CHAPTER 5 STRATIGRAPHY

5.1 Introduction

The Thompson Nickel Belt contains a wide variety of metasedimentary, metavolcanic, mafic-ultramafic intrusive, and felsic intrusive rocks. Although all of the rocks are metamorphosed to at least mid-amphibolite facies, the metamorphic grades vary from area to area. Because this results in different mineral assemblages for the same lithologies, sedimentary, volcanic, and igneous terminology will be used in the following discussion in order to simplify the descriptions.

Upper amphibolite to granulite-facies basement gneisses grade into the Archean Pikwitonei granulite across a south-eastward gradient of decreasing Proterozoic deformation and recrystallization (Rance, 1966; Bleeker, 1990a and references therein). An Archean age for the gneisses has been established by U-Pb zircon geochronology, but there is also a prominent Proterozoic granitoid component in the basement (Machado, 1990; **Section 10.3**). The basement gneisses are unconformably overlain by medium- to high-grade metasedimentary and metavolcanic rocks of the Paleoproterozoic Ospwagan Group, informally introduced by Scoates et al. (1977). The Ospwagan Group has been traditionally subdivided into five conformable formations (Bleeker & Macek, 1988; Macek & Bleeker, 1989; Bleeker, 1990a and b; **Fig. 5.1**): 1) a basal quartzite unit (Manasan Fm.), 2) a thin carbonate unit (Thompson Fm.), 3) several cycles of fine-grained siliciclastic rocks, iron-formation, and chert (Pipe Fm.), 4) an upper turbidite unit (Setting Fm.), and 5) overlying mafic volcanic rocks (previously known as the Ospwagan Fm.). All units of the Ospwagan Group have been intruded by mafic-ultramafic sills, mafic dikes, and granitoid intrusions. In the southern part of the belt these rocks are unconformably overlain by Paleozoic sediments.

During the compilation work done for this project (TNB Geology Working Group, 2001), the stratigraphy within the four sedimentary formations of the Ospwagan Group has been confirmed to be robust and to apply to both the exposed part of the TNB and to the extensive southern part that is hidden under Phanerozoic rocks. The mafic volcanic and intrusive rocks formerly referred to as the "Ospwagan Formation" are not demonstrably conformable, but can be linked to the underlying Setting Formation via a series of mafic intrusions that appear to be geochemically similar, and are therefore presently considered to be part of the Ospwagan Group. However, because the Code for Stratigraphic Nomenclature prohibits groups and formations from having the same name, these rocks have been renamed the Bah Lake assemblage. Importantly, the Ospwagan Group is now recognised to be the exclusive host of the ultramafic sills associated with the Ni-Cu-(PGE) deposits in the TNB (TNB Geology Working Group, 2001).

New mapping in the Setting Lake area provides evidence that a younger Paleoproterozoic fluvial-alluvial succession, the Grass River Group (Zwanzig, 1997), unconformably overlies the Ospwagan Group. Elsewhere along the Superior Boundary Zone (SBZ), the Ospwagan Group is in fault contact with the Burntwood Group, the turbidite unit that stratigraphically underlies the Grass River Group and other continental arenites in the internal zone of Trans-Hudson Orogen. All of these metasedimentary units appear to be, at least in part, time-equivalent to the Grass River Group. However, the relationship between the Burntwood and Ospwagan Groups requires further testing.

The revised stratigraphy is summarised in **Tables 5.1** and **5.2**. The new stratigraphic data are the result of local mapping in the southern part of the exposed TNB and of the belt-wide compilation of proprietary exploration drill core (TNB Geology Working Group, 2001). The compilation map indicates the lateral continuity of the major formations and provides an order of magnitude estimate of their stratigraphic thicknesses along the TNB. The conclusions drawn from this map (indicated below and elsewhere in this report) are supported by local observations of apparent sedimentary facies changes observed on the limited exposures in the TNB. The mapping at Setting Lake, in particular, has provided a more detailed stratigraphy for the upper part of the Ospwagan Group. It has also provided a new stratigraphic subdivision and initial petrographic description of the metasedimentary

Table 5.1 Stratigraphic units in the TNB used in maps (left column, italic) and text

INTRUSIONS			**TYPE**		**LITHOLOGIC SUBDIVISION**		
pg	P	Paleoproterozoic and uncertain age	Ps	Granitoid plutons (S-type) ± garnet, cordierite, muscovite	Ps2	Pegmatite, pegmatitic granite	
lg					Ps1	Leucogranite, leucogranodiorite	
bg		Kiski Creek	Pk	Felsic-intermediate, potassic plutons (calc-alkaline to alkaline)	Pk4	Biotite granite	
hg		Five Mile			Pk3	Hornblende-biotite granite	
qm		West Pakwa			Pk2	Quartz monzonite	
qs		East Pakwa			Pk1	Quartz syenite	
dr		West Setting	Pi	Intermediate-felsic composition plutons (calc-alkaline to sanukitoid)	Pi 3	Granodiorite gneiss	
bm		Bucko			Pi2	Hornblende quartz monzonite	
qd		West Kiski			Pi1	Quartz diorite	
GROUP			**FORMATION**		**MEMBER / FACIES / LITHOLOGY**		
S2	G	**Grass River** Magnetite-bearing paragneiss	Gs	**Unnamed** quartz meta-arenite ± sillimanite, generally migmatitic, locally pebbly	Gs2	Felsic, pebble metaconglomerate, quartz meta-arenite	
s1 s					Gs1	Crossbedded arkosic metasandstone ± pebbles	
B2			Gb	**Unnamed** quartz meta-arenite + biotite, generally migmatitic, locally pebbly	Gb2	Felsic gneiss (volcanic?)	
b1 b					Gb1	Pebbly metasandstone	
h2 h			Gh	**Unnamed** quartz meta-arenite ± hornblende	Gh2	Quartz meta-arenite, interbedded metaconglomerate	
H2					Gh1	Quartz meta-arenite ± hornblende ± garnet	
cp			Gc	**Unnamed** felsic metaconglomerate, interbedded quartz meta-arenite			
Bp	B	**Burntwood** Greywacke, migmatite + garnet-graphite ± cordierite-sillimanite	Bp	**Unnamed** quartz-feldspar (pelitic?) gneiss + cordierite + garnet ± magnetite			
B, Bm Bw			Bw	**Unnamed** quartz-feldspar paragneiss (metagreywacke-mudstone?) + garnet-biotite			
SILLS and DYKES			**TYPE**				
db, gb	S	Mafic–ultramafic sills	Sm	Gabbro, amphibolite			
um			Su	Ultramafic sills			

Table 5.1 (continued)

GROUP			FORMATION		MEMBER / FACIES / LITHOLOGY		SUBUNIT	
Ba	O	**Ospwagan**	Ob	**Bah Lake** Mafic-ultramafic flows and sills	Ob4	Amphibolite		
gb		Paragneiss and amphibolite			Ob3	Gabbro, diabase		
O					Ob2	Pillowed, massive metabasalt		
pp					Ob1	Metapicrite		
S cc			Os	**Setting** Quartzite and schist	Os2	Quartzose metagreywacke to conglomerate	Os2a	gedrite-cordierite rock
					Os1	Feldspathic quartzite, thin pelite interbeds		
P P3 si			Op	**Pipe** Pelite, semi-pelite, unclassified iron-formation (Op_f), silicate-facies iron-formation (Op_i), oxide-facies iron-formation (Op_o), sulfide-facies iron-formation (Op_u), calcareous sedimentary rock, marble (Op_d)	Op3	iron-formation, chert, metaquartzite, semi-pelite, minor marl	Op3i	silicate iron-formation
dm							Op3d	dolomitic marble
ox							Op3o	oxide iron-formation
P2 su					Op2	quartz-feldspar-biotite schist (metapelites?), minor chert, marl	Op2u	sulfide iron-formation
P1 si					Op1	Silicate-facies iron-formation, chert	Op1i	Silicate iron-formation
su							Op1u	Sulfide iron-formation
T T3			Ot	**Thompson** Calcareous sedimentary rock, marble	Ot3	Olivine-diopside marble		
T2					Ot2	quartz-feldspar-biotite schist (semi-pelite?), marl		
T1					Ot1	Thinly layered marlstone and dolomitic marble		
M M2			Om	**Manasan** Quartzite, semi-pelite	Om2	Semi-pelitic schist	pegmatite at top (Ps2)	
M1					Om1	Quartzite		
A 6	A	Archean basement gneiss	Ag	**Unnamed** felsic to intermediate, layered, migmatitic gneiss; mafic-ultra-mafic inclusions	Ag6	Biotite granite orthogneiss		
5					Ag5	Leucotonalite gneiss		
4					Ag4	Magnetite-rich migmatite		
3					Ag3	K-feldspar syenite		
2					Ag2	Enderbite gneiss		
1					Ag1	Layered gabbro		
``					```	Trend of aeromagnetic pattern		

rocks that occur in the adjoining part of the Kisseynew Domain, where they are locally interleaved with the Ospwagan Group. The younger stratigraphic section is relatively well exposed on the shorelines of islands and peninsulas, and along the northwest shore of Setting Lake.

Because of pervasive folding and thrusting, the stratigraphic thickness estimates given in this report are speculative, but they are constrained to some degree by improved understanding of the geometry and structural style, and by estimates of total finite strain (**Section 6.9.2**). Sections were measured on areas of the map where the stratigraphy is most complete and where there are no obvious repetitions of the principal marker units, such as Ot3 marble or Op2 and Op3 iron-formation members. Better measurement can be made in the future on down-plunge sections.

Table 5.2a TNB stratigraphy (Central and Southernmost part of the Northern Region)

Formation/ Assemblage	Member/ Unit	William Lake	Wabowden	Setting-Brostrom-Soab Area
Grass River Group		not found	not found	polymictic conglomerate, meta-arenites, minor amphibolites
Mafic intrusions		tholeiitic, some differentiated ???	tholeiitic	tholeiitic, some differentiated; number of sills in Setting Fm increases upwards
UM intrusions		dunite, metadunite, metaperidotite, metapyroxenite		metadunite, metaperidotite, metapyroxenite
Ni-Cu-(PGE) Sulfides		William Lake, Nose	Bucko, Bowden, Manibridge	Soab, Hambone
Bah Lake assemblage[1]	Komatiites ??			
	Komatiitic Basalts (AKA "Picrites")	?? amphibolites with metamorphic Ol		massive undifferentiated with Ol poikiloblasts & rare Pyx spinifex? 12-16% MgO
	Tholeiites	amphibolites, not characterized in terms of morphology or stratigraphic location	????	massive & pillowed; 6-14% MgO, possibly less fractionated at base and more fractionated at top, v. minor interflow chert, no sulfides
Setting Fm	Os2	not found	not known	coarse quartz wacke
	Os1	present	not known	arkosic quartzite with sulfide-bearing pelitic interbeds
Pipe Fm	Op3	present	not known	silicate-facies IF & sulfide-facies IF
	Op2	thick, mid amph & upper amph: sill-gnt & ms schists	not known	pelite (thick) & sulfide-facies IF
	Op1	present	not known	silicate-facies IF & sulfide-facies IF
Thompson Fm	Ot3	megacrystic dolomitic marble	present (Manibridge)	not found
	Ot2	not found	not found	not found
	Ot1	thin-layered marl	present (Manibridge)	present
Manasan Fm	Om2	present	present (Manibridge)	present, exposed at Brostrom, not exposed at Setting Lake, mylonitized
	Om1	present	???	present, exposed at Brostrom, not exposed at Setting Lake, mylonitized
Basement		present, but not exposed	exposed	exposed

Notes: Compiled by J. Macek with major contributions from Inco and Falconbridge staff, H. Zwanzig, and W. Bleeker. Stratigraphy based primarily on the stratigraphic type sections at the Pipe and Thompson pits. The upper part of the section is less well defined than the lower part, thus reliability decreases up section. The stratigraphy of the southern part of the TNB is based primarily on DDH data, so it is less well defined than that of the northern part (which is based on outcrop and DDH data). In many parts of the stratigraphy, there are few good regional markers (e.g., concretions). Even in structurally complicated areas, however, Ospwagan Group rocks may be distinguished from basement gneisses by the presence of IF & quartzite. Metapelites (Qtz – Ms – Bt – Gar ± Sill ± And ± Staur ± Opx schists and gneisses) range from lower to upper amphibolite facies.
[1]May include allochthonous rocks.

Table 5.2b TNB stratigraphy (Central and Northern Regions)

Formation/ Assemblage	Member/ Unit	Pipe-Ospwagan Lake Area	Thompson	Moak-Mystery Lake
Grass River Group		not found	not found	not found
Mafic intrusions		tholeiitic, some differentiated	tholeiitic, 6-9% MgO, differentiated, 1855±13 Ma	tholeiitic, some differentiated
UM intrusions		metadunite, metaperidotite, metapyroxenite	metadunite, metaperidotite, metapyroxenite	metadunite, metaperidotite, metapyroxenite
Ni-Cu-(PGE) Sulfides		Pipe 1, Pipe 2, Birchtree	Thompson	Moak, Mystery
Bah Lake assemblage[1]	Komatiites ??	massive undifferentiated, rare differentiated with flow-top breccias, Ol spinifex zones??, and Ol cumulate bases, up to 22% MgO		massive undifferentiated, rare differentiated with flow-top breccias, Ol spinifex zones, and Ol cumulate bases, up to 22% MgO; magnetite-facies IF at base
	Komatiitic Basalts (AKA "Picrites")	massive undifferentiated with Ol poikiloblasts & rare Pyx spinifex ?, 12-16% MgO		massive undifferentiated with Ol poikiloblasts & rare Pyx spinifex ? 12-16% MgO
	Tholeiites	massive & pillowed, 6-9% MgO; some plagioclase-phyric, v. minor interflow chert, no sulfides		massive & pillowed, 6-9% MgO; some Plag-phyric, v. minor interflow chert, some oxide-facies IF & sulfide-facies IF
Setting Fm	Os2	present	not found	not found
	Os1	present	present	present
Pipe Fm	Op3	silicate-facies IF Dol marble & sulfide-facies IF	silicate-facies IF (thin) sulfide-facies IF (thin)	silicate-facies IF (thin) sulfide-facies IF ???
	Op2	sulfide-facies IF pelite	sulfide-facies IF pelite	sulfide-facies IF pelite
	Op1	sulfide-facies IF	sulfide-facies IF (v thin)	??? (mylonitized)
Thompson Fm	Ot3	present at Pipe, but too deformed to subdivide	megacrystic dolomitic marble; red clinohumite layers in lower part	???
	Ot2	Ot1 present at Lower Ospwagan Lake	semi-pelite	not found
	Ot1		thin-layered marl	present
Manasan Fm	Om2	semi-pelite with pegmatitic segregations	semi-pelite with pegmatitic segregations and sillimanite porphyroblasts	present
	Om1	unconformable lower contact, basal quartz-rich conglomerate, graded bedding, fining upwards	present	present
Basement		tonalitic and local enderbitic gneiss with amphibolite; primarily 2.6-2.8 Ga, some >3.0 Ga	exposed	exposed

Notes: [1]May include allochthonous rocks.

