochemistry (**Section 6.4.4**). The LITHOPROBE seismic line S3B over the Paleozoic rocks at Easterville (**Fig. 6.13**) suggests that east-directed thrusts are a prominent feature of the southern part of the TNB. These involve nearly unmetamorphosed Paleoproterozoic rocks (Winnipegosis komatiite belt) and can serve as a model for the early geometry of the SBFZ.

Structural mapping at Setting Lake (Zwanzig, 1997, 1998, 1999a) and exploration drilling there and west of Mystery Lake (MEL zone) indicate that the SBFZ is not a simple ENE-trending break (cf. Churchill-Superior boundary fault: Bleeker, 1990b), but that it is folded with the lithologies in the TNB. A tight fold or fault sliver containing Grass River Group gneiss south of Setting Lake and east of Kiski Lake is interpreted to lie structurally below the Ospwagan Group (**Fig. 6.3**; Zwanzig, 1998). This is consistent with an overall easterly dip of a boundary that is cut by the Setting Lake fault and folded by the more steeply dipping, NNE-trending structures that dominate the TNB.

On Setting Lake and directly to the northwest, Bah Lake assemblage volcanic rocks have been interpreted to be unconformably overlain by the Grass River Group (Zwanzig, 1997; **Section 5.2.3**). Because these sedimentary rocks are coeval with younger, non-marine equivalents of the Burntwood Group (**Section 5.2.4**) and regionally have the same sediment provenance, they can be inferred to have been deposited after the Reindeer Zone came into structural contact with the Ospwagan Group. Consequently, the SBFZ is interpreted to comprise faults at low structural levels and a coeval unconformity at the highest structural level. It must therefore be a broadly syn-sedimentary structure, formed during deposition of the Grass River Group. In the context of this structural history, the SBFZ is interpreted to have formed after D_1, but to have been involved in D_2-D_4 deformation. The fault zone was reactivated in the Setting Lake fault (**Section 6.5.3**).

The Burntwood Group is generally in contact with a relatively thin sheet of amphibolite, which has local pillow structures and is interpreted as a fault slice of Bah Lake assemblage volcanic rocks. The metavolcanic rocks in this sheet are stratigraphically overlain by the basal formation in the Grass River Group along the contact that is interpreted as the unconformity. The fault placed older rocks over younger, suggesting that this part of the SBFZ originated as a thrust. The rocks belonging to the Kisseynew Domain probably underthrust the Ospwagan Group that occupies the entire southern bay of Setting Lake. All early faults have been heavily intruded by pegmatitic leucogranite and parts of the structural packages occur as large rafts. Nevertheless, the intrusions have not substantially disrupted the early structures, and primary features, such as pillow tops and flow-top breccias, are preserved.

At the south end of Setting Lake, the Ospwagan Group is in fault contact with the Grass River Group and with a sliver of Bah Lake assemblage volcanic rocks (**Fig. 6.11**; TNB Geology Working Group, 2001). The belts of Grass River Group along the southeast shore face northwest, the same direction as the overlying Ospwagan Group. Consequently, the fault has placed older rocks (Pipe Formation) stratigraphically over younger (Grass River Group) and is interpreted to be a thrust. Farther northeast, the same succession of Ospwagan Group lithologies extends stratigraphically down to the unconformity, which rests on a sliver of Archean basement rocks (TNB Geology Working Group, 2001). This northwest-younging package of rocks is in fault contact with relatively well preserved northwest-younging Bah Lake assemblage volcanic rocks to the southeast. The contact with the volcanic rocks was interpreted to be a thrust fault folded in the Kiski Creek fold (**Figs. 6.3** and **6.11**; Zwanzig, 1998). The thrust probably connects with the fault to the northwest. This relationship suggests that southwest-directed thrusting during D_2 (post–Grass River) deformation involved the basement rocks, the Ospwagan Group, and the Grass River Group. Although the facing direction is currently northwest in the hanging wall and footwall rocks (**Fig. 6.11b**), the dip during thrusting was probably northeast to produce an overlap to the southwest (**Fig. 6.11a**). Imbrication to the southwest is consistent with the direction in which the faults cut up-section. A crosscutting, north-trending fault may have reactivated a footwall ramp in the original thrust.

Facing direction in the western belt of Grass River Group rocks at the south end of Setting Lake is uncertain; these sedimentary rocks overlie a narrow belt of amphibolite derived from Bah Lake assemblage volcanic rocks, probably in an early syncline. The amphibolite, in turn, is in contact with the Burntwood Group to the northwest along the SBFZ.

North of Setting Lake, the SBFZ appears to truncate units at a higher angle and may be more oblique with a transcurrent component. An oblique fault is consistent with the straight, relatively narrow zone of protracted high-temperature deformation and granitoid intrusion that characterizes the TNB. The slightly more northerly trend of the SBFZ, relative to that of the adjacent folds, is consistent with a model of sinistral displacement (Bleeker, 1990b). A thrust, that occurs at the south end of Setting Lake (UTM 6077000N, 513500E in Map 2001FN-2, TNB Geology Working Group, 2001), is an expected feature within the SBFZ. However, the interpretation that the Ospwagan Group overrode the Kisseynew gneissic rocks along a southwest-directed thrust suggests a dextral component of displacement along the SBFZ during the thrusting (D_2 deformation *in* **Section 6.2.4**) A reversal in vergence from southwest during D_2 to northwest during D_3 would have been accompanied by this interpreted change in the horizontal component of displacement, but not the vertical, east-side-up component.

6.5.5 Fish Creek and Pakwa Lake Shear Zones

Structural data collected in the main part of the Kisseynew Domain are not abundant, but there are small shear zones, particularly in the vicinity of the linear southeast flank of the Five Mile synform. A major shear zone probably exists along Fish Creek, which has a trend of exactly 030° (like other lineaments in the TNB). Moreover, shear-sense indicators show only sinistral components of displacement on horizontal outcrops (**Fig. 6.9c**). East-side-up displacement in the shear bands and local lenses of mylonite are also present, as in the TNB.