5.2 Stratigraphic Descriptions

5.2.1 Basement Gneiss (Unit Ag)

The basement rocks in the TNB comprise felsic to intermediate migmatitic gneiss (unit Ag) with several (Archean and Proterozoic) components, most of which are interpreted as orthogneiss. A distinctive feature of the basement gneisses, compared to highly metamorphosed paragneisses of the Ospwagan Group, is the common occurrence of widely scattered mafic lenses, many of which appear to be boudins of early dykes that are coarsely recrystallized and strongly foliated or contain a plagioclase-rich leucosome phase.

Limited work in the Setting Lake area indicates that pink- to grey-weathering migmatitic felsic gneisses are the predominate lithology. They comprise thin layers of fine-grained, pale grey, tonalitic leucosome and larger, discrete lenses and veins of pink pegmatite, granodiorite, and quartz syenite (<30%) hosted in an early felsic or intermediate fraction. (The grey leucosome phases are interpreted to be Archean, The pink leucosome phases locally cut Proterozoic dykes and are therefore younger, but their age(s) need to be rigorously determined. All components generally exhibit planar to isoclinally-folded (stromatic) fabrics. In many localities, this coarse Archean gneissosity is cut at an acute angle (commonly <10°) by mafic-ultramafic Proterozoic dykes with foliated to massive cores. Near the contact with the overlying Ospwagan Group, the basement gneiss is generally strongly foliated and cataclastic, a characteristic feature throughout the TNB (see also Bleeker, 1990a).

Biotite gneiss with white leucosome and rare garnet porphyroblasts occurs locally and probably represents a paragneiss. Elsewhere (e.g., at the cairn for Pisew Falls), the dark fraction of the basement gneiss grades from dioritic (30-50% hornblende) to granitic in composition. Local, stubby to square hornblende aggregates (>30 mm) in a leucosome are interpreted to represent pyroxene pseudomorphs that retrogressed after granulite-facies metamorphism. Strongly layered garnetiferous mafic tectonite forms units that range up to several hundred metres in thickness (e.g., east of Brostrom Lake). Large-scale units are also defined in the basement by a high magnetite content with a prominent aeromagnetic signature. These units define the regional structural grain and major folds and discontinuities on the compilation maps (TNB Geology Working Group, 2001). Highly foliated plutons, commonly augen gneiss, that grade into the basement migmatite are considered to be Archean, but the ages of the other intrusions are not known.

5.2.2 Ospwagan Group (Unit O)

The Ospwagan Group is composed of quartzites, semi-pelitic to pelitic schists and paragneisses, with lesser marbles, and local silicate and sulfide facies iron-formations.

Despite the general structural parallelism of these rocks, there is a well-characterized angular unconformity between the basement gneiss and the Ospwagan Group (Bleeker, 1990a and references therein). One locality that clearly shows an angle between the Archean gneissosity and the base of the Ospwagan Group is located on the east shore near the north end of Mystery Lake (Zwanzig, 2000; J. Macek, pers. comm.). The basal quartzite (Om1) member of the Manasan Formation (see below) in this locality has a distinctive, glassier appearance than the underlying quartzofeldspathic basement gneiss, but elsewhere this unit is very thin and is obscured in many places by mylonitic fabrics and pegmatites. Sheet-like intrusions of leucogranite occupy the contact in many areas (e.g., the shore of Brostrom Lake). Nonetheless, the thin, non-repeated, basal quartzite (Om1) member of the Manasan Formation is so widespread in the exposed and sub-Paleozoic parts of the TNB (**Figs. 5.1, 5.2,** and **5.3**; see also TNB Geology Working Group, 2001) that this contact must be in place, indicating that the Ospwagan Group must be autochthonous. The interpretation that the Proterozoic rocks are intact has important implications for the location of ultramafic intrusions and nickel deposits (**Section 5.4.4**). For example, lateral sedimentary facies variations at the unit and bed scale, such as the relative proportions of clastic to chemical sedimentary rocks, may reflect syn-depositional basement structures that may have influenced the emplacement of the feeder dikes to the sills. No feeders have been identified in this study, but this concept represents a fruitful area for further research.

The regional compilation (TNB Geology Working Group, 2001) indicates that the stratigraphic subdivision of the sedimentary units of the Ospwagan Group into four conformable formations (**Table 5.1**), most with several members, is robust and valid for more than 200 km along the TNB. Particularly useful has been the recognition of calcareous units (mainly Thompson Formation [unit Ot], locally termed skarn) and their position in a distinctive succession. The more abundant pelite, semi-pelite, and quartz wacke (Pipe Formation [unit Op] and Setting Formation [unit Os]) resemble layered basement gneiss. Thus, quartzite and marble, which are virtually indestructible under almost any metamorphic conditions, are the key to recognising the Ospwagan Group stratigraphy in highly deformed, migmatitic units, even where these units are only a few centimetres thick as a result of structural attenuation. Other particularly useful marker units are the clinohumite- and olivine-bearing marble units in the Thompson Formation. Importantly, the ultramafic intrusions that were previously interpreted to be intruded into the Archean basement (e.g., Bucko) have been reinterpreted to be present in migmatitic and granulite-facies paragneisses of the lower Ospwagan Group. This increases the proportion of ultramafic intrusions that occur in the lower part of the Ospwagan Group and strengthens previous interpretations of that part of the sequence being preferentially intruded (**Section 5.4.4**)

The determination of stratigraphic location is easier within the thin, lithologically-distinctive lower units of the Ospwagan Group (i.e., Manasan Fm., Thompson Fm.) than in the thicker, more uniform, pelite, semi-pelite, and interlayered chert and iron-formation units in the central part of the Ospwagan Group (i.e., Pipe Fm.). Stratigraphic positions within the Pipe Formation are easily obscured by unrecognised strike faults and tight folds, but some control is provided by various facies of iron-formation in the different members and by marker units, including a yellow dolomitic marble that occurs within the Op3 iron-formation member.

The uppermost sedimentary unit in the Ospwagan Group, the Setting Formation, is exposed in the Thompson pit and on islands in Setting Lake, and locally provides evidence of stratigraphic facing in graded beds. Its members, feldspathic quartzite with thin pelite interbeds (member Os1) and predominantly thick-bedded, coarse-grained metaturbidite (member Os2), are not found in clear stratigraphic succession but may be lateral sedimentary facies. Nevertheless, member Os2 is overlain by basalt that belongs to the upper unit in the Ospwagan Group (the Bah Lake assemblage [unit Ob]) and is intruded by abundant Bah Lake sills.

Each of these units is described in more detail below.

5.2.2.1 Manasan Formation (Unit Om)

The Manasan Formation (unit Om) is composed of quartzites and semi-pelitic to pelitic schists and gneisses. The type section is at the Manasan Quarry. It unconformably overlies the basement gneiss (unit Ag) and is conformably overlain by marble or skarn of the Thompson Formation (unit Ot) or, where this is not observed, by semi-pelite of the Pipe Formation. The Manasan Formation ranges in thickness from a few tens of centimetres (in areas of pervasive structural attenuation) to greater than 200 m near Nichols Lake. However, the great thickness in the Nichols Lake area may represent structural repetition.

The Manasan Formation has two members, a lower member of quartzite (member Om1) and an upper member of semi-pelite, impure quartzite, and pelite (member Om2). These members have been traced for ~200 km along the entire length of TNB and represent a regionally-extensive upward-fining sequence of basal siliciclastic rocks. Rough thickness estimates (affected by deformation) are ~200 m for member Om1 and ~50 m for member Om2 at Nichols Lake, and ~100 m and ~25 m, respectively, at Manasan Quarry. The thickest total section of unit Om in the southwestern part of the exposed section of the TNB is ~100 m near Soab Creek (TNB Geology Working Group, 2001). Although these thickness estimates have errors approaching 100% (relative) owing to deformation, member Om2 is clearly more prominent in the southwest TNB than elsewhere. Structural thinning and/or primary thinning has locally reduced the thickness of member Om1 to a few metres or centimetres.

The Manasan Formation (unit Om) is exposed in the Manasan Quarry (~20 km south of Thompson along Highway 6), in the outcrops along the east side of the Pipe II open pit (~30 km south of Thompson along Highway 6), in a road cut along Highway 6, in a small outcrop southeast of Pisew Falls, and in an outcrop at the south end of Brostrom Lake. The rocks in these areas include yellow-weathering quartzite and quartzite beds (<80 cm) with 20% intercalated brown semi-pelite (beds <5 cm). On the western (east-facing) limb of the Brostrom syncline (**Section 6.4.4**), beds of massive orthoquartzite (3-40 cm thick, making up 60% of the rock) are interlayered with beds of brown-weathering quartz-rich semi-pelite (0.5-15 cm). Local garnet porphyroblasts range up to 7 mm in diameter. Black, biotite-rich partings are spaced 5 to 10 mm apart. The folded basal contact of unit Om1 is locally occupied by a sheet of white leucogranite (unit Pg). Semi-pelite (unit Om2) is exposed at the south end of Brostrom Lake as biotite gneiss with 10% garnet porphyroblasts (<15 mm) and 35% thin veins of granite leucosome or porphyroclasts of feldspar. The contact between units Om1 and Om2 is interpreted to be gradational and the sequence to be consistently upward-fining, throughout the TNB.

5.2.2.2 Thompson Formation (Unit Ot)

The Thompson Formation is composed primarily of calcareous semi-pelites and marbles. The type section is at Thompson Open Pit.

The Thompson Formation (unit Ot) was described by Macek and Bleeker (1989), Bleeker and Macek (1988), and Bleeker (1990a), who separated it into three members: a lower member of thinly layered calcareous (feldspar-diopside-hornblende-biotite ± quartz) semi-pelite, pelite and chert (Ot1), a middle, relatively thin (1-3 m in the type locality) member of veined biotite gneiss (Ot2) that resembles the Om2 semi-pelitic gneisses, and an upper member of siliceous dolomitic marbles with minor intercalated chert layers (Ot3), which represents a principal marker unit within the Ospwagan Group stratigraphy.

It is impossible to judge the original thickness of the Thompson Formation in the highly deformed Ospwagan Group, particularly where marble, which flowed from the attenuated fold limbs into the hinge zones, is prominent. It is assumed that the thick unit of the Thompson Formation near Manasan Quarry has flowed into the plane of exposure, laterally and from above or below. Nevertheless, the total relative volume of Thompson Formation, when compared to the underlying Manasan Formation and overlying Pipe Formation, should reflect the original proportion if integrated over the entire fold. A visual inspection of the compilation map (TNB Geology Working Group, 2001) suggests that the Thompson structure, and its likely continuation to Owl Lake, show a greater proportion of unit Ot/Op than the Setting Lake area. A volume comparison with unit Om suggests a thickness of ~50 m in the Thompson–Manasan area, but restoration of structural attenuation indicates that the thickness after deposition may have been greater by a factor of five (**Fig. 5.1**). Nevertheless, the thinning of unit Ot to the southwest corresponds with the thinning of unit Om, with an increase in the turbidite fraction in member Op3, and with local coarsening in the Setting Formation from member Os1 to member Os2 (see below), suggesting that at least some of the thinning is stratigraphic. The proportions of units can be derived more rigorously using GIS tools with a weighting factor for the proportion of included hinge area.

5.2.2.3 Pipe Formation (Unit Op)

The Pipe Formation is composed of pelitic to semi-pelitic schists and paragneisses interbedded with metamorphosed silicate-facies, sulfide-facies, and cherty iron-formations. The type section is adjacent to the Pipe II open pit.

The Pipe Formation (unit Op) was studied in detail by Macek and Bleeker (1989) and Bleeker and Macek (1988), who divided the section at the Pipe II open pit into three members: a lower member of silicate-facies iron-formation, sulfide-facies iron-formation, and chert (Op1), a middle member of quartz-feldspar-biotite-muscovite ± sillimanite schist (metapelite), minor chert, and marl (Op2), and an upper member of iron-formation, chert, metaquartzite, semi-pelite, and minor marl (Op3).

The Pipe Formation has not been assessed in sufficient detail in the southern part of the TNB to allow an analysis of its regional sedimentary facies changes. Although the Pipe Formation is relatively thick in this region, it is virtually unexposed. Only local parts are known from target drilling. Local variations are partly due to changes in the intensity of deformation, recrystallization, and pegmatite intrusion. Pelite (mainly member Op2) rich in quartz-sillimanite knots (faserkiesel) and semi-pelite to quartzite (mainly member Op3) interpreted as siltstone are most abundant in drill core in the south and at Thompson pit in the northeast (Bleeker, 1990a).

The Pipe Formation generally appears to be thicker and more pelitic in the west (cf. sections in Bleeker, 1990a, and apparent thickness distribution in **Figs. 5.1, 5.2,** and **5.3**: TNB Geology Working Group, 2001). Although the pelite was probably ductile and therefore relatively mobile during deformation, rough estimates of thickness obtained from the shapes of folds are ~500 m between Lower Ospwagan Lake and Nichols Lake, ~600 m further south near Soab Creek, ~800 m in the western upright limb of the Thompson nappe, and ~800 m at Setting Lake (**Section 6.2**).

About 150 m of structurally-attenuated pelite to semi-pelite is exposed on the west-central shore of Brostrom Lake. This section includes siliceous biotite gneiss with less than 15% garnet (<3 mm) and 20 to 40% granitic leucosome (<3 cm thick), and the same rock with 15% fine-grained quartzite interbeds (4-40 cm thick). These rocks are probably more strongly metamorphosed equivalents of the pelitic schist and interlayered quartzite and schist that represent Op2 and Op3 members in the section at the Thompson pit. The sulfide-facies iron-formation exposed in many drill core sections through member Op2 is not exposed on the surface. The general absence of visible sillimanite in outcrop can also be attributed to a lack of exposure of non-resistant units. About 100 m higher in the section, semi-pelite contains 10 cm-thick laminated layers with garnet and amphibole and 5-10 cm-thick layers of garnet-amphibolite, which are interpreted as silicate-facies iron-formation of member Op3. This is overlain by thinly layered (1-3 cm) biotite- and garnet-rich (<55%) ferruginous gneiss.