6.6 Structural Synopsis: Discussion and Future Work

The compilation (TNB Geology Working Group, 2001) and new mapping (Zwanzig, 1998) support the nappe hypothesis (Bleeker, 1990b), but the origin of these structures is not obvious: models of their evolution differ among various workers. The vergence, age, and amount of overlap are still uncertain. The outcrop pattern of the Ospwagan Group, magnetic structure of the basement rocks, and Archean rock types that appear on the compilation map provide a new look at the regional structure. A simple visual pattern analysis of the map has been applied to the exposed TNB, but a three-dimensional analysis has been used in the Setting Lake area. Earlier structural data have also been used to reassess the geometry of the better-studied area, from Pipe Lake to Moak Lake. Structural mapping between Soab Lake and Joey Lake is required to complete the analysis.

Tight longitudinal to reclined synclines in the Ospwagan Group extend in a constant NNE direction for up to 120 km. The synclines flank chains of basement domes, extend across them, and are refolded as mantles to the domes. The Thompson synclinal nappe appears to be traceable over distances of 60 km or more as a major syncline that extends 10 km across strike in the subsurface. The basement cap rock joins the deeper basement structure east of Thompson, suggesting a southwesterly or westerly vergence for the synclinal Thompson nappe and the inferred overlying basement nappe. A similar structure, the Soab Creek structure, extends along the west side of Setting Lake and from there northeast along the Grass River, possibly for more than 100 km. This structure also appears to be rooted in the east or northeast and can be interpreted to represent the southern extension of the Thompson nappe.

The internal structure of the nappes or giant synclines is not well known, but appears to be relatively simple. Full stratigraphic sections of the Ospwagan Group are commonly contained in planar segments of the large fold limbs and there is only a single major reversal in facing in each syncline. Map-scale parasitic folds are interpreted to be highly asymmetric, with limbs commonly less than 1 km in length (TNB Geology Working Group, 2001). Structural analysis has shown that where such folds are exposed they were developed during D_3 (**Section 6.2.5**; Ducharme and Zwanzig, 1999) and that their asymmetric style has preserved overall stratigraphic younging within the nappes. The thickest fold limbs are developed in the best preserved, least metamorphosed rocks in the western part of the TNB, between Mystery Lake and the Pipe II pit, and southeast of Bah Lake. Further east, in upper amphibolite to granulite facies rocks of the Ospwagan Group and the basement, the folds are much more highly attenuated. Overall strain and metamorphic grade increase and proportions of Ospwagan Group rocks decrease toward the southeast. Folds are particularly tight and the Ospwagan Group is most attenuated southeast of the Grass River lineament. This pattern is consistent with the inferred regional northwest shortening and southeast-side-up displacement during D_3 and D_4 (**Section 6.2**).

The pattern of late folds is interpreted to be a result of upright, NNE-trending structures that are superposed on recumbent or moderately inclined folds on a scale of tens of kilometres. The late folds are parallel to and were apparently controlled by three principal high-strain zones: the Grass River lineament, the Burntwood mylonite zone, and the Setting Lake fault. All of these are subparallel to the SBFZ, which appears to have served as a crustal-scale detachment and as an overall control on deformation in the TNB. The strain in the linear zones is consistent with the geometry of late folds. On a regional scale, displacement in these zones appears to have been southeast-side-up and, in the advanced stages, to have included a strong sinistral component. Final deformation occurred in brittle-ductile faults under conditions of lower greenschist facies metamorphism. This youngest displacement was on conjugate faults and shears that produced further northeast compression, but likely with horizontal extension of the TNB.

The high-strain zones are interpreted to be linked to coeval folds at their tips. The main set of late folds (F_3 in **Section 6.2.5**), such as the large, northeast-plunging, Z-shaped structures at the northeast end of Upper Ospwagan Lake and at the Pipe II pit, occur at the south end of the Burntwood mylonite zone and its *en échelon* extension along the southeast shores of Ospwagan Lake. The folds transferred the displacement from one high-strain zone to another in a manner similar to fault-propagation folds. The shapes of these folds are consistent with a combined southeast-side-up and sinistral sense of displacement.

Greater strain is inferred to have occurred along the Grass River lineament and in the highly elongate apressed folds that flank it. The flanking Pollog and Soab domes, and the Sasagiu dome at its tip, have the shape of sheath folds and exhibit large subvertical extension. The regional geology is consistent with uplift of the basement areas to the southeast. This is shown by the presence of highly attenuated recumbent folds that are interpreted as the roots of the major nappe(s) east of the Grass River lineament. The Setting Lake fault, on the other hand, exhibits evidence of greater amounts of late strain and retrogression. Remnants of the Grass River Group and its basal unconformity that dominate the footwall are locally preserved in the hanging wall.

The fold pile that constitutes the main part of the TNB appears to have been only loosely attached to the Kisseynew Domain to the northwest. There is a gradient in the late strain across the SBFZ, which forms the original crustal-scale suture. Late folds are well developed in the adjacent part of the Kisseynew Domain, but they are slightly more open than those in the TNB, their plunges are generally less steep, and they do not appear to have been transposed into a steep stretching direction. Older, northerly trending, shallow-plunging lineations are preserved, which is consistent with the older metamorphic U-Pb ages in the Kisseynew Domain. There is generally little retrogression to low-temperature assemblages and overprinted foliations suggest protracted metamorphism without significant uplift and cooling. Nevertheless, the rocks in the Kisseynew Domain are considered to have been coarsely crystalline during the late deformation.