Along strike from Brostrom Lake, the Pipe Formation is exposed in road cuts along Highway 6 in the Soab synclinal structure (**Section 6.4.4**). The outcrops comprise semi-pelite interlayered with 20 to 50% fine-grained protoquartzite (quartzose subgraywacke). Some individual layers of brownish-grey semi-pelite are more than 1 m thick. Garnet porphyroblasts (5%) and rare lenses of calc-silicate (3-10 cm thick) occur in some of the semi-pelite layers. Distinctive, thin, discontinuous layers of salmon-pink granitoid leucosome make up 30% of the outcrop. Quartzose greywacke with graded bedding has been mapped as Pipe Formation at the south end of Setting Lake. Regional variations cannot be traced properly without detailed stratigraphic sections, but a hypothesis that the proportions of sand and silt components, representing turbidite beds, increases to the southwest in the Pipe Formation may be worth testing. Such a transition would link the Setting Lake area to the Thompson structure (**Section 6.4.3**). Regionally, there appears to be a change from more clastic rocks in the Op3 member in the south to more silicate-facies iron-formation at the Pipe II pit and, further north, to oxide- and silicate-facies iron-formation in the western part of the Thompson area (**Figs. 5.2** and **5.3**).

5.2.2.4 Setting Formation (Unit Os)

The Setting Formation is composed of quartzites, wackes, and semi-pelitic to pelitic schists and paragneisses. Although Setting Lake is the type area, the rocks in this area are tightly folded (Ducharme and Zwanzig, 1999) and exposed on isolated islands, groups of which are separated by faults (TNB Geology Working Group, 2001). There is no complete stratigraphic section anywhere in the TNB, but folds are asymmetric such that most units young to the northwest and provide an overall northwest stratigraphic facing, the same as the general stratigraphic top of the Ospwagan Group in that area.

Where the top of the Setting Formation is known in areas northeast of the Soab mines, the better-preserved sections generally have thicknesses in the range of 50-200 m. This is estimated to have been closer to a minimum of 300-400 m before deformation.

The sedimentary rocks that occur on islands furthest to the south in Setting Lake range from light grey, fine-grained protoquartzite (quartzose subgraywacke) to dark brown, ferruginous pelite, similar to the Os1 member elsewhere in the TNB. They are characterized by the presence of graphite and variable amounts of K-feldspar. The pelite (mica schist) contains garnet ± sillimanite (faserkiesel) and iron sulfides (**Table 5.1**). One island features a northwest-facing, upward-coarsening succession with quartzite beds (70% quartz) up to 20 cm thick and 2 cm thick pelite beds (<30% biotite) at the top (Zwanzig, 1997).

Greywacke-mudstone and pebbly greywacke (member Os2) are well exposed on the more northerly islands in Setting Lake, in close proximity to the Bah Lake assemblage (**Fig. 5.3**). These rocks are also graphitic and commonly contain sparse pyrrhotite. They can contain abundant K-feldspar, but consistently have 40-50% plagioclase in the mode. Their primary structures are typical of turbidites (Zwanzig, 1997). This unusually coarse-grained sequence is underlain by about 60 m of ferruginous siltstone. The upper contact of this unit with the greywacke is gradational through light grey beds of fine-grained sandstone or chert that are interlayered with both units. The coarser greywacke is estimated to have a thickness of 160 m by unfolding the section (Ducharme and Zwanzig, 1999). However, the flattening of conglomerate clasts (average Y:Z = 5.6) suggests a significant amount of flattening and therefore an original stratigraphic thickness of 400-500 m. These rocks display classic Bouma-type turbidite divisions: light grey quartzose graded divisions, dark grey siltstone (graded or laminated), and dark brown pelite. Sedimentary structures include flame structures, shale rip-ups, and rare parallel-laminated and cross-laminated divisions. Pebbles and cobbles composed of chert, quartzite and rare mafic rock occur in different parts of the unit, but are coarsest (<20 cm) approximately 50 m above the ferruginous siltstone and at the top of the greywacke in the north. The coarse clasts generally show coarse-tail normal grading, most common in the lower part of the beds (**Fig. 5.1**).

At Setting Lake, Mystery Lake and Thompson, heterolithic gabbro sills, presumably belonging to the Bah Lake assemblage, intrude the felsic detrital rocks of the Setting Lake Formation (**Fig. 5.1** and **5.3**). The sills are typically only a few metres thick, but the larger sills can display diffuse modal layering and contain footwall- and hanging wall-derived metasedimentary rock xenoliths. A good example of this is found in one of the thicker sills studied, which is located an island in the north-central part of Mystery Lake and was described by Theyer et al. (1999). The sills exhibit chilled contacts against the Setting Formation. If the sills represent subvolcanic intrusions associated with the Bah Lake assemblage, this would indicate that much of the Bah Lake assemblage may be autochthonous with respect to the Ospwagan Group and the TNB.

A lens of coarse gedrite (Mg-Fe clinoamphibole) schist (member Os2a), nearly 100 m by 25 m, occurs within the coarse greywacke sequence (member Os2) where these rocks are intruded by mafic sills on Setting Lake. The schist is similar to metamorphosed Fe-Mg-rich alteration products that are generally associated with hydrothermal vents. The stratiform nature of the schist suggests that the mafic magmatism and the attendant high heat flow occurred near the sea floor, possibly before complete lithification of the Setting Formation.

5.2.2.5 Bah Lake assemblage (Unit Ob)

The mafic to ultramafic volcanic rocks and rare interflow metasedimentary rocks at the top of the Ospwagan Group were originally named the *Ospwagan Formation* (Scoates et al., 1977; Albino and Macek, 1981; Bleeker, 1990a). In order to 1) satisfy the Code of Stratigraphic Nomenclature, 2) allow for a possible origin from more than one source, and 3) include subvolcanic sills and dykes (Ob4), which cannot be consistently distinguished from thick flows, these rocks have been renamed the *Bah Lake assemblage* (Zwanzig, 1999a).

These rocks include massive and pillowed basalt with apparently subordinate komatiitic basalt (Ob2), including *picrites* (Ob1) (as used locally). The Bah Lake assemblage is best exposed in the area between Setting Lake in the south and the Pipe open pit mine in the north. The assemblage is apparently poorly developed in the sub-Paleozoic portion of the TNB, as demonstrated on the recently published geological compilation maps for the belt (TNB Geology Working Group, 2001). In part, this may reflect the fact that most of the drilling that has occurred in the sub-Paleozoic portion of the TNB targeted conductors in the Pipe Formation and was therefore unlikely to intersect the Bah Lake assemblage. Recent mapping suggests that, as is the case with the ultramafic sills elsewhere in the Ospwagan Group, the more mafic component of the Bah Lake assemblage is under-represented in outcrop in comparison to basaltic units. A further difficulty arises in recognising flows with schistose or coarsely olivine-poikiloblastic textures. Parts of the assemblage are coarsely recrystallized amphibolite (Ob3). The new work shows that there are regional and local variations in major- and trace element geochemistry that may represent more than one magma source (**Section 8.4.4.2** and **8.5.2.2**). The rocks may also represent more than one structural panel and possible stratigraphic association. However, they are an assemblage that appears to have formed in a single tectonic environment and has a fixed early structural position above the Setting Formation but below the Grass River Group.

Stratigraphic discrimination of the mafic to ultramafic intrusive and volcanic units of the Bah Lake assemblage is hampered by the presence of several complicating factors:

1) Local faulting of the competent units,
2) A general lack of known stratigraphic tops,
3) Fine- to medium-grained sills that are generally not distinguishable from thick flows (especially in drill core or at high metamorphic grades), and
4) Possibly allochthonous mafic rocks that are closely related or chemically similar to the main mafic units and may have been thrust onto the TNB from an adjacent basin at the margin of the Kisseynew Domain.

A 500-1000m thick homoclinal succession of gabbros and weakly deformed basalts that exhibit moderately well preserved pillow structures in the Bah Lake area, ~6 km southwest of Soab South Mine site has been designated as the type section (Zwanzig, 1999a). However, because neither the bottom nor the top of the unit is exposed at that locality, the contact relationships of the sequence are constrained from other locations.

The field relationships at Setting and Bah Lakes provide some degree of stratigraphic control for the existence of a chemically more primitive lower section, an evolved upper section, and variable amounts of sills. The whole data set can be interpreted in terms of magma evolution involving fractionation, crustal contamination, and possibly more than one mantle source (**Section 8.5**).

During this study, different parts of the Bah Lake assemblage have been examined by several workers, including:

1) Sheared pillow basalt and high-Mg basalt with unequivocal spinifex textures, as well as komatiitic flows, encountered in INCO drill core from Mystery Lake (CAMIRO TNB Research Group, 2000),

2) Massive and pillow basalt flows that are interleaved with apparently subordinate massive ultramafic flows (poikiloblastic picrite) on Upper Ospwagan Lake (Theyer and Freund, 1998),

3) Basalt, and gabbro intermingled with tonalitic gneiss and Ospwagan Group paragneiss (semi-pelite, iron formation, quartzite) in a structurally complex zone in the area between Pipe and Soab South mines (CAMIRO TNB Research Group, 1999),

4) A suite of massive to intensely sheared metabasaltic rocks along the western shoreline of the Grass River, north of Pisew Falls and south of Insole Lake,

5) A monotonous sequence of massive and pillow basalt and gabbro (about 40% intrusive) that is relatively well exposed east of Bah Lake and extends north to Soab Lake and northeast to the Grass River (Peck et al., 1999; CAMIRO TNB Research Group, 2000; Chandler, 1999),

6) Narrow belts (apparently connected to the rocks at Bah Lake) of normal- to high-Mg basalt that overlie thick gabbro sills of a similar composition that intruded the Setting Formation along the south and northwest shores of Setting Lake (Zwanzig, 1999a), and

7) Narrow belts of moderately to highly recrystallized basalt and gabbro with a slightly more evolved composition in an area that extends from Bah Lake into the Kisseynew Domain (CAMIRO TNB Research Group, 1999). Because it was unclear whether these rocks belong to the Bah Lake assemblage, or a different suite of mafic magmas, these rocks were assigned to a separate unit (Fish Lake amphibolites, Fa) in previous reports.

Detailed accounts of the field observations for some of the study areas listed above are given in Peck et al. (1998, 1999). Below we review geological observations obtained during the current CAMIRO project for three of the best-known exposures of the Bah Lake assemblage in the TNB.

Setting Lake – Bah Lake Area

On Setting Lake, >90% of the Bah Lake assemblage is interpreted as gabbro sills (<50 m thick). However, a narrow belt of basalts (interpreted as the lower part of the Bah Lake assemblage) appears to be in contact with the Setting Formation. Some of the sills in the Setting Lake area are weakly differentiated and have a dark green to brown weathering, coarse-grained (<10 mm) base with up to 15% plagioclase. The tops of the sills are grey and contain ~60% plagioclase. The sills exhibit the same range of compositions (**Section 8.5.2**) and young in the same direction as the flows and are interpreted to be subvolcanic expressions of the same magmatic episode. The northwest contact of the Bah Lake assemblage on northern Setting Lake is a fault, but a local sliver of Grass River Group basal conglomerate is preserved along a northwest-facing unconformity.

In the Bah Lake area, the percentage of sills is much lower (<10%) and the assemblage is dominated by a >1000 m thick continuous succession of massive and pillow basalt flows, which provided the type section for that part of the assemblage and was extensively sampled for geochemical analysis.

It should be noted that it is not always possible to distinguish unequivocally between sills and flows because primary textures in the Bah Lake assemblage are commonly obliterated by annealed, high-grade metamorphic textures. In some localities (e.g., Grass River), high-grade metamorphism has generated up to 15% leucosome in metagabbroic rocks of the Bah Lake assemblage. The leucosome is apparently related to incipient migmatization during upper amphibolite to granulite facies metamorphism.

Upper Ospwagan Lake

Upper Ospwagan Lake is located in the northern part of the TNB, ~27 km southwest of the city of Thompson. It is underlain by Archean gneiss that is in turn overlain by members of the Ospwagan Group and the Bah Lake assemblage. Interlayered komatiitic and basaltic flows of the Bah Lake assemblage are exposed on the northeastern shore of Upper Ospwagan Lake. Several massive, gabbroic layers up to 20 m thick are intercalated with the basalts and are interpreted to be sills. Field investigations concentrated on the stratigraphy of the volcanic rocks exposed on or close to the northern shoreline of Upper Ospwagan Lake (Theyer and Freund, 1998).

The rocks mapped as “picrites” (olivine-enriched basalts) are actually komatiitic rocks that developed olivine poikiloblasts during high-grade metamorphism (Theyer and Freund, 1998). The olivine poikiloblastic komatiites can be subdivided into pillowed, brecciated, megacrystic, and massive flows. A rudimentary stratigraphy in the megacrystic flow units is indicated by gradual variations in the distribution and arrangement of olivine poikiloblasts. A typical flow unit comprises (from stratigraphic top to bottom):

1) An autobreccia layer that comprises subrounded to rounded centimetre- to decimetre-sized olivine poikiloblastic clasts,
2) A homogeneous olivine-poikiloblastic layer, one to several metres thick, and
3) A basal fine-grained layer, several tens of centimetres thick.

The contacts between successive flow units are typically abrupt (Theyer and Freund, 1998). This feature, repeatedly observed in the “picrites” on Upper Ospwagan Lake, is interpreted to reflect primary flow features such as chemical and physical inhomogeneities produced by flow sorting.

Gradational, interleaved contacts between basalt and “picrite” sequences suggest that these rocks may have been erupted from common vents or fissures. Similar interleaving of ultramafic and mafic flows is also observed in the Fox River Belt (D. Peck, unpubl. data).