6.6.1 Revised Tectonic Model and Future Work

A modified hypothesis has been proposed for the origin of the Thompson nappe and the related Soab Creek structure with its truncation along the SBFZ. The model suggests para-autochthonous development of these structures, consistent with the widely preserved unconformity at the base of the Ospwagan Group and a locally preserved unconformity at the base of the Grass River Group. This raises the possibility of delineating early depositional structures formed during the extension of the TNB basement and possible early thrusting. The structural analysis in this report is incomplete and therefore raises the following questions, which should be addressed in future work:

1) ENE-trending Archean basement structures are preserved in the TNB. What was their influence on the Proterozoic structure, some of which assumes the Archean trend? Did they, along with the NNE-trending Molson dike swarm, determine the shape of the sedimentary basin and sub-basins hosting the Ospwagan Group, and control variations in sedimentary facies? Did they serve as zones of weakness for the intrusion of ultramafic bodies with their associated nickel deposits?

2) The earliest Proterozoic structures were proposed to be nappes (Bleeker, 1990a), but may instead have been syn-depositional folds formed during crustal extension and normal faulting, possibly in a half graben, such as in some modern rift environments (Sharp et al., 2000). Were such folds cut by mafic-ultramafic dikes during continued rifting? The large syncline that contains the Ospwagan Group and evolved into the Thompson synclinal nappe may have started to form as a simple, open, upright growth-fold, possibly in a half graben above a normal fault situated along the present SBFZ.

3) The structural analysis indicates that sheet-like structures of the Ospwagan Group and possible ultramafic intrusions, refolded like the Thompson nappe, exist in the Kisseynew Domain adjacent to the TNB. These structures may present targets for further nickel exploration. Future work is required in the probable northwestern extension of the TNB to confirm this analysis and benefit from it.

4) When was the Ospwagan Group juxtaposed with the rocks of the Trans-Hudson Orogen internal zone? Did this occur during deposition of the Grass River Group, unconformably on the Bah Lake folded volcanic rocks, and was it accompanied by westward underthrusting of the Burntwood Group turbidite facies? A high-precision geochronological database is required to resolve this question.

5) The intrusion of granitic plutons, including those with sinukitoid affinity (CAMIRO TNB Research Group, 1999) started ca. 1.84 Ga. Are these 'stitching' plutons that welded the crustal plates and do they provide a minimum age of collision?

6) Ductile basement involvement most likely started only after about 15 km of tectonic burial, much greater than the thickness of the Ospwagan Group. Did such burial occur during early upright folding and under thick sheets of Bah Lake assemblage volcanic rocks that were thrust from an outboard volcanic basin east over the largely unstretched Superior crust (as is suggested in the seismic profile across the southern part of the TNB)? Early metamorphic grade was probably upper greenschist to lower amphibolite facies in the TNB, which did not allow significant metamorphic zircon growth. However, metamorphic zircon growth may have occurred in the adjacent Kisseynew Domain during migmatite development there.

7) What was the vergence and amount of overlap of the Thompson nappe? How far does it extend north and how is it joined to the Soab Creek structure in the south? An analysis of the oval, ring-shaped structures east of the Grass River lineament may further elucidate these questions and provide a reliable southeastern limit for nickel exploration. Did fold vergence reverse as the Thompson nappe and the Soab Creek structure developed, and was this the result of eastward underthrusting by the internal zone of the Trans-Hudson Orogen and westward overthrusting of the basement gneiss? If correct, this scenario should be consistent with more accurate east-west structure sections using down-plunge projection (e.g. Zwanzig, 1999b) rather than the cartons in current use.

8) Doming and shear occurred during a final cycle of high-temperature superposed deformation. The early structures were refolded, transposed toward the northeast, and uplifted in the southeast. Further attenuation took place during subsequent retrogressive metamorphism. Can an understanding of this deformation be used for a qualitative reconstruction of the early structures and possible basin paleogeography, and related to the pattern of ultramafic intrusion?

PART II. TRANSPRESSIONAL MODEL

6.7 Introduction

In the model described in the first part of this chapter, folding is considered to be the primary feature of the structure of the TNB and the model results mainly from the analysis of fold geometry. In contrast, and following the approach of Fueten and Robin (1989), it can be considered that the TNB is primarily a zone of localized ductile strain. The analysis of the finite strain patterns points to a transpressional model for the evolution of the TNB.

As the basic concepts of finite strain analysis may not be familiar to all readers, they are briefly explained in **Section 6.8**. The structural data are presented in **Section 6.9** and interpretations are presented in **Section 6.10**. These results will be discussed further in **Section 10.4** in the light of new geochronological data.

6.8 Methodology and Conventions

The aim of structural analysis is to determine the kinematics associated with rock deformation in tectonic zones. Structural analysis must first examine the deformation at small scales (generally at the outcrop scale) and then integrate the individual measurements in order to define the finite strain pattern at larger scales (e.g., regional or crustal scale). The first step of the analysis (**Section 6.9**) involves the determination of first-order deformation parameters in different parts of the study area (in particular the orientation of the principal finite strain axes, the type of strain ellipsoid and strain intensity) and outlines the spatial variation of finite strains. The larger the number of local measurements the better the definition of the finite strain pattern. The second step of the analysis (**Section 6.10**) involves the establishment of the relative timing of acquisition of significant structures and the definition of the relationships between observed deformations and possible boundary displacements (i.e., characterizing the deformation regime). These data will characterize the variation of the deformation with time for each point of the study area. The progression from small- to large-scale features during the acquisition and interpretation of the data is essential and justifies the microtectonic approach: the local analysis is meaningful only if it permits the reconstruction of the geodynamics of the tectonic units.

A structural analysis is significantly more reliable if it is accompanied by determinations of P, T, and timing relationships because integration of all data is expected to reveal the relative motions (horizontal and vertical) of the different tectonic units. The coherence of the relative displacement of each tectonic unit (e.g., Ospwagan Group supracrustal rocks and Archean basement) in time must then be assessed in order to estimate motions at the boundaries and establish a tectonic model. In the case of the TNB, estimates of pressure and temperature for key units are scarce and the available data does not help to constrain relative vertical movement of the different units. However, during this project U-Pb ages were obtained for many of the structurally significant units.

6.8.1 Orientation of the Principal Strain Axes

During deformation, an initially spherical object will be transformed into an ellipsoid (the finite strain ellipsoid: **Fig. 6.14**) that documents the total accumulated strain according to the change in length along the three principal strain axes λ_1, λ_2, and λ_3. λ_1 is the principal stretching axis, λ_3 is the principal shortening axis, and λ_2 is the intermediate axis ($\lambda_1 > \lambda_2 > \lambda_3$).

The first step of the tectonic analysis in the field is to determine the orientation of the principal strain axes using relevant structures. For example, it has been shown (Flinn, 1962) that in most situations, the foliation plane defined by preferred orientations of metamorphic minerals is the λ_1-λ_2 plane of the strain ellipsoid. The stretching lineation will be on the foliation plane, parallel to the λ_1 axis. Hence, foliation and stretching lineation define the complete orientation of the three principal strain axes at each sampling point (**Fig. 6.15**). Other structures can provide information on the orientation of finite strain; structures such as the axes of passive folds or boudins tend to rotate toward the principal stretching direction with increasing strain and, at large strains their preferred orientation will be parallel to $\lambda 1$. The integration at the map scale of local measurements of foliation and lineation permits the construction of finite strain trajectories.

6.8.2 Type of Finite Strain Ellipsoid

Depending on the change in length of the intermediate strain axis, λ_2, three types of strain ellipsoid can be defined. Plane-strain ellipsoids occur for $\lambda_2 = 1$, flattening-type ellipsoids for $\lambda_2 > 1$; and constriction-type ellipsoids for $\lambda_2 < 1$. The different types of strain ellipsoids can be represented in a λ_2/λ_3 versus λ_1/λ_2 diagram (Flinn, 1962; **Fig. 6.16**). The shape of the finite strain ellipsoid can be quantified by the parameter $K = (\lambda_1/\lambda_2-1)/(\lambda_2/\lambda_3-1)$ (Flinn, 1962). If $K = 1$, then the deformation involved plane strain, if $1 > K \geq 0$, then the deformation involved flattening strain, and if $1 < K \leq \infty$, then the deformation involved constrictive strain.

The type of strain ellipsoid can be qualitatively estimated in the field. For example, chocolate-tablet boudinage indicates stretching along two perpendicular directions, that is to say it indicates flattening strain, whereas pencil cleavages or double folding indicate shortening along two perpendicular directions, indicating constrictive strain. The parameter K can be estimated by the measurement of the axial ratios of deformed markers such as volcanic pillows, pebbles, fossils, reduction spots, deformed mineral aggregates, or xenoliths in magmatic bodies.

6.8.3 Strain Intensity

To describe the strain ellipsoid completely, the strain intensity must be estimated. This can be done qualitatively in the field by the observation of structures whose development requires large strains such as trails of boudins, sheath folds (Quinquis et al., 1978), rolling structures (Van den Driessche and Brun, 1987), or C-S-C' structures (Berthé et al., 1979 a, b). More generally, large strains are revealed by ubiquitous parallelism of metamorphic layering and of lineation, both of which are indicative of strong reorientation of planar and linear features. Strain intensity can also be estimated from the shape of markers. A classically used intensity parameter is defined by $r = (\lambda_1/\lambda_2 + \lambda_2/\lambda_3) - 1$ (Watterson, 1968).

6.8.4 Shear Criteria

Kinematic analysis requires the estimation of possible boundary conditions (i.e., displacements) capable of producing the observed strains. There are two basic regimes of deformation: coaxial and non-coaxial (**Fig. 6.14**). During coaxial deformation, the principal axes of incremental and finite strains remain parallel, whereas during non-coaxial deformation they rotate. In two dimensions, examples of coaxial and non-coaxial deformations are pure shearing and simple shearing, respectively. The characterization of the deformation regime is based on shear criteria. The shear criteria are revealed by structures that can record changes in the orientation of principal strains during incremental deformation. In general, coaxial deformation produces symmetric structural patterns, whereas non-coaxial deformation yields asymmetric patterns (**Figs. 6.17** and **6.18**; Choukroune et al., 1987; Cobbold and Gapais, 1987; Gapais et al., 1987). At the thin section or outcrop scale, several structures are typical of non-coaxial deformation, including C-S-C' fabrics, asymmetric shadow-zones around rigid objects, rolling structures, asymmetric lattice fabrics, and asymmetric boudin trails. However, the most reliable indicators are shear instabilities, such as shear bands and shear zones, because they can occur at all scales.

6.8.5 Strain History

From the orientation of the principal strain axes together with the type of finite strain ellipsoid, an estimate of strain intensity, and the determination of the shear criteria (**Sections 6.8.1** to **6.8.4**) it is possible to construct strain trajectories, determine variations of K and r values at the map scale, and establish the finite strain pattern, thereby completing the first stage of a structural study.

The second part of the structural analysis is to determine, for each point, the relative timing of the observed structures, the kinematic significance of each structure, and whether the different structures can be explained by a single event of progressive deformation or by multiple discrete events. These steps are necessary because structures evolve with changing deformation conditions and increases in strain intensity during a deformation event. Early-formed structures and pre-existing ones undergo reorientation and deformation, and new structures can develop successively during deformation. Therefore, superposition of structures, like superposed folds, or cross-cutting sets of faults or shear zones can occur during either a single progressive deformation event, or during a number of distinct, superposed tectonic events.