On the basis of their whole-rock Mg and Cr contents (**Section 8.5.2.1**), the microspinifex textured rocks on Lower Ospwagan Lake have been classified as komatiitic basalts (Theyer, 2000). Although it has been suggested that some of the ultramafic flows exposed on Upper Ospwagan Lake are co-genetic with the large ultramafic body that is known to underlie much of Lower Ospwagan Lake (e.g., Peredery, 1979; Bleeker, 1990b), our geochemical data for these rocks indicate that they are not petrogenetically related: the Bah Lake volcanic rocks are not only commonly depleted in immobile highly incompatible lithophile elements (whereas the Lower Ospwagan Lake ultramafic body and other bodies of this type elsewhere in the TNB are enriched in highly incompatible lithophile elements), but also possess higher TiO_2 and lower MnO and SiO_2 at similar MgO contents (**Sections 8.4.4.1** and **8.4.4.2**). Although there is evidence that *some* of the trace elements have been mobile during metamorphism, particularly in ultramafic cumulate rocks that contain very low abundances of incompatible elements, strong positive correlations between Ce/Sm and Th/Nb (elements that appear to have been relatively immobile under most circumstances: **Section 7.2.3.1**) suggest that these geochemical differences have not been *generated* by metamorphism. Although we cannot exclude the possibility that the lavas in the Bah Lake assemblage passed through the UM sills and left no crystallized products, at this stage there is no evidence that the sills acted as feeders for the mafic-ultramafic lavas, sills, and dikes in the Bah Lake assemblage.

Mystery Lake

Mystery Lake is located in the northern part of the TNB, ~12 km northeast of the city of Thompson. It is underlain by sheared Archean basement, paragneisses of the Ospwagan Group, the Bah Lake assemblage (including lavas, sills, and dykes), and one or more large ultramafic intrusions. These rocks are bound to the west and east by Archean polymetamorphic ortho- and paragneisses that are interpreted to be retrograded parts of the Pikwitonei granulite domain (Weber, 1990). Immediately west of Mystery Lake, the Ospwagan Group appears to have been intruded by the Mystery Lake granodiorite, which has a 1.836 Ga U-Pb monazite age (Syme et al., 1993). However, some of the granodiorite on Mystery Lake may be as old as 1.874 Ga (Toope et al., 2000).

The Bah Lake assemblage along Mystery Lake comprises predominantly pillowed, massive, and brecciated basalt flows with intimately associated, but subordinate, komatiitic basalt flows. Some of the komatiitic basalt flows display well-defined pyroxene spinifex textures. Owing to intense shearing and sparse outcrop, it was not possible to produce a measured stratigraphic section for the Bah Lake assemblage at Mystery Lake. However, the observed geology appears to be very similar to exposures of the Bah Lake assemblage on Upper Ospwagan and Liz Lakes.

Detailed petrographic studies indicate that although most of the acicular textures observed in the Bah Lake assemblage rocks along Mystery Lake are metamorphic textures produced by randomly-oriented, porphyroblastic tremolite needles or ophitic plagioclase, some of these textures, including those in rocks exposed on the northeastern shore of a small island in the north-central part of Mystery Lake (Theyer et al., 1999), are true spinifex textures. Three discrete rock types have been recognised at this locality. The southernmost is a ~2m long shoreline exposure of spinifex-textured komatiitic basalt that display mm- to cm-sized, radial to randomly-oriented needles of chlorite after pyroxene in an aphanitic matrix. The second is ~5 m to the north and comprises massive, fine-grained ophitic basalt with mm-long, randomly-oriented, acicular, stubby and skeletal plagioclase laths in a chloritized and carbonatized amphibolitic matrix. The plagioclase laths are consistent with crystallization of a supersaturated basaltic magma, and are interpreted to have developed in a similar manner to acicular pyroxene spinifex textures. Further to the north, a pyroxene spinifex-textured komatiitic basalt is exposed for ~2 m along the shoreline. This rock is characterized by mm-long, plumose, radial, and sheaf spinifex-textured aggregates of undetermined composition. Both the grain size and complexity of the spinifex textures at this locality gradually increase in a northerly direction, implying that the unit youngs southward. The spinifex-textured komatiitic basalt is overlain to the north by brecciated basalt, which is in turn overlain by pillow basalt, basaltic flow breccia, and rubble (Theyer et al., 1999).

Synthesis

Based on existing field observations, there appear to be at least four petrologically distinctive suites of volcanic and hypabyssal rocks that comprise the Bah Lake assemblage in the TNB.

1) The first suite is represented by monotonous massive to pillowed basalt flows and sills (e.g., Mid Lake, Bah Lake, Soab area), interpreted as juvenile crust not associated with metasedimentary rocks. These relatively well preserved pillowed and gabbroic units occur in a continuous succession east of Bah Lake. This sequence is currently over 1000 m thick, but flattening of the pillows suggests that it was originally thicker. The section has been sampled extensively for geochemical analysis (**Sections 8.4** and **8.5**).
2) The second suite is represented by massive and pillow basalt flows that have a close spatial association with volcanogenic metasedimentary rocks that locally include banded iron-formation and sulfidized banded iron-formation (e.g., Moak-Mystery, Mid Lake, Joey Lake-Soab North mine areas). In both the Mid Lake and Moak-Mystery Lake study areas, the massive and pillow basalts appear to conformably overlie chert-sulfide and chert-oxide iron-formation, which may represent a transition from clastic to chemical sedimentation coincident with the onset of volcanism (i.e., denoting a change from active to passive tectonics) in a deepening TNB rift basin.
3) The third suite comprises interlayered basalt, komatiitic basalt, and komatiite, that include massive and pillowed lava flows and associated interflow sills (e.g., Mystery Lake, Ospwagan Lake, Liz Lake). Based on drill core information and recent mapping, we believe that this suite of volcanic rocks is underrepresented in outcrop relative to the more basaltic suites described above, but is not co-genetic with the first two suites.
4) A possible fourth suite includes slightly Fe-enriched basaltic rocks that are closely related to the volcanic pile east of Bah Lake, but extend into the Kisseynew Domain. These "outboard" basalts and sills are in fault contact with the Burntwood Group turbidite and are unconformably overlain by the Grass River Group. An allochthonous origin for these rocks cannot be ruled out.

It is not clear whether the first two suites represent stratigraphically different units or whether they simply reflect manifestations of different degrees of tectonic reworking of a once uniform basaltic substrate that conformably overlies the metasedimentary rocks of the Ospwagan Group. There is no obvious relationship between any of these suites of mafic rocks and known nickel deposits or the ultramafic sills lower in the section.

Based on geochemical data (**Section 8.5.2.2**), the Taylor River dyke, a gabbroic intrusion locally exposed along the east shoreline of the Taylor River to the west and south of Upper Ospwagan Lake, may also represent a distinctive period of mafic magmatism in the TNB. It is not clear if a coarse-grained pyroxenite exposed in the south and west parts of Paint Lake is part of a distinct magmatic event in the TNB. One sample of these rocks has been dated at 1.841 Ga by C. Böhm at the University of Alberta and therefore appears to be younger than the main 1.88 Ga Molson dyke age. Despite completion of detailed mapping and geochemical sampling of the Bah Lake assemblage during this project, a regional understanding of its thickness, volcanic facies and relationship to the TNB ultramafic sills remains elusive.

5.2.3 Grass River Group (Unit G)

The Grass River Group is composed of metaconglomerates, intermediate to mafic clastic rocks (sandstone and possibly tuff), pebbly sandstone and quartzofeldspathic rock derived from crossbedded arkose (Zwanzig, 1998). It is confined to the Kisseynew Domain margin, but a tentative stratigraphic relationship has been established with the Ospwagan Group (Zwanzig, 1998). Rocks of the Grass River Group are exposed along the margin of the southern TNB at Setting, Fish, Five Mile, and August Lakes, are repeated across large folds and faults (**Fig. 4.1**), and comprise a series of non-marine magnetite-bearing siliciclastic rocks (Zwanzig, 1997) that overlie the Bah Lake assemblage. They are generally in fault contact with the Bah Lake assemblage (Burntwood Group: Zwanzig, 1999a, 1999b), but a sheared unconformity appears to be preserved within imbricate fault slices in the hanging wall of the Setting Lake Fault (**Section 6.5.3**). Within the Kisseynew Domain, the Grass River Group is interpreted to grade stratigraphically downward toward an outboard basin and into the Burntwood Group turbidite facies.

The apparently younger (**Section 10.2.1**) metasandstones, metaconglomerates, and partly coeval turbidites in the Grass River Group can be distinguished from the older siliciclastic rocks in the Ospwagan Group by the presence of magnetite (< 2%), scarcity of pyrrhotite, and absence of garnet and graphite. They are interpreted to lie stratigraphically above a major unconformity on the mafic flows and sills of the Bah Lake assemblage and the amphibolite that is interpreted to have been derived from it. Where exposed, the contact of the Grass River Group is sheared, but a persistent basal conglomerate (unit Gc) and characteristic hornblende-bearing, in many places pebbly, meta-arenite (unit Gh) were traced for tens of kilometres above the mafic rocks (unit Ob) but below the coherent upward-facing sequence of formations (units Gb and Gs) that form much of the Grass River Group. This relationship appears to rule out the presence of a continuous fault between the Grass River Group and the Ospwagan Group. Apparent fining-upward sequences and upward-facing trough cross-bedding suggest that the sequence youngs away from the underlying Bah Lake assemblage.

On the west shore of Kiski Lake and locally at August Lake, the Grass River Group appears to grade stratigraphically downward into the Burntwood Group (B) marine turbidites, and laterally into the Kisseynew basin. The lower formations (units Gc and Gh) taper out into the Kisseynew Domain, where a basal hornblende- or garnet-bearing unit (unit Gh1) or an underlying transitional pelite (unit Bp) occur. The upper formations in the Grass River Group (units Gb and Gs) form an outboard-thickening wedge. Probable felsic volcanic rocks (unit Gb2) and a felsic conglomerate unit (unit Gs2) occur in poorly constrained stratigraphic locations in the west. Rapid lateral facies changes in the Grass River Group preclude regional subdivisions at the member level.

The total preserved thickness of the Grass River Group is ~800 m, but the thickness away from attenuated fold limbs is estimated to be 1.3-2.2 km and was probably >3 km before deformation. The basal conglomerate with arenite interbeds (unit Gc) is ~150 m thick in the southern part of Setting Lake, where it is overlain by ≥400 m of pebbly hornblende-bearing arenite (unit Gh) and an abbreviated section of units Gb and Gs. Away from the flattened fold limbs in the north (Fish Lake–Bah Lake area), thickness estimates are ~120 m for unit Gh, ~400 m for unit Gb, and ≥500 m for unit Gs, whereas thicknesses in the limbs of the next fold north at August Lake presently range from ~900 m for a very felsic facies of unit Gb (with local Gb2) to >180 m for unit Gs.

The basal formation (unit Gc) forms a northerly tapering wedge of polymictic conglomerate and interbedded and infolded arenite exposed along the northwest shore of Setting Lake, but tapers out along the logging road north of the lake. The unit contains variable amounts of hornblende porphyroblasts. The basal contact with the underlying Bah Lake assemblage is exposed on one small island and at two places on the logging road. In the south, unit Gc is an upward fining succession with relict cross-bedding. Flattened cobbles and pebbles are dominated by sedimentary rocks, mafic-ultramafic rocks, quartz, and generally ferruginous chert. Some contain previously folded quartz veins. The geochemistry of the mafic clasts is similar to that of the underlying Bah Lake assemblage (CAMIRO TNB Research Group, 1999), further supporting an autochthonous, conformable origin. Further north, medium-grained, highly flattened granite boulders lie directly on the Bah Lake assemblage. These were collected for U-Pb dating, but have yet to be analysed. A thin interval of dark matrix at the base suggests that the contact is not a fault, but mafic clasts occur only in the upper part of the unit where interbedded arenite is abundant.

The hornblende-bearing arenite formation (unit Gh) tapers from ~400 m on Setting Lake to zero thickness to the northwest. The rock is relatively quartz poor (average 35-40%), with more plagioclase and small but highly variable amounts of K-feldspar. Hornblende is present in half the samples, but normally constitutes <5% of the rock. Hornblende is more abundant in the higher-grade rocks to the west, where it has formed along with K/Na-feldspar from calcite/calcic plagioclase and biotite. This hornblende (25-50%) gneiss, rich in K-feldspar and containing trace amounts of magnetite, titanite, and apatite, is interpreted as a transitional, intermediate to alkaline igneous rock, possibly a reworked tuff. Trace element data for similar rocks in unit Gc and Gs are presented in **Section 8.6.3.2** and show similarities to Missi Group volcanic rocks on the South flank of the Kisseynew Domain (H. Zwanzig, unpublished data). The hornblende-rich gneiss forms one or more marker units, generally a short distance above unit Gc on northern Setting Lake. It grades into quartz- and plagioclase-rich arenite with K-feldspar and hornblende. In the south, the main sandstone commonly contains pebble beds, scattered pebbles, and rare cobble pavements. Further west, there are local conglomerate beds in the upper part of unit Gh, but these beds contain more felsic clasts than near the basal conglomerate.

Within formation Gb, where biotite is the only major mafic mineral (ave. 10%), quartz makes up 50% of the rock, on average, and magnetite about 1%. The southern, coarser beds generally have small, scattered felsic pebbles. In some of the large folds in the northwest, unit Gb is the only unit present and weathers medium grey to pale pink rather than grey or buff as in the south. Local units of pink, nearly massive, felsic gneiss (Unit Gb3) appear to have similar trace element compositions to Missi Group rhyolitic tuffs from the south flank of the Kisseynew Domain (**Section 8.6.3.2**) and are interpreted to represent metarhyolites.

The uppermost sandstone formation (unit Gs) is relatively quartzose (ave. 60%) and contains K-feldspar and distinctive cream-coloured, flattened, quartz-sillimanite knots. These rocks are commonly cross-bedded; magnetite (~1%) is scattered or highly concentrated in placers in the crossbeds. Felsic pebbles are scattered in this unit and occur in an upper, well-bedded, pebble conglomerate formation (member Gs2). The clasts are mainly quartz or rhyolitic to arkosic. The conglomerate of unit Gs is best developed on Pakwa Lake, in the most outboard part of the Grass River Group, but occurs also at the deepest structural level on Setting Lake.