In general, the determination of which of these two possibilities best explains the observed structures is a complex task. To carry it out, it is necessary to classify structures according to their geographical importance (e.g., distinguish local perturbations from regionally significant structures) and to examine kinematic compatibilities in time and space between relevant structures. Basically, the challenge is to estimate what, in a given structural pattern, could reflect temporal changes in boundary conditions and/or tectonic process (e.g., changes in directions of regional stresses).

A good example of structural evolution during progressive deformation is given by the analysis of C-S-C' structures (Berthé et al., 1979 a and b; Gapais and White, 1982; Burg et al., 1984). During simple shearing of an initially isotropic material (a granite for example), the onset of the deformation is marked by the development of two types of surfaces: 1) a pervasive schistosity, S surfaces, that are marked by preferred mineral orientations at 45° to the bulk shearing direction; and 2) localized shear bands, C surfaces, that are marked by higher bulk strains and are parallel to the bulk shearing direction (**Fig. 6.19**). With increasing shearing, the amount and length of the C surfaces increase, whereas the S surfaces rotate toward bulk shear direction (that is, they become parallel to C). At large strains, C and S planes are sub-parallel and define a mylonitic fabric. Owing to the anisotropy of the material, during continuing deformation, a second set of shear planes (C') develops that is synthetic (i.e., in the same shear sense) to the bulk shear sense and at low angle to the penetrative fabric (**Fig. 6.19**).

However, C-S fabrics are special cases, not only because they correspond to particular kinematics, but also because their development reflects particular mechanical properties. Such fabrics are therefore favoured by specific syn-tectonic thermal histories (e.g., progressive cooling from high temperature conditions: Gapais, 1989). Much more common are shear zone patterns that are defined by arrays of two or more sets of shear zones.

Geometric analysis of the shear zone pattern (Gapais et al., 1987) reveals whether the pattern is compatible with a single event or if it is necessary to invoke distinct events to explain its characteristics.

It must also be noted that the development of these structural features varies in time and space. Therefore, one can observe in the field substantial variations in structural features even if they were formed during a single deformation event. In heterogeneous material, progressive, shearing can also result in the development of successive folds, resulting in interference patterns.

6.8.6 P-T Conditions

The determination of P-T conditions during deformation is critical for tectonic interpretations because it can reveal the vertical path followed by the different structural units during deformation. As P-T data are very scarce for the TNB, and non-existent for structurally significant units, these parameters are not considered in the present study.

6.8.7 Geochronology

Precise dating of structurally well-characterized samples is critical for the complete description of the tectonic history of an area. Because the absolute timing of the successive deformation steps will often be the only way to discriminate between these two possibilities, interpretations in terms of progressive deformation versus multiple deformation events must be verified by geochronology. This part of the study is reported **Section 10.4**.

6.9 TNB Structural Data

6.9.1 Principal Strain Axes and Foliation Trajectories

6.9.1.1 Foliations

The first-order ductile structures that define the present-day geometry of the TNB are: 1) a regionally pervasive foliation, 2) a regional, steeply plunging stretching lineation, 3) sets of shear zones and shear bands at different scales, and 4) dome-shaped, double-plunging NNE-trending fold structures.

One of the first requirements to carry out finite strain analysis is the study of maps of strain trajectories. As these did not exist for the TNB, a compilation map of strain trajectories was produced based on the substantial amount of structural data depicted on preliminary MEM maps. As part of this project, A. Duhamel (BSc student at UQAM) was contracted to average the more than 4,000 local foliation measurements recorded on the MEM maps of the TNB and adjacent Archean. This was done by superimposing a 1 km square grid on each map and calculating the mean foliation orientation in each square. This procedure was considered to be reliable because of the rather regular orientations of the foliations at the local scale. The mean value of each square was then transferred to the corresponding square of a 1/250 000 compilation map. The final map is shown in **Figure 6.20** and more detailed foliation maps for Ospwagan Lake and Setting Lake are shown in **Figures 6.21a** and **6.21b**, respectively.

The final map shows that the foliation in the Archean Superior Province follows a regular east-west trend and has a relatively shallow dip (often close to 45°) both to the north and the south. This Archean east-west trend is reoriented and transposed to NNE-SSW in the vicinity of the eastern boundary of the TNB. In the TNB itself, the foliation strikes mainly 030°-040° and is sub-parallel to the belt boundaries. Locally, 050°-070° trends are observed, in particular in the eastern part of the belt (e.g., Grass River and Halfway Lake).

More detailed foliation trajectory maps of Ospwagan and Setting Lakes areas are shown in **Figures 6.21a** and **b**. These maps were obtained by interpolation based on more than seven hundred measurements of foliation, cleavage and schistosity (Stephenson, 1974; Macek and Russell, 1978; this work). The foliation trajectories outline the following significant heterogeneities in the strain pattern.

1) Local wrapping of the regional foliation around lower-strain domains that preserve an older folded foliation (e.g., area 1 in **Fig. 6.21b**). Locally, earlier fabrics can be distinguished in the field as a foliation that is often parallel to the metamorphic and lithological layering. They are particularly well preserved in fold hinges or dome-shaped structures, where metamorphic layering is at a high angle to the latest regional foliation. Field relationships indicate that before folding, this foliation was generally flat lying or gently dipping.
2) In the vicinity of some granitic bodies in the Setting Lake area, foliation trajectories tend to define triple points (e.g., areas 2 and 2a in **Fig. 6.21b**). This is particularly clear for the small granite at the southwest of the lake, between Setting and Pakwa Lakes (area 2, **Fig. 6.21b**). Such triple points could result from local interference between ballooning of the pluton during emplacement and regional deformation (Brun and Pons, 1980). If so, this would indicate that granite emplacement was syn-tectonic. However, further analysis is needed to confirm this interpretation.
3) Locally, the foliation has a 050°-070° strike that is oblique to the main structural grain (**Fig. 6.21a** and **b**). Less well-developed SSE trends are also present. These two sets of orientations occur locally along ENE and SSE elongate bands. The fact that foliation trajectories converge toward these bands leads us to interpret the latter as the trace of map-scale shear zones (e.g., areas 3 on **Fig. 6.21b).** This interpretation is similar to those of Ramsay and Graham (1970) and Cobbold and Barbotin (1988). ENE and SSE striking zones are conjugate, with dextral and sinistral horizontal shear components, respectively (**Fig. 6.21a** and **b**).

Several poles to foliation planes from different areas are reported on stereograms (**Fig. 6.22**). The foliation is dominantly steeply dipping to the E-SE and trends 030°-035° (maximum density on stereogram is 031°N - 84°E). This mean foliation orientation is similar to that reported in other studies of the belt (e.g., Bleeker, 1990b).

6.9.1.2 Lineations

The stretching lineation is marked by preferred mineral orientation and elongate objects (e.g., xenoliths) within the foliation plane and it is generally steeply plunging. Nevertheless, data are scattered on a great circle that outlines the average regional foliation plane (**Fig. 6.22**). This pattern is identical to those described in **Part I** and by Bleeker (1990b) for linear fabrics (fold axes and mineral lineations). This demonstrates that this pattern can be extended to the whole TNB. The scattering of lineations and fold axes along the regional foliation plane can reflect variations in the degree of reorientation of linear features toward the overall stretching direction, and/or local differences in thrusting and wrenching components.

6.9.2 Strain Type and Strain Intensity

The overall stretching lineation is steeply plunging. However, most horizontal outcrops show evidence of horizontal stretching (e.g., boudins, tension gashes, shear zones with horizontal shear component). Furthermore, chocolate-tablet boudinage has been observed in the Thompson South Pit and the Soab lineament and suggests local flattening-type strains. This is compatible with K values of less than 1 (around 0.13) obtained on xenoliths from one outcrop of Archean gneisses. The shape of sillimanite patches in the northern part of Thompson T3 pit also indicates flattening strains. A preliminary geometric analysis of shear zone patterns throughout the TNB is also consistent with bulk regional flattening (see **Section 6.9.3**). Exhaustive estimates of the shape of the finite strain ellipsoid are difficult because of the lack of regionally distributed markers and of vertical outcrops at low angle to the regional lineation. Nevertheless, observations suggest that flattening strains associated with sub-vertical principal stretch dominate in the TNB.

Constrictive strains occur locally in particular areas. Thus, pencil-shaped fabrics, corresponding to local interference between the regional fabric and earlier foliations and metamorphic layering can be observed in preserved fold hinges (e.g., Pipe II pit).

Structures at all scales are indicative of very large strains. At the same location were the K parameter was calculated, the shape of xenoliths indicates sub-horizontal shortening of about 70% (r = 5.5, for K value around 0.13). Large finite strains across the belt are also indicated by the occurrence of rolling and C-S-C' structures, by the reorientation of axes of folds in the foliation plane (observed at all scales), with local sheath-like folds (Bleeker, 1990b; Zwanzig this work), and by the parallelism between the lithological contacts, the belt boundaries and planar fabrics.

6.9.3 Shear Zones

6.9.3.1 Geometry of Arrays of Shear Zones

Shear bands are observed at all scales throughout the belt (**Fig. 6.23**). The recognition of shear zones in the field is made possible by the identification of the associated strain gradient and, at the map scale, by the systematic deflection of foliation trajectories.

A given planar shear band, shear zone or fault is geometrically defined by its orientation, its associated shear direction, and its associated shear sense. In the brittle field, shear direction and shear sense on individual faults are generally easily identified by slickenlines and syn-kinematic crystallization. In the ductile field, where the bulk deformation is of the simple shearing type (e.g., C-S fabrics), the mineral lineation on shearing planes indicates the shear direction and the sigmoidal geometry of the foliation across the strain gradients underlines the shear sense (Ramsay and Graham, 1970; Berthé et al., 1979 a, b).

In the TNB, assessing the shear direction along individual shear zones is not easy because: 1) the regional pervasive strain is large and differs from simple shear; 2) many zones contain syn-kinematic granitic melts and their internal solid-state is frequently lower than that of the surrounding rocks, and c) outcrops are generally 2D. Nevertheless, we made estimates of the geometrical characteristics of several shear bands. Estimates are based on the assumption that the preferred orientations of shear zones with respect to the bulk finite strain field are those which tend to maximize the amount of parallel shear and to minimize the amount of parallel stretch (Cobbold and Gapais, 1986; Gapais and Cobbold, 1987; Gapais et al., 1987, 1991). In other words, the type of shear strain that occurred in a given shear zone is not expected to deviate strongly from simple shear, irrespective of the type of bulk finite strain field (**Fig. 6.18**). It follows that the preferred mineral orientation within the shear plane constitutes a reasonable approximation of the shear direction.

A preliminary analysis of 73 outcrop-scale shear bands throughout the TNB was carried out during the summer of 2000. Stereograms of measured shear planes and associated shear direction and shear sense are shown in **Figures 6.24a** and **6.24b**. **Figure 6.24c** is a histogram that shows the frequency of the dips of shear zones. The following features are noteworthy:

1) Two groups of shear bands with conjugate orientations are observed about the mean regional foliation: one dips to the southeast, the other to the northwest (**Fig. 6.24c**). Most measured shear zones have a reverse shear component, with a dominant dip-slip shear component. This indicates that the shear zone array contributed to principal sub-vertical stretching, as shown by the regional stretching direction (**Fig. 6.22**).
2) Reverse shear zones with top-to-the-northwest motion dominate over conjugate shear zones with top-to-the-southeast motions (**Fig. 6.24a**). This is consistent with microstructural data (Fueten and Robin, 1989) and models proposed by Bleeker (1990b) for the late stages of evolution of the TNB.
3) Southeast-dipping shear zones show substantial scattering in shear directions, from dominantly dip-slip to shallowly plunging. Thus, the pattern shows predominant sets of bands with dominant reverse components, and less developed bands with dominant strike-slip components. This pattern is indicative, at least at the outcrop scale, of the occurrence of components of finite stretch along $\lambda 1$ (sub-vertical) and $\lambda 2$ (sub-horizontal) principal strain axes and is therefore consistent with bulk flattening strains (see **Fig. 6.18**).