The thicknesses of the units that make up the Grass River Group, the lithological characteristics of the rocks, their detrital zircon spectrum (**Section 10.2.1**), and their relationship to the Burntwood Group strongly suggest that the Grass River Group is correlative with the Sickle Group and Missi Group on the north and south flanks of the Kisseynew Domain (Zwanzig, 1990, 1999b). The presence of tuff with a geochemical fingerprint identical to volcanic units in the Missi Group (CAMIRO TNB Research Group, 1999) provides a strong link with the rocks in the west. The presence of the unique underlying pelite (interpreted as unit Bp) strengthens the link with the Sickle Group to the north, where the same sequence exists and overlies both pelite (McRitchie, 1977) and "MORB-like" marginal basin basalt. The observed distribution of sedimentary facies suggests onlap-offlap relationships. Such relationships are critical to understanding the TNB–Kisseynew Domain boundary zone.

5.2.4 Burntwood Group (Unit B)

The Burntwood Group comprises turbiditic greywacke-mudstone units that are in indirect contact with the Ospwagan Group only along major strike faults (Superior Boundary Fault Zone in **Section 6.5.4**). The type section is at File Lake (Bailes, 1980; Zwanzig, 1999b).

Dark grey weathering, graphitic, garnet-biotite gneiss (unit Bw) on the most south-westerly islands in Setting Lake has been interpreted as metagreywacke-mudstone. It is in fault contact with Bah Lake assemblage (member Ob4) to the east, but the fault is intruded by leucogranodiorite (unit Pg). Although this part of the Burntwood Group contains up to 5% quartz-feldspar veins and up to 60% leucogranodiorite dykes, there is relict graded bedding similar to that in File Lake Formation metaturbidite in the type area at File Lake (Bailes, 1980; Zwanzig, 1999b). At Setting Lake and west of the Soab South mine site, the rock is fine grained, contains <5 mm garnet (10-15%), and sillimanite as rare bundles of microscopic fibrolite. The relict beds are 2-30 cm thick and grade from lighter psammite to darker pelite that show younging reversals suggestive of isoclinal folding. Calc-silicate lenses, interpreted as having been derived from calcareous concretions (<5 cm thick), occur locally. Narrow belts of Burntwood Group on Kiski and Pakwa Lakes contain sporadic hornblende, magnetite, or pyrrhotite, and have been mapped as part of a Burntwood Group–Grass River Group conformable transition (unit Bp).

On Fish Lake and farther to the northwest, the Burntwood Group consists of migmatite with 25-75% granitoid leucosome in dykes, veins, and lenses of various relative ages. The oldest leucosome typically contains cordierite porphyroblasts (<50 mm long), with garnet and sillimanite mainly in a biotite-rich selvage. Garnet ranges from 5 to 10 mm in these rocks, but the original compositional grading in the bedding is locally preserved. Sharp contacts with the granitoid rocks that contain garnet, cordierite, and local graphite suggest that unit (Pg) represents an injection complex of either crustally derived or crustally contaminated magma (S-type granite).

5.2.5 Winnipegosis Komatiite Belt

This section provides a synoptic account of the geology of the Winnipegosis Komatiite Belt (WKB). A more detailed description is given in the 1998 Annual Report for the project (CAMIRO TNB Research Group, 1998).

The WKB is a >150 km long, northeast-trending Proterozoic greenstone belt developed within the Superior Boundary Zone in central Manitoba (Peck and Theyer, 1998). The western boundary of the WKB is believed to be a fault contact against the Sub-Paleozoic extension of the Thompson Nickel belt (TNB), whereas the eastern margin abuts Archean orthogneiss of the Superior Province. The initial description of the WKB (Hulbert et al., 1994) as a series of mildly-metamorphosed and weakly-deformed mafic and ultramafic extrusive and intrusive rocks and sedimentary rocks has been confirmed by studies carried out by P. Theyer with the support of Cominco staff. Rocks from the WKB have been observed as far north as the Falconbridge Ltd. Baker Lake permit (Central region of this study) and as far south as Swan Lake area of the former Cominco Ltd. Rabbit Point property (Southern region of this study). Regionally, the WKB has a stronger affinity in terms of structural geology and metamorphism to the Fox River Belt than it does to the TNB. From the limited number of ages currently available for each region, the WKB appears to be younger than the Thompson Nickel Belt and is characterized by a distinctively different stratigraphy and tectonic history. A single U-Pb age of ~1.864 Ga (Hulbert et al., 1994) has been reported for coarse-grained mafic rocks in the WKB (which may represent either a thick flow or sill).

Drill core for eleven holes drilled in the area of the former Rabbit Point property (Cominco Special Permit 90-1: **Fig. 5.5**) was relogged in the summers of 1996 and 1997. The rocks intersected in this drilling campaign include komatiitic, komatiitic basaltic, and tholeiitic basaltic cumulate and non-cumulate volcanic and intrusive rocks, pelitic sulfide- and graphite-bearing black shales and argillites, silicate-facies iron-formation, and dolostone. The rocks are extremely well preserved, having experienced only sub-greenschist facies metamorphism and minor tectonism in the form of metre thick tectonic breccia zones.

It was generally not possible to determine whether given ultramafic bodies intersected in the Cominco core were intrusive or extrusive. Locally, this distinction was made on the basis of on unequivocal flow features such as flow-top breccias, olivine or pyroxene spinifex textures, and aphanitic chilled margins. Thus, only those ultramafic rocks exhibiting strong evidence of being extrusive were classified as being volcanic.

Geochemical data for ultramafic and mafic rocks in the WKB are discussed in **Section 8.5.2** of this report and in more detail in the 1998 CAMIRO TNB Project Annual Report.

5.3 Regional Lithofacies and Tectonostratigraphic Interpretation

The stratigraphic framework, formational thickness, and sedimentary characteristics of the Ospwagan Group, as illustrated in the simplified stratigraphic columns in **Figures 5.1** to **5.3**, are discussed in this section. The sequence appears to have been deposited near a passively rifted margin on a foundered platform that experienced a subsequent period of active rifting and ultramafic to mafic magmatism, as represented by the mineralized and non-mineralized ultramafic sills in the Ospwagan Group and the mafic-ultramafic flows, sills, and dikes in the Bah Lake assemblage. The stratigraphic succession and interpreted tectonostratigraphic relationships with the younger sedimentary rocks of the Kisseynew Domain shown in **Figures 5.1** to **5.3** involve a major fault zone (Superior Boundary Fault Zone: **Section 6.5.4**) as well as a younger unconformity that may mark the collision between the TNB and the Trans-Hudson Orogen. The overlying fluvial-alluvial Grass River Group and its deep-water turbidite facies, the Burntwood Group, are interpreted to be syntectonic deposits derived mainly and progressively from the encroaching Trans-Hudson arc terrain. The outboard facies of the Grass River Group, which appear to contain rhyolite tuffs similar to those in the Flin Flon Belt at Snow Lake, were deposited during the intrusion of high-K quartz monzonite in the TNB basement gneiss.

Any stratigraphic model for the belt should explain the following observations and conclusions extracted from the highly metamorphosed and deformed sedimentary and volcanic rocks of the TNB. A hypothetical scenario is developed here that may stimulate further discussion of, and work on, the TNB.

1) The Ospwagan Group is largely *in situ* and unconformably overlies Archean basement gneisses.

2) Formations and members of the Ospwagan Group have a remarkable continuity, consistent with platform or passive-margin successions.

3) Volcanic rocks are absent, or at least not prominent, in the lower and middle parts of the sedimentary succession.

4) The basal quartzite member (Om1) of the Manasan Formation forms a sand blanket with only local pebbles at the base; gravelly cross-bedding and thick conglomerate wedges with high taper that would indicate an alluvial environment at a rift shoulder are absent. The taper of the whole formation is low, as shown by thicknesses that range from ~300 m (partly restored) at Nichols Lake, ~75 m west of Thompson, to a few metres or less (deformed) in the southwest at Setting Lake. Significant changes in thickness occur mainly in fold hinges and are interpreted to be structural rather than stratigraphic. The overlying upward-fining semi-pelite and pelite (member Om2) are thin (<100 m) and represent a marine transgression at a low subsidence rate, typical of a passive margin (drift stage) or platform.

5) The Thompson Formation, including calcareous ‘skarns’, comprises argillaceous and pure carbonate rocks, and was probably not much greater than 50 m in thickness. Larger outcrop areas of unit Ot represent fold hinges and other tectonically-thickened domains where the rock is interpreted to have flowed from fold limbs (where it can be only a few centimetres thick). Unit Ot was presumably deposited on a stable platform, distant from a source of detritus or bypassed by detritus.

6) The Pipe Formation comprises a series of upward-fining sequences (members Op1 to Op3), each from siliciclastic to chemical sedimentary rocks. An eastern belt that extends from the Thompson pit to Setting Lake is interpreted to thicken southward from ~500 to ~900 m, possibly with another thick belt (‘Pipe band’) lying to the northwest. Although this may be within the range of structural thickening, it is plausible that subsidence increased to the west (see caption of **Fig. 5.2**). Unit Op appears to fine northwestward from more quartzitic turbidite beds (mainly in member Op3) to more pelite, chert, and silicate-facies iron-formation (with an aluminous detrital component) and, distally, to oxide-facies iron-formation. If the rocks are considered to be para-autochthonous, these interpreted changes in facies and thickness suggest a northwest direction of sediment transport (**Fig. 5.4**). The change from sulfide-facies to silicate- and oxide-facies iron-formation, upward and northwestward, may represent a transition from deeper to shallower or from stagnant to more open marine conditions, possibly as the platform tilted and foundered. Some of the calcareous rocks, such as the banded diopside rock at the top of member Op3 (**Fig. 5.1**; Bleeker, 1990a), may represent resedimented carbonate from the eroding platform to the southeast.

7) The sudden influx of quartzose sand, deposited as Setting Formation turbidite (member Os1) indicates uplift of the source and more rapid subsidence in the TNB. The local upward coarsening to conglomeratic or pebbly beds (member Os2) represents the least mature and first truly syn-orogenic sedimentary rocks. Consequently, unit Os deposition can be interpreted as the result of renewed rifting, this time active rifting in a marine environment.

8) The contaminated, mineralized and non-mineralized ultramafic sills in the TNB do not intrude any rocks above the middle of member Os1, but they are cut by dykes from the younger, mafic stage(s) of magmatism (i.e., Bah Lake assemblage and/or Molson suite). Thus, the initial pulse of komatiitic magmatism and related Ni-Cu-PGE mineralization appears to have occurred during deposition of member Os1 and is consistent with renewed rifting at that time.

9) Overlying mafic-ultramafic flows, dikes, and sills of the Bah Lake assemblage (unit Ob) resemble a rift-drift sequence formed during the separation of Archean crust northwest of the TNB. Prominent features of unit Ob include: i) a gabbro to pyroxene gabbro sill complex (member Ob3) that is intrusive into the base of the coarse turbidite, ii) stratiform Fe-Mg hydrothermal alteration (member Os2a), iii) capping pillow basalt (member Ob2) with local picrite (member Ob1) at Setting Lake, and iv) a >1 km-thick sill and flow complex (unit Ob) at Bah Lake. They suggest deposition near a marine escarpment at a normal fault and magma feeder system. These structures were probably overturned and reactivated along the Setting Lake Fault during subsequent deformation. The slightly evolved basaltic rocks to the west (unit Fa) may be a remnant of an outboard ocean basin floor (drift sequence), presently underlain by an allochthonous Burntwood Group substrate (**Fig. 5.4**). Thin chert and calc-silicate rock on August Lake are prospects for ocean-floor sediments, but need careful study.

The Ospwagan Group is very similar to, although thinner than, the Lower Paleozoic continental terrace wedge that lies outboard of the carbonate platform of the southern Canadian Cordillera (Zwanzig, 1973 and references therein). That succession comprises sulfide-rich shale above quartzite and dolomitic limestone, and an overlying series of ferruginous and calcareous phyllites with ultramafic sheets and cherty argillite that is overlain, in turn, by quartz wacke and mafic volcanic rocks. The presence of iron-formation in the Paleoproterozoic Ospwagan Group is related to differences in the ancient seawater, atmosphere, and life forms.

The Grass River Group in the Setting Lake area likely represents the earliest record of collisional tectonics along the SBZ. This group comprises a lower succession of metamorphosed, upward-fining, fluvial-alluvial sandstone and conglomerate, and an overlying succession of upward-coarsening arkosic arenite to felsic tuffaceous sandstone (Zwanzig, 1997, 1998). Gravelly cross-bedding, 'floating' pebbles in sandstone, ripped-up shale drapes, and upward-fining groups of beds all indicate alluvial, fluvial and sheet-flood (alluvial plane) deposition (**Fig. 5.4**).

Fining and, presumably, sediment transport was to the north in the coarse lower units (units Gc, Gh) that contain mafic and chert clasts. Their hornblende content and slightly more mafic composition is probably related to the erosion of their basaltic substrate. A local mafic-ultramafic and ferruginous chert source is evident only in the basal conglomerate. The units form short, thick sequences with high northward taper and were probably deposited near syn-depositional faults. Detrital zircon spectra (**Section 10.2.1.2**) and felsic sedimentary and volcanic clasts indicate a juvenile arc-related Paleoproterozoic source (i.e., the approaching internal zone of the Trans-Hudson Orogen, as yet, lying outboard of the TNB).

The upper formations (units Gb and Gs) thicken considerably to the west, although there is no control of the amount of structural repetition. They have the felsic composition and probable component of tuff and intercalated rhyolite that indicate their affinity with the late successor arc in the Flin Flon and southern Kisseynew domains. The preliminary detrital zircon spectrum is consistent with the age of the correlative Missi Group and indicates coeval deposition and emplacement of the 1836 Ma Bucko quartz monzonite, during closure of the basin that separated the internal zone of the Trans-Hudson Orogen and the Superior craton. Abundant, large-scale cross-bedding and magnetite placers in unit Gs indicate continued subaerial deposition. During the deposition of these units, little sediment onlap occurred; the TNB probably stood high, but had a mafic volcanic cover that supplied no detrital zircons.

5.4 Ultramafic Bodies

5.4.1 Introduction

Assessing the stratigraphic relationships between the ultramafic bodies of the TNB and the host Ospwagan Group metasedimentary rocks is a significant challenge because of their limited exposure and discontinuous nature. Owing to their high degree of serpentinization, the ultramafic bodies in the northern exposed portion in the TNB have experienced intense glacial erosion and form recessive topographical features that are now filled by lakes. Although extensive drilling and geophysical surveys by Inco, Falconbridge, and HBED have shown that most of the ultramafic bodies occur as discrete boudins, the geometry and internal structure of many of the bodies is still poorly constrained and only one dimensional information is available from drill hole data.

5.4.2 Contact Relationships

The ultramafic bodies are generally lensoid to tabular in shape. Although they almost always have tectonized contacts with the country rocks, the majority of the deformation is restricted to the margins, with the degree of preservation of primary fabrics increasing away from the contacts toward the cores of the bodies.

On both a regional and local level, the ultramafic bodies appear to have experienced all phases of deformation experienced by the surrounding metasedimentary rocks, indicating that they were emplaced after sedimentation, but prior to the initial phases of deformation (Peredery, 1982; Bleeker, 1990a). Although tectonism and frequent pegmatite intrusions along the margins of the ultramafic bodies have obscured the original contacts, in rare cases contacts do appear to be preserved (e.g., part of the lower contact of the large ultramafic body at Ospwagan Lake with laminated semi-pelitic rocks of the Pipe Formation). Under such circumstances, the adjacent sediments show clear signs of thermal metamorphism including bleaching, silicification, and the loss of lamination for distances up to 5-10 m from the contact. Although subsequent regional metamorphism may have overprinted all but the strongest effects of contact metamorphism, a thermal aureole of <10 m appears to be relatively thin given the size of the Ospwagan Lake ultramafic body (current surface exposure ~7 km^2) and the high temperature of the ultramafic magma from which it formed (~1600°C: **Section 8.8.1.1**). This suggests that either the sedimentary rocks were already lithified and relatively warm at the time of emplacement of the ultramafic bodies, or that the bodies were emplaced during metamorphism (see discussion by Menard et al., 1996).

5.4.3 Internal Stratigraphy

Where individual, relatively untectonized ultramafic bodies have been studied in detail (e.g., Pipe 1, Spur South, W-56 South body at William Lake), they commonly show an asymmetric variation in cumulus olivine content, as well as in whole-rock MgO content (**Fig. 5.6**). Most bodies are characterized by a relatively thin pyroxenitic basal zone that rapidly grades upward (stratigraphically) into a thick zone of chromite-bearing olivine ortho- or mesocumulate peridotites and olivine adcumulate dunites. With increasing stratigraphic height, the rocks become progressively less olivine-rich and grade towards a pyroxenitic upper margin. Similar asymmetric trends have been observed in many intrusive and extrusive ultramafic and mafic bodies in less deformed areas (e.g., Kambalda, Western Australia: Donaldson, 1983; Lesher, 1983; Dumont, Canada: Duke, 1986; Pechenga, Russia: Hanski and Smolkin, 1989; Mount Keith, Western Australia: Hopf and Head, 1998; Forrestania, Western Australia: Porter & McKay, 1981). In these instances of lower strain and lower metamorphic grade, it is possible to show that the broad upwards decrease in olivine content correlates with the stratigraphic facing direction of the bodies. Where the facing directions are known for the metasedimentary rocks surrounding each of the TNB ultramafic bodies examined in detail, they agree with those inferred from the petrological and geochemical variations within the bodies, indicating that most of the bodies were probably concordant or semi-concordant with the sediments during emplacement.

In some instances (most commonly in the drilling by Falconbridge in the central region of the TNB, e.g., the W-56 North and W-21 ultramafic bodies along the William Lake trend, **Fig. 5.7**), the differentiation within the ultramafic bodies is more pronounced and the upper parts of the bodies contain plagioclase- and garnet-bearing amphibolite horizons that can be traced between drill holes at similar stratigraphic heights within individual bodies. The amphibolites grade up- and down-hole into chromite-undersaturated olivine cumulate rocks, indicating that they are differentiation products rather than separate intrusions. The locations of these zones in the upper parts of the ultramafic bodies therefore not only confirm that the bodies are sills, but also provide a way-up indicator. The low chromite contents of the olivine cumulates that constitute the majority of the ultramafic bodies indicate that the sills formed by the initial intrusion of Cr-undersaturated magmas that crystallized/accumulated olivine and subsequently olivine ± chromite (see discussion in Lesher & Stone, 1996) along solidification fronts that propagated inwards from the sill's upper and lower contacts. The final evolved liquids were considerably more basaltic and solidified as gabbro in the centre or upper parts of the sill and were subsequently metamorphosed to amphibolite. The high MgO contents of the cumulate rocks above the amphibolite layer (up to 36 wt%), which are greater than the inferred liquid, may reflect either trapping of phenocryst olivine along the chilled upper contact of the intrusion or the introduction of a second pulse of magma that beheaded the previously formed layer.

The presence of a range of different types of ultramafic bodies in the TNB, including: 1) massive dunites, 2) massive peridotites, 3) differentiated bodies containing lower and upper pyroxenite zones, and 4) differentiated bodies that contain cumulate lower zones and amphibolite upper zones, indicates variations in the relative amounts of accumulation and differentiation that probably relate to differences in the volume of magma processed by the bodies and the amount of liquid trapped when the magma ponded (**Fig. 5.8**). If an ultramafic magma is emplaced rapidly such that there is insufficient time for the accumulation of olivine and/or differentiation of the magma (e.g., a thin dyke or sill emplaced into cool country rocks), then the composition of the resulting body will be homogenous and will have a similar bulk composition to the original magma (lower left part of **Fig. 5.8**). Alternatively, if an ultramafic magma is emplaced under dynamic, open-system conditions, then large volumes of magma may be processed through the magma chamber leading to the production of thick olivine cumulate zones. If the magma is then expelled before it ponds in the chamber, then the composition of the body will be dominated by the initial accumulation process, the cumulate zone will exhibit negligible differentiation, and the body will possess only thin, if any, zones of less cumulate-rich material (e.g., gabbro which is later converted to mafic amphibolite: top left of **Fig. 5.8**). Finally, if an ultramafic body forms by the injection of a single pulse of magma, which then proceeds to differentiate *in situ*, then the composition of the body will be dominated by differentiation, and the resulting body will contain both mafic and ultramafic zones whose integrated composition will be similar to that of the original magma (bottom right of **Fig. 5.8**). Although a complete spectrum may be expected between these three end-members (see discussion by Lesher et al., 1984) and may be found in other segments of the Circum-Superior boundary Zone (e.g, ultramafic and differentiated sills underlying the Raglan Horizon of the Cape Smith Horizon, northern Québec; Fox River Sill, northern Manitoba) the range of ultramafic bodies that occurs in the TNB indicate that almost all bodies have experienced large amounts of olivine accumulation, with only moderate to low amounts of differentiation. This suggests that most of the bodies represent conduits formed under relatively dynamic environments and that the magma ponded late in their production. Although there are rare examples of magmatic Ni-Cu-(PGE) deposits that appear to have formed in relatively static environments (e.g., Huangshan district, China), most economic deposits are believed to form under dynamic conditions, where the magma is transported under turbulent conditions and is able to not only thermally erode the country-rocks but also to interact efficiently with any sulfide liquid present (Lesher et al., 2001). The recognition of non-dynamic magma systems has important implications for mineral exploration and will be discussed in more detail in **Chapter 11.**

5.4.4 Stratigraphic Location

One of the objectives of the current project was to determine the relationship between the size and mineralization status of the TNB ultramafic bodies and their stratigraphic setting. Part of this goal was to assess whether the ultramafic bodies were preferentially emplaced along specific horizons and whether there was a systematic difference in the degree of mineralization between those emplaced at different horizons. In order to accomplish this, a detailed database that contained information on the locations, country rocks, and degree of mineralization for each of the ultramafic bodies was generated. This information was obtained from the digital data for the recently compiled maps of the belt (TNB Geology Working Group, 2001). Because these maps were produced by one of the most experienced geologists currently working in the TNB, and were based on both detailed logging of a large number of drill holes and the interpretation of geophysical data, the data on which they are based not only avoid a bias towards mineralized bodies that would have been inherent in the examination of drill cores alone (and toward the most recently obtained drill core that commonly showed less alteration in the ultramafic body owing their intersection at greater depths, and so were preferred for the geochemical study), but also include information for many of the smaller bodies that would not have been examined otherwise. Because all ultramafic bodies currently present at the surface are included in the map database, a quantitative assessment of the distribution of the ultramafic bodies within the stratigraphy is possible through spatial analysis. However, in most cases it is impossible to determine the mineralization status of the bodies from the map alone and, within the time available, the necessary information about the mineralization state of all the bodies could not be obtained. As a consequence, the discussion of the relationship between mineralization and stratigraphy presented is only qualitative. However, the results of the spatial analysis suggest that a more detailed assessment of the stratigraphic and/or volcanological controls on mineralization may be warranted.

Prior to the start of this project, it was recognised that although ultramafic bodies were present at a number a number of stratigraphic levels within the Ospwagan metasedimentary sequence, qualitatively they appeared to be most common near the base of the sequence (i.e., in the Manasan, Thompson, and lower Pipe Formations) or in the underlying basement rocks, and that the presence of magmatic Ni-sulfide mineralization depended on the emplacement of the ultramafic body along one of the two thick sulfidic sediment horizons within the lower Pipe Formation (in the lower part of the Op1 member at Pipe Pit and Birchtree Mine, or the upper part of the Op2 member at Thompson Mine: Bleeker, 1990a; Bleeker & Macek, 1996). Although examination of the new maps of the northern portion of the exposed TNB shows this to be largely true, with the majority of the ultramafic bodies located at or close to the contact between the Manasan and/or Thompson Formation and the Pipe Formation (the Thompson Formation frequently being too thin to be represented at the scale of the map), it also indicates that many bodies have been emplaced higher in the sequence, in either the upper parts of the Pipe Formation (North Manasan?), the Setting Formation (Lower Ospwagan Lake, eastern Upper Ospwagan Lake), or even the lowermost units of the Bah Lake Formation (Mystery Lake North).

In order to investigate the observations above, a stratigraphic index was calculated for each ultramafic body in the northern (exposed) portion of the TNB, based on the relative proportions of each formation with which it was in contact. The index was calculated by reducing the map to an array of 5 m x 5 m pixels and calculating the total area of each formation within 10 m of each body. Because the ultramafic bodies were frequently in contact with more than one formation, indicating that they were located close to or on a stratigraphic contact, a weighted average was calculated by allocating weights of 0, 1, 2, 3, 4, and 5 to the basement (represented by biotite-gneiss on the maps), Manasan Formation, Thompson Formation (represented by "skarn" on the maps), Pipe Formation (including rocks mapped as Fe-formations and cherts), Setting Formation, and Bah Lake assemblage (represented by "mafic volcanic rocks" on the maps), respectively. Values between 0.25 units below and 0.25 units above an integer value (e.g., 1.75 to 2.25) were assigned to the associated formation. Values between 0.25 units above an integer value and 0.25 below the next value (e.g., 2.25 to 2.75) were assumed to lie on the contact. Although relatively crude, the use of a weighted average to infer the stratigraphic position of the ultramafic bodies allowed the analysis to cope with problems arising from thin units that were not represented at the scale of mapping, but inferred to be present. For example, in a number of cases, a body is mapped as being in contact with Manasan, with a weighting of 1, and Pipe Formation rocks, with a weighting of 3, with no Thompson Formation apparently present. Under such conditions, the weighted average calculated for the index was commonly close to 2, suggesting emplacement into the Thompson Formation. Owing to the large area covered by the analysis, the results are grouped by general location in order to investigate whether the controls on sill emplacement varied along the belt. The southern group included all bodies between northern Setting Lake and Spur South in the west and south of Liz Lake in the east, the central group included the bodies from Spur South/Liz Lake to south of Birchtree and Thompson Mines, and the northern group that included the bodies at Birchtree and Thompson north to Moak Lake (**Fig. 5.9**).

The results of the analysis are shown in **Figures 5.10** and **5.11**. Although there are minor variations in absolute values from different areas of the exposed TNB, in general the ultramafic bodies from all three areas show a similar distribution of host rocks. By far the greatest number of the bodies appear to have been emplaced into either the Pipe Formation (59%), the Thompson Formation (12%), or along their contact (17%), consistent with the qualitative observations above. There appears to be no discernible relationship between the size of the ultramafic bodies and their level of emplacement, as demonstrated by the fact that some of the largest bodies occur in the basement (Moak), Pipe Formation (North Manasan), and Setting Formation (North Mystery Lake), as well as at the Thompson/Pipe (Lower Ospwagan Lake West) and Pipe/Setting (Mystery Lake) contacts. However, it notable that the largest ultramafic bodies are either non-mineralized (e.g., North Mystery Lake, Upper Ospwagan Lake) or only poorly mineralized (e.g., Ospwagan Lake), suggesting that mineralization may be related to the size of the body.

In light of recent observations of metacarbonate rocks in drill core from the southern portion of the exposed TNB, in areas that were previously assumed to be Archean basement (e.g., Bucko Mine: J. Macek, pers. comm., 1999), it appears that the host rocks to the bodies that were previously interpreted to be in the basement may simply be highly metamorphosed lower Ospwagan Group metasedimentary rocks (the carbonates representing the “skarns” of the Thompson Formation). This suggests that there may be a similar relationship between the stratigraphic levels of emplacement and mineralization in both the northern and southern parts of the *exposed* TNB.

In order to characterize the relationship between stratigraphic level of emplacement, ultramafic body size, and mineralization status more fully, it would be necessary to repeat the spatial analysis and include information about the mineralization status of each of the ultramafic bodies. This may be achieved by either linking the mineralization status of the bodies from which the samples in the geochemical database were taken to the polygons used in the map or by inputting additional information about the bodies from the company sponsors. Because the former is likely to produce data for only the larger and better-characterized bodies, it is likely to produce a biased sample set; for optimal characterization, all the bodies will need to be considered, irrespective of their size and mineralization status.

5.4.5 Interpretation

5.4.5.1 Sills vs. Flows

During the course of the project, no evidence has been found to contradict the existing interpretation of the ultramafic bodies as a series of sills that intruded at various stratigraphic levels in the Ospwagan Group metasedimentary rocks (Bleeker, 1990a). Evidence to support this interpretation includes the observations that:

1) The ultramafic bodies occur at multiple stratigraphic levels in the Ospwagan Group.
2) None of the ultramafic bodies show any positive evidence for an extrusive origin (e.g., quench textures, volcaniclastic textures, pillow structures, or interflow sediments).
3) The ultramafic bodies are frequently extremely thick, partially differentiated, and contain minerals with coarse textures and uniform compositions (olivine ± chromite), consistent with slow cooling.
4) Only thin chill zones occur at the top of the bodies and the upper contact is not associated with any particular sedimentary rock.