In general, if the orientation, the shear direction, and the shear sense are known for individual ductile shear zones within a shear zone array, then data can be statistically analyzed in a way similar to that classically done for kinematic analysis of brittle fault sets (e.g., using the right dihedral method: Angelier and Mechler, 1979; see also Cobbold et al., 1991 for application to ductile shear zones). The results of this statistical analysis for the TNB reveal the following points:

1) The shear zone pattern is compatible with sub-vertical principal stretching and SE sub-horizontal principal shortening. This is consistent with the general strain pattern defined by the regional foliation and lineation (**Fig. 6.24a** and **b**).

2) Most measured shear zones have compatible infinitesimal kinematic stretching and shortening fields (69 of 73 zones; **Fig. 6.24a** and **b**). In other words, if a small deformation involving a sub-vertical stretching and southeast-directed sub-horizontal shortening was applied on the present-day shear zone array, most shear zones would accommodate the imposed strain.
3) Eigenvalues describing the distribution of shear bands indicate some stretching along the intermediate axis (intermediate eigenvalue > 0) and are therefore compatible with bulk flattening.

More detailed analysis of the above data is illustrated by frequency histograms showing distribution of measured shear zones according to their strike and shear component (**Fig. 6.25**). Most faults are reverse faults, with subsidiary components of strike-slip. Reverse-dextral bands show a peak around 045°-070°N. Conjugate reverse-sinistral bands show a peak around 005°-040°N. The trend of the regional foliation lies between these two sets. A few bands with a pure reverse shear component (pitch of shear direction higher than 85°) have also been measured, as well as some dextral shear bands with a normal shear component and a strike of 035°-075°N. Examples of these can be found in the northern part of Thompson T3 pit.

From the above analysis, we conclude that:

1) Shear bands and regional fabric (foliation and lineation) are kinematically compatible, indicating mainly sub-vertical stretching throughout the TNB;
2) The motions associated with most bands indicate top to the west; and
3) In the horizontal plane, perpendicular to the principal stretching, the pattern is rather symmetric.

However, NE-ENE striking bands with dextral strike-slip components appear more developed than the conjugate N-NE striking bands with sinistral component. This could reflect an overall component of dextral wrenching along the belt. The significance of the set of NE-ENE normal-dextral shear bands must be confirmed by further analysis. However, if significant, extensional strain components existed along NE-ENE directions then the regional horizontal shortening was accompanied by bulk dextral motion along the TNB.

6.9.3.2 Syn-Kinematic Thermal Conditions

It was observed in the field that, whereas many of the measured shear zones and shear bands are melt bearing zones, others record lower amphibolite to greenschist conditions. The latest bands often contain low temperature minerals, mainly epidote. Most examined shear bands are geometrically compatible, irrespective of the qualitative estimate of associated thermal conditions. This indicates that the belt was affected by similar kinematics from ductile to semi-brittle regimes, which accompanied uplift from medium pressure–high temperature metamorphic conditions.

6.9.4 Relationships Between Deformation and Granite Intrusions

At the outcrop scale, syn-tectonic melting is inferred from the occurrence of granitic melts in shear zones, as well as by the occurrence of melt veins oriented axial planar to folds. At larger scales, local foliation triple points associated with granitic bodies are suggestive of syn-kinematic emplacement. This is also suggested by two types of structures observed in some granitic bodies. Some show isotropic textures or weak magmatic fabrics. This is the case for the granite that crops out on South Jonas road, southwest of the Wintering Lake granite, and covers approximately 100 km^2 (U-Pb samples TB 99-42 and TB 20-08: sample locations in **Fig. 10.9**). Several outcrops of this granite show little or no deformation, but the country rocks close to the western contact show considerable strains, compatible with the overall pattern of deformation of the TNB. At map-scale, the granite is elongate along a NE-ENE direction. This is also the trend of shear zones with dextral strike-slip component. Another outcrop of very weakly deformed granite was observed and sampled on South Jonas Road (U-Pb sample TB 20-51: sample location in **Fig. 10.9**).

Other granitoids show pervasive C-S fabrics, such as the one in the northern Setting Lake area, which displays top-to-the-west C-S fabrics, with well-developed mylonite and ultramylonite bands (U-Pb sample TB 20-69 sampling location is shown in **Fig. 10.9**). Although it has been shown that this type of structure is developed when shearing occurs during granitoid cooling (Gapais, 1989), deformation of a pre-tectonic granite along a retrograde P-T path from high temperature conditions can also develop C-S fabrics, and we know that the deformation in the TNB is retrograde from partial melting conditions. For example the Mystery Lake pluton shows local C-S fabrics (Bleeker, 1990a) and a preliminary examination of associated deformation mechanisms shows evidence of syn-cooling shearing. However, the contrast between the rather simple shear structures observed in the Setting Lake granite and the complex sets of conjugate and localized shear bands found throughout the TNB suggests a possible pre-tectonic emplacement within an individual shear zone with top-to-the-west motion. In addition, several outcrops in this area show pegmatite dikes cutting across the regional foliation attributed to the last major ductile deformation event.

These examples show that there are several structural features that suggest the syn-tectonic emplacement of map-scale granitic bodies may have occurred along major shear zones within the belt. This point needs further structural analysis and will be reconsidered in **Chapter 10** (**Section 10.4**).

6.9.5 Earlier Deformations

The overall strain pattern observed in the TNB results mainly from the last deformation event, which occurred from high to low temperature and obliterated earlier structures. This event, which caused the first order structure observed all along the belt, was described by Bleeker (1990b) and corresponds to his phases F_3 to F_7.

There is evidence of earlier deformations prior to this major event (see **Part I** of this chapter), such as remnants of earlier folded fabrics seen on the foliation maps. Where best preserved, in particular in fold hinges, these fabrics appear to be sub-parallel to the lithological layering. Field relationships suggest that the fabrics were initially flat lying or moderately dipping, and are now transposed along fold limbs associated with subsequent sub-horizontal shortening. A typical and very frequent outcrop-scale structure observed throughout the TNB consists of folded trails of boudins of amphibolite and pegmatite (**Fig. 6.23e**). These superposed structures, which indicate shortening of previously stretched markers, require particularly large relative rotations between the marker and the strain ellipsoid and are therefore most easily explained by a succession of two different deformation events. The boudinage is often intense and suggests that the development of early fabrics was associated with substantial strains. The pre-folding orientation of principal strain axes is difficult to assess. Where flat-lying fabrics occur, north to northeast-striking (at low angle to the TNB), high-grade mineral lineations can be observed. This is the case at Sasagiu Rapids and at larger scale, in the Kisseynew Domain west of Thompson.

Along the road between Thompson and Lynn Lake, close to the TNB boundary, folds and ENE-striking sub-vertical fabrics similar to those found in the TNB rework flat-lying fabrics. Further west, the TNB overprint disappears.

In the TNB, the Ospwagan Group was affected by the early deformation event but as the deposition age for the sediments is unknown (**Section 10.3.2.1**), it is not possible to propose a minimum age for the early deformation.

6.10 Discussion and Interpretation

The strain pattern observed within the TNB is very consistent and results from the last deformation event. This deformation is marked by the following characteristics:

1) A steeply ESE dipping foliation that is often mylonitic,
2) A steeply plunging stretching lineation (down-dip in average),
3) Centimetre to hundred-metre scale shear bands, often associated with melt concentrations and perhaps also with syn-kinematic granitic intrusions,
4) Very large strains that led to fold reorientation and local sheath fold development,
5) A large amount of horizontal shortening and sub-vertical stretching (**Fig. 6.26**),
6) Orthorhombic symmetry of the strain pattern in the horizontal plane (This, combined with the lack of clear evidence of partitioning between vertical and strike-slip motions suggests that the strike-slip component was probably limited with respect to horizontal shortening and sub-vertical flow. However, foliation trajectories, distribution of associated shear bands, local observation of 050° normal-dextral shears and the asymmetric tear shape of the Setting Lake granite are consistent with a regional component of dextral strike-slip),
7) A much less symmetric distribution of shear bands and shear zones in the vertical plane, most of which indicate top to the west motions (in agreement with the Superior side up interpretation of Fueten and Robin (1989)).

The kinematic compatibility of all the structures (foliation, lineation, shear zones) indicates that this strain pattern could have resulted from a single progressive deformation that evolved from high-grade (partial melting) to low-grade (greenschist facies) metamorphic conditions. In addition, the overall strain pattern is consistent with transpressive kinematics. As shown by Lin et al. (1998) and by Merle and Gapais (1997), finite strains of flattening type are compatible with transpressive kinematics. Therefore, the occurrence of those features in the TNB further support the hypothesis that the TNB underwent transpressional tectonics.

In summary, the overall strain pattern of the TNB is interpreted to have resulted from a single tectonic event that was characterized by similar kinematic conditions from ca. 1850 Ma to 1754 and possibly to 1720 Ma (**Section 10.4**). U-Pb ages obtained on syn-kinematic granitic and pegmatitic bodies clearly indicate that the transpressive tectonics and the Superior side up motion lasted ca. 100 Ma.

Although this model is in agreement with the field observations, the few available metamorphic studies (Russel, 1981; Paktunç and Baer, 1986; Bleeker, 1990b), the seismic LITHOPROBE profile (White et al., 1999), and the Fueten and Robin (1989) model, it differs significantly from that proposed by Bleeker (1990b) and favoured by White et al. (1999). The main differences are the following:

1) The F_1 and F_2 tectonic phases of the model proposed by Bleeker (1990b) are interpreted to result from the emplacement of east-verging nappes. We agree with the existence of early deformation in the TNB, but conclude that the absence of reliable structural and geochronological data concerning this early event precludes any tectonic interpretation.
2) We interpret the F_3 to F_5 tectonic phases (and even F_6 and F_7 of Bleeker, 1990b) to result from a single, unique event of progressive transpression that evolved from high to low temperature conditions.

Bleeker (1990b) also described transpressive deformation, but restricted it to a late event that occurred from 1770 Ma to 1720 Ma. The key point of his model is the emplacement of an east-verging nappe (corresponding to his F_1 and F_2 phases) between 1883 Ma and 1770 Ma (Fig. 9 of Bleeker, 1990b). However, U-Pb data clearly indicate that the transpressive tectonics and the Superior-side up motion occurred from ca.1850 Ma to 1754 and possibly to 1720 Ma (**Section 10.4**).

This kinematic analysis and the new geochronological data (**Section 10.4**) emphasize that it would be highly desirable to carry out a detailed re-examination of the deformation history of the Kisseynew and Pikwitonei provinces adjacent to the TNB in order to unravel the tectonic history of the eastern Trans-Hudson Orogen more fully.

Concerning ore deposits, the effects of transpressive ductile deformation and associated shear zones on their potential remobilization must be further examined. In particular, understanding the processes that led to the localization of the main known ore bodies along particularly high-strain, steeply-dipping, substantially retrogressed and young (**Section 10.4**) deformation zones is certainly critical in terms of future exploration.