5.4.5.2 Level of Sill Emplacement

The ability of a magma to rise up through the crust and forms sills or flows will be controlled by a number of separate, but interrelated factors including:

1) Magma density (which will vary as a function of composition, temperature and pressure),
2) Sediment density (which will vary as a function of mineral composition, texture, and degree of consolidation/lithification),
3) Sediment rheology (which will vary as a function of lithology and lithification).

Although the precise location of the sills will be determined by the yield strength of the host rocks (i.e., rheology), the overall driving force behind magma ascent and emplacement is the buoyancy of the magma relative to the surrounding country rocks; a magma may be expected to rise only if its density is less than the bulk density of the overlying crust. Calculations indicate that the densities of most mafic, intermediate, and felsic magmas at their liquidus temperatures should be close to or less than those of most common upper crust rocks (e.g., $\rho^{Gabbro}_{1200°C} \sim 2.59$ gcm^{-3}, $\rho^{Granodiorite}_{1100°C} \sim 2.34$ gcm^{-3}, and $\rho^{Granite}_{900°C} \sim 2.26 - 2.35$ gcm^{-3}, vs. $\rho^{Shale} \sim 2.06 - 2.66$ gcm^{-3}, $\rho^{Sandstone} \sim 2.17 - 2.70$ gcm^{-3}, $\rho^{Limestone} \sim 2.26 - 2.80$ gcm^{-3}: Daly et al., 1966; Spera, 2000), such that their ascent is not substantially limited by their buoyancy. However, owing to their high Mg-Fe contents and low alkali and volatile contents, most ultramafic (komatiitic) magmas are significantly denser than most common upper crustal rocks (despite their high liquidus temperatures), and will only ascend into sialic upper crust with difficulty. Consequently, the principal questions regarding the stratigraphic controls on the emplacement of the TNB ultramafic bodies are: a) how did the magmas manage to reach the Ospwagan Group metasediments, and b) why were they preferentially emplaced within the Pipe and Thompson Formations?

In order to investigate the controls on the emplacement of the UM bodies, a number of simple numerical models were constructed for the density structure of the Ospwagan Group in the vicinity of Thompson Mine using the stratigraphy determined by Bleeker (1990a) and typical densities for consolidated sedimentary rocks and gneisses (**Table 5.3**). Magma densities were calculated as a function of temperature, pressure, and composition for three potential mafic and ultramafic magmas (two picrites/komatiitic basalts and one basalt from the Ospwagan and Mystery Lake areas) using an empirical equation of state and constants for oxide components taken from Spera (2000).

Table 5.3 Densities used in modelling of ultramafic sill emplacement.

Lithology	Density (cm^{-3})
Sandstone	2.70
Pelite	2.70
Marl	2.73
Limestone	2.75
Komatiitic Magma	**2.72 – 2.74**
Gneiss	2.85
Iron Formation	2.90*
Mafic Volcanic Rocks	2.97
Gabbroic Sill	2.97
Ultramafic Sill	3.28

*Density of iron-formation calculated from the average chemical composition of typical Pipe silicate-facies iron-formations collected for this study and assuming all Al_2O_3 originated in a pelitic component (ρ = 2.7gcm^{-3}, 50%), all S was contained in pyrrhotite (ρ = 4.6g cm^{-3}, 5%), all iron was present as minnesotaite (ρ = 3.1 g cm^{-3}, 35%), and the remaining material was quartz (ρ = 2.65 g cm^{-3}, 10%). All other values adapted from Daly et al. (1966).

In the first model (**Fig. 5.12a**), the sediments were assumed to be unconsolidated and to contain ~10% trapped water. Despite the presence of denser iron formations in the sequence, the bulk densities of the sediments would have ranged between only 2.53 and 2.68 gcm^{-3}, which is considerably less than would have been required for the emplacement of the mafic and/or ultramafic magmas (with densities of between 2.72 gcm^{-3} (basalt) and 2.74 gcm^{-3} (komatiitic basalt)). Owing to the low densities of the sediments, the bulk density of the crust would have not exceeded that of the magmas for up to 500 m into the basement (which was assumed to have a density of ~ 2.85 gcm^{-3}, at the upper end of that expected for granitic rocks (2.52 – 2.81 gcm^{-3}: Daly et al., 1966), but within the ranges expected for gneisses and granulite-facies rocks (2.61 – 2.84 gcm^{-3} and 2.63 – 3.10 gcm^{-3}, respectively: Daly et al., 1966). This model indicates that the ultramafic sills could not have been emplaced into the Ospwagan Group sediments if they still contained appreciable water and confirms the interpretations above that the sediments must have been lithified prior to sill emplacement.

Model 2 (**Fig. 5.12b**) was calculated assuming similar stratigraphic thicknesses as in the first model, but with only 0.5-1.0% pore water in the sediments. Although very dependent on the thicknesses and densities chosen for the different units, under such conditions, the densities of the magmas match that of the overlying bulk sediment at a point between the top of the Thompson Formation and the first iron-formations of the Pipe Formation, consistent with the locations of the majority of the ultramafic bodies determined by the spatial analysis in **Section 5.4.4**. Intrusion at this level would therefore be expected owing to the pronounced decrease in bulk density that should occur at this contact. However, in areas where the high-density carbonate rocks of the Thompson Formation were thinner, the density of the magmas could have exceeded the bulk density of the sedimentary rocks at greater depths, resulting in deeper emplacement, possibly in the basement. Similarly, where the iron-formations of the upper Pipe Formation were thicker, the bulk density of the sediments could have been greater and the magmas would have been emplaced higher in the sequence. This model suggest that the emplacement of the sills into the lower (sulfide-bearing) units of the Pipe Formation may therefore be restricted to regions in which the iron formations in the upper units of the Pipe Formation (Op2 and Op3) are either thicker or more abundant.

Once the magma reached neutral buoyancy it would have spread out to form a sill and have started to assimilate the country rocks as well as to fractionate olivine to produce the thick cumulate zones present in most bodies. By doing so, it would have not only created space for further magma emplacement, but would also have increased the bulk density of the sediment column and reduced the density of the magma (**Fig. 5.12c**). Because the differentiated (and contaminated) magma would have eventually been less dense than the surrounding rocks, it would have been able to ascend further within the sediment pile, until such time as it achieved neutral buoyancy again, whereupon it could have formed a second, less olivine cumulate-rich sill (**Fig. 5.12d**). This would most likely have occurred at the upper contact of another relatively dense sedimentary unit. In **Figure 5.12d**, this is represented by the emplacement of a gabbroic sill above the uppermost silicate iron formation in the Pipe Formation. The intrusion of the mafic body in the uppermost Pipe Formation would have further increased the bulk density of the sediment pile, enabling the emplacement of an additional (interconnected) ultramafic body at higher levels (**Fig. 5.12e**), and ultimately allowing the eruption of the magmas.

The preliminary model described above can account for both the prevalence of ultramafic sills within the upper Thompson and/or Pipe Formations, the presence of gabbroic sills similar to those described in the upper Pipe or Setting Formations on Mystery Lake (**Section 5.2.7**), and the presence of a few large ultramafic sills in the upper parts of the Ospwagan stratigraphy. It also predicts that there could have been more mafic intrusive activity in the upper parts of the Ospwagan Group than is currently observed, particularly above some of the larger ultramafic sills.

The intrusion of sills within or at the upper contacts of denser layers of the stratigraphy has great significance for the metallogeny of the magmatic Ni-Cu-(PGE) ores because the majority of the sulfide-facies iron-formations and sulfide-rich layers of the Pipe Formation are closely associated with dense silicate facies iron formations, which will act as density filters for ascending magmas. If the ultramafic bodies were preferentially emplaced along these horizons, then they would have been predisposed to interaction with the sulfide-bearing units, leading to the interaction of the magmas with an external source of sulfur and the production of ores.

5.5 Mafic Sills

It is clear that the Bah Lake assemblage contains a much higher proportion of mafic intrusions (dykes and sills) than was previously recognised. This is most evident in the Soab – Bah Lake region along the old Soab rail bed, along the western shoreline of the Grass River, and along the eastern part of Setting Lake, where sills either dominate or form a significant portion of the Bah Lake assemblage.

Several of the largest known mafic and mafic-ultramafic dykes and sills in the northern part of the TNB were investigated during this project. The aim of these investigations was to determine their relative ages using both field observations and U-Pb geochronology (**Section 10.2**) and to establish geochemical affinities (if any) with the Bah Lake assemblage volcanic rocks, the 1.88 Ga Molson dyke swarm (Heaman et al., 1986), and the 1.88 Ga TNB ultramafic sills (Hulbert & Hamilton, unpubl. U-Pb age, Setting Lake ultramafic body). The intrusions studied include (from north to south):

1) A layered peridotite-pyroxenite-gabbro intrusion (Grass River intrusion) that occupies part of the Grass River lineament along the Grass River,
2) Multiple, boudinaged m- to dm-wide gabbroic intrusions within the Soab North Mine - Joey Lake area,
3) A poorly exposed mafic intrusion along the Taylor River (Taylor River intrusion) immediately to the west of Ospwagan Lake,
4) A layered gabbroic intrusion containing plagioclase megacrysts (Bah Lake intrusion) and exposed in the Bah Lake area , and
5) A broadly conformable layered gabbroic sill (South Pit intrusion) at the Thompson Mine South Pit (Kraus et al., 1998).

5.5.1 Grass River Intrusion

The Grass River intrusion is the best preserved and, we believe, one of the largest intrusions in the TNB. It occupies or is proximal to the Grass River lineament, a complex high strain zone that defines or is adjacent to the Archean-Proterozoic boundary along the east side of the TNB between Pisew Falls in the south and the northwestern part of Paint Lake in the north. The Grass River intrusion, based on drill core and surface outcrop data, comprises a series of dm- to km-long, NNE-trending ultramafic boudins that are closely associated with remnants of layered mafic-ultramafic rocks (pyroxenite-peridotite±gabbro) as seen in drill core and in narrow outcrops along the western shoreline of the Grass River near the entrance to Phillips Lake. Field observations in the Phillips Lake area suggest that the exposed layered mafic-ultramafic rocks were emplaced into adjacent mafic volcanic rocks (a probable chilled margin against the basalts was observed at one location). Provided that the volcanic rocks in this area are younger than the Ospwagan Group metasedimentary units, the Grass River intrusion post-dates the Ospwagan Group sedimentary sequences and at least part of the Bah Lake assemblage. Unfortunately, geochronological sampling of the Grass River intrusion did not provide suitable material for U-Pb dating (**Table 10.1**; **Section 10.2**). The Grass River intrusion is one of the largest and most primitive of a few NNE-trending, dyke-like mafic-ultramafic intrusions in the exposed part of the TNB (interestingly, most of these well preserved bodies occur in high strain zones along the eastern or western boundaries of the TNB or in the central part of the TNB). It also appears to contain the highest proportion of gabbro and pyroxenite of the studied TNB ultramafic sills. Initially, this intrusion was interpreted to represent a dyke-like body (e.g., Peck et al., 1998), but drill core data suggests that the ultramafic component of the intrusion, which underlies the Grass River in the Phillips Lake area, may have locally intruded into metasedimentary rocks of the Ospwagan Group.

5.5.2 Soab Intrusion

The Soab intrusion (also colloquially referred to as "Jay's dyke"), a ~50-100 m-thick layered gabbroic to peridotitic body, is exposed on a road cut on Highway 6 immediately to the north of the Soab North deposit and along Soab Creek near its eastern terminus at the Grass River. It is in contact with pebbly to massive quartzites and fine-grained basalt. Despite the apparent lack of deformation in the Highway 6 road cut exposure of the Soab intrusion (Peck et al., 1998), immediately to the west of this road cut, the intrusion is strongly folded (interpreted to be the result of F_3 folding) and boudinaged. These observations highlight the extremely variable effects of deformation on the TNB ultramafic-mafic intrusions, and the need for caution when interpreting primary characteristics of these bodies.

5.5.3 Taylor River Intrusion

The Taylor River intrusion is exposed in shoreline outcrops along the Taylor River and may also extend northward into the western part of Lower Ospwagan Lake. It comprises massive and locally well layered medium- to coarse-grained gabbro. Primary contacts with adjacent metasedimentary units have not been observed.

5.5.4 Bah Lake Intrusion

The Bah Lake intrusion is several tens of metres wide and comprises a medium- to coarse-grained leucogabbro to melagabbro layers, many of which contain abundant plagioclase megacrysts (Peck et al., 1998). Sedimentary-type layering structures are locally present in this intrusion. The Bah Lake intrusion appears to be one of several NNE-trending megacrystic gabbro bodies in the Setting Lake area. Similar intrusions are exposed along the eastern shoreline of Setting Lake.

5.5.5 Thompson Mine (South Pit) Intrusion

In the Thompson Mine South Pit, a ~50 m-wide gabbroic to dioritic intrusion is exposed on the west side of the open pit. This intrusion has been dated at 1855+/-13 Ma (Bleeker and Hamilton, 2001; **Section 10.2.4**). Mapping by Kraus et al. (1998) indicates that the South Pit intrusion is compositionally layered on a cm to dm scale, and comprises an upper and lower hybrid marginal sequence, a thin rhythmically-layered gabbro zone, and a thick, massive garnetiferous leucodiorite zone. The intrusion appears to have been emplaced along an angular unconformity between the basal member of the Manasan Formation (quartzitic conglomerate) and Archean basement rocks (tonalitic orthogneiss). It is probably part of a much larger gabbro intrusion that is weakly discordant to the Ospwagan Group stratigraphy and cuts up stratigraphy from the T1 to T3 pits on the southeast end of the Thompson structure. Thus, the intrusion is essentially a dyke, but on an outcrop scale it appears to be a sill. Herein lies a major difficulty in the study of mafic and ultramafic intrusions in the TNB. Most of the intrusions emplaced into the Ospwagan Group would have had a strong tendency to form sills owing to the fissility of the host rocks and the presence of low melting point argillaceous sediments (pelites), particularly within the Pipe Formation. As noted above, residual mafic magmas generated within predominantly ultramafic magma chambers in the Ospwagan Group may have had a strong buoyant force that allowed them to ascend to higher crustal levels to form dykes, sills or lava sequences (**Section 5.4.5.2**). It is therefore logical to assume that the general paucity of mafic rocks in direct contact with the TNB ultramafic sills may largely reflect the depth of emplacement, such that whatever mafic residual magmas were generated escaped to higher crustal levels. Although the most likely repository for these mafic magmas in the TNB would appear to be the Bah Lake assemblage, the lithophile and chalcophile trace element compositions argue against a direct relationship between the Bah Lake assemblage and the ultramafic sills (**Section 8.4.4**).

5.5.6 Other Intrusions

Recent drilling by Falconbridge Ltd. and HBED in the William Lake area intersected several differentiated ultramafic-mafic bodies in the Pipe Formation that contain significant volumes of gabbro, melanogabbro, and pyroxenite in addition to abundant peridotite. Differentiated ultramafic-mafic sills are fairly common in the Cape Smith and Fox River Belts. We have considered the possibility that differentiated mafic-ultramafic sills may have originally been more abundant in the TNB, but that the mafic and ultramafic portions of the intrusions may have become separated owing to different rheological responses during the more prolonged and complex deformation in the TNB. Although possible, it is worth noting that the differentiated mafic-ultramafic sills in the CSB (and probably also the FRB) were probably derived from petrogenetically more evolved magmas than the ultramafic sills in the TNB or the ultramafic lava channels in the CSB. As discussed in **Section 5.4.5.2**, the difference in the composition of the sills in the different areas most likely relates to the relative bouyancy of the magma during emplacement and timing of sill emplacement relative to sedimentation and rifting, which would have influenced the ability of the crust in the different areas to filter mafic-ultramafic magmas.

Thin gabbroic bodies exposed in the Joey Lake – Soab region of the central part of the TNB are interpreted to represent remnants of originally metre-sized sills and/or dykes. They occur in small sand and gravel pits along the old Soab Mine – Pipe Mine railbed and along Highway 6, and form boudins enveloped primarily by metasedimentary rocks that are believed to be correlative with the Manasan and Pipe Formations. In a few places, these rocks account for over 80% of the outcrop, but more typically they represent <20% of a given area of outcrop. Some of the bodies may represent basalt (as discussed above), but most of the gabbroic rocks in the area preserve chilled intrusive contacts and/or are discordant to the original sedimentary bedding structures in the host rocks.

5.6 Stratigraphic Interpretations

5.6.1 Basin Evolution

The sediments and igneous rocks of the TNB have been interpreted to have been deposited in a rift that evolved through an initial period of continental thinning and passive rifting, during which the sediments of the Ospwagan Group were deposited, and a subsequent by period of active rifting (emplacement of ultramafic sills) and the development of some immature oceanic-type crust (emplacement of the Bah Lake assemblage) (Bleeker, 1990a, Bleeker & Macek, 1996). A similar interpretation has been proposed for other parts of the Circum-Superior Belt including the Fox River Belt (Baragar and Scoates, 1987) and the Cape Smith Belt (St. Onge et al., 1989; St-Onge & Lucas, 1993).

Although such an interpretation explains the geological relationships on a regional scale (~300-400 km) and provides a broad view of the evolving rift basin, intense deformation and metamorphism hamper interpretations at the local and mine scale (<100 m) that are required in production and exploration. Subsidence and topography can vary markedly on a local scale, which can have a marked influence on the distribution and types of sediment and the localization of structures that act as loci or conduits for fluid or magma/lava flow. In the case of the intrusive komatiite-associated Ni-Cu-(PGE) deposits in the TNB, early structures may have localized the accumulation of S-rich iron-formation and later structures may have facilitated intrusion of the host magmas along the iron-formations. In the case of the extrusive komatiite-associated Ni-Cu-(PGE) deposits in the CSB, early structures may have localized the accumulation of more S-rich facies of the upper Povungnituk Group *and* the emplacement of the host lava channels onto those rocks. Clearly, local tectonic controls on lava channels, magma conduits, and sulfur distribution may have had an important impact on the formation of the ore deposits.

The Ospwagan Group is largely *in situ* above an unconformity on the Archean basement gneiss and formations and members in the Ospwagan Group have a remarkable continuity consistent with platform or passive-margin successions. Whereas this arrangement of sediments suggests deposition in a large, shallow depression, and argues for little topography, the form and geometry of the rift are not well defined. The basal quartzite member (Om1) of the Manasan Formation formed a sand blanket with only local pebbles at the base; the sediments are relatively mature, suggesting they were transported a considerable distance from their source, and the taper of the whole formation is low, implying that the depression into which the sediments were deposited had to be large enough for a significant degree of sediment sorting to occur and/or the extent of uplift at the margins had to be low enough to not result in the production of a significant coarse clastic component. Although details of the shape of the basin are unknown and the details of the marginal control structures are undefined, we interpret the region to have been an extensive shallow depression. We do not know if it was 50 km wide or 500 km wide, but given the inferred tectonic setting, we assume that it was an essentially linear depression with controlling structures to the east and west of the present belt.

Useful comparisons can be made with the Red Sea, which is an excellent example of a linear rift, and with the Gulf of California, which is a good example of a transcurrent rift. The Red Sea has developed as a linear rift, with some transform offsets, within the Afro-Arabian Dome, a larger region of uplift (Almond, 1986). The relief and topography along its margins are quite limited. For example, at the base of the Middle Tertiary stratigraphy of the coastal plain there is a thin sheet of bedded sandstones and pebble conglomerates that is not dissimilar to the Manasan Formation and has been interpreted to have been derived from a low altitude, low relief Precambrian surface (Schmidt et al., 1983). Such a surface would be 1) consistent with development over thinning ductile lithosphere, and 2) may have interdigitated lacustrine environments as an initial phase of sedimentation. Subsequent inundation by the sea depends upon continued subsidence or sea level rise. Condie et al. (2000) argue that because shallow marine intracratonic sedimentary rocks are common in the Proterozoic, by inference, sea level was also high. Basal sedimentation along the Red Sea coastal plane consists of sands and gravels, extends almost the entire length of the sea, but is only 40-50 km wide. Relief in this region is less than 200 m and sedimentation is quite uniform. Subtle variations do occur along the length of the sea and are controlled by transform faults. It is possible that the region developed in a linear rift offset by transform faults in a transcurrent setting, like the Gulf of California, but this seems less likely. In this environment local depocenters develop adjacent to growth faults within a larger basin (cf. Einsele, 1986), which are associated with significant coarse conglomerate components. Such regions are also surrounded by significant high relief and high altitude topography.

Because coarse conglomerates are not abundant in the Ospwagan Group and because the stratigraphy seems so consistent on the regional scale, we infer that the basin was more likely to have been generated in a rift setting (e.g., Red Sea) than in a transcurrent setting (e.g., Gulf of California).

The upward-fining semi-pelites and pelites of Om2 are thin (<100 m) and represent a marine transgression at a low subsidence rate, typical of a passive margin (drift stage) or platform. Water depths need not have been great and the absence of any coarse clastic debris is consistent with a low-energy environment and a lack of any significant relief. The Thompson Formation, including the “skarns”, comprises argillaceous and pure carbonates, which were probably not much thicker than 50 m. However, there can be significant variations in the thickness of these units. It is possible that some of the variations may represent original facies variations, perhaps influenced by topography during sedimentation, but it is clear that most of the variations represent tectonic thickening and attenuation (see above). If the Ot unit was originally laterally extensive, then this would be consistent with deposition on a stable platform that was distant from a source of detritus or bypassed by detritus. This also points to a largely protected low energy environment. If there is some degree of lateral variation to the sequence, then there may have been some local variability in terms of water chemistry or depositional setting.

The Pipe Formation comprises a series of upward-fining sequences from siliciclastic to chemical sedimentary rocks (Op1 to Op3). Fragmentation, imbrication, and reworking of silicic fragments suggest deposition on a slope and repeated grading within successive layers suggests periodic slope instability. There is also sporadic incorporation of aphyric dark glassy fragments, which suggests there may have been some nearby volcanic activity. As noted above (**Section 5.3**), the Pipe Formation appears to be divisible into an eastern belt that extends from Thompson Pit to Setting Lake and is interpreted to thicken south from 500 to 900 m, and another thick belt (“Pipe band”) that lies to the northwest. Although these variations may be within the range of structural thickening, it is plausible that subsidence increased to the west (see caption to **Fig. 5.2**). There appears to be northwest fining in Op from more quartzitic turbidite beds (mainly in Op3) to more pelite, chert, and silicate-facies iron-formation (with an aluminous detrital component) and distally, with oxide-facies iron formation. If the rocks are para-autochthonous, which seems at least possible (if not likely), then these interpreted changes in facies and thickness suggest a northwest direction of sediment transport (**Fig. 5.4**; **Section 6.6.1**).

Most Archean and Proterozoic iron-formations are believed to have been generated by hydrothermal exhalation and/or leaching of silicate and iron from mafic volcanic rocks, with iron being precipitated by periodic mixing with oxygenated waters (see below), so the banded oxide- and sulfide-ironstones and siliceous metasediments in the Pipe Formation suggest some kind of volcanic or hydrothermal influence. Volcanic rocks are not known at this stratigraphic level, unless the emplacement of some of the ultramafic bodies occurred at this time and produced extrusive volcanic rocks that have subsequently been eroded or tectonically displaced (see discussion in **Section 8.8.2**). It is not clear whether local volcanic or hydrothermal activity on a nearby slope could contribute enough silica and iron via exhalation and hydrothermal leaching; the iron-formations in the Pipe Formation are regionally-extensive, but they are not as thick as their counterparts in the Sokoman Iron-Formation in the Labrador Trough, so this seems possible. Although there are many areas where the deposition of these layers has gone on essentially undisturbed, the presence of intraformational breccia layers in sulfide-rich rocks that must have formed below wave base indicates periodic tectonic disturbances and/or shelf instabilities as the rift margin subsided. The change from sulfide-facies to other iron formations, upward and northwest, may represent a change from locally stagnant to more open marine conditions, possibly as the platform tilted and foundered. Some of the calcareous rocks, such as the banded diopside rock at the top of Op3 (Bleeker, 1990a), may represent re-sedimented carbonate from the eroding platform to the southeast.

The scale and distribution of hydrothermal activity can be important in exploration. Although the iron-formations in the Pipe Formation *appear* to be laterally extensive and to have not been deposited around local vents, volcanic mounds and hydrothermal fields within axial rifts are of the order of a few hundred meters in size (cf. Gracia et al., 1998; Hawkins, 1995), which is smaller than the typical distance between exploration drill holes, and may occur over regions of hydrothermal activity that can be traced for 10-15 km (cf. Gracia et al., 1998; Gamble and Wright, 1995). Volcanic mounds are usually surrounded by talus and other mass-wasting features as well as "brine" pools where there is relatively undisturbed (chemical?) sedimentation. Although the intense deformation experienced by the rocks in the TNB makes it difficult to determine the original distribution of sulfidic sediments, some of the larger sulfide deposits may represent areas where sulfides preferentially accumulated.

The sudden influx of sandy quartzose sediment, deposited as turbidite of the Setting Formation (member Os1), indicates uplift of the source, more rapid subsidence in the TNB, and the creation of a significantly deeper basin. The local upward coarsening to conglomeratic or pebbly beds (Os2) represents the least mature and first truly syn-orogenic sediments. Because none of the ultramafic bodies lies above the middle of Os1 and they are cut by the dykes from the younger, mafic stage(s) of magmatism, the onset of subsidence is interpreted to have been accompanied by ultramafic magmatism. Consequently, Os1 deposition can be interpreted to correspond to a phase of renewed, more active rifting in a marine environment during the onset of abundant magmatism in the TNB and the Ni-Cu-(PGE) mineralization in the TNB to be associated with this pulse of komatiitic magmatism.

The basaltic rocks of the Bah Lake assemblage (unit Ob) resemble a rift-drift sequence formed during separation of Archean crust northwest of the TNB, analogous to the Chukotat Formation in the Cape Smith Belt (St-Onge & Lucas, 1993). They are consistent with deposition near a marine escarpment at a normal fault and magma feeder system, suggesting that a mature, possibly symmetrical rift basin had formed. As noted above, these structures were probably overturned and reactivated as the Setting Lake fault during subsequent deformation. The slightly evolved basalts of the Fish Lake amphibolites to the west may be a remnant of an outboard ocean basin floor (drift sequence), presently underlain by an allochthonous Burntwood Group substrate. The thin chert and calc-silicate rocks on August Lake may represent ocean-floor sediments.

The Ospwagan Group is very similar to, although much thinner than the Lower Paleozoic continental terrace wedge that lies outboard of the carbonate platform of the southern Canadian Cordillera (Zwanzig, 1973 and references therein). It is also similar to the

Proterozoic Svecokarelian sediments associated with the Outokumpu Cu-Ni deposit in central Finland (Koistinen, 1981), which comprises a sequence (from base to top) of: quartzite and dolomitic limestone, sulfide-rich shale, ferruginous and calcareous phyllites with ultramafic sheets and cherty argillite, and quartz wacke and mafic volcanic rocks. The presence of iron-formation in the Paleoproterozoic Ospwagan Group is presumably related to differences in the ancient seawater chemistry (fO_2, fCO_2, fS_2, aFe^{2+}, aSi) influenced by volcanic and or hydrothermal activity, atmospheric chemistry, and life forms. Most workers believe that banded iron-formations formed by upwelling of deep, anoxic ocean waters that carried hydrothermally-derived Fe^{2+} and Si onto continental shelves where they mixed with cooler, more oxidized waters (Klein and Beukes, 1992) and it has been proposed that these fluids may have originated in an ocean ridge system or oceanic plateau (Isley, 1995). The physical and chemical details of the hydrothermal vent sites described in the literature vary, but the sedimentary assemblages and therefore fluid chemistries are broadly similar. The degree of recrystallization and metamorphism varies considerably, but most banded iron-formation sections appear to have contained amorphous silica (preserved as chert), Fe-hydroxides and sulfides (preserved as hematite, magnetite, or pyrite/pyrrhotite), Fe-carbonates (preserved as siderite or ankerite, often with significant Mn), and Fe-Mg silicates (preserved as chamosite, greenalite, and minnesotite). Many sequences contain volcaniclastic (pyroclastic or epiclastic) horizons or Al-rich components such as chlorite or stilpnomelane that indicate the presence of an aluminous component. The metamorphic equivalents of these lithologies occur the Pipe Pit section. All present day hydrothermal fields are connected with active magmatism and tectonism, which may remain cyclically active over a period of a few hundred thousand years.

The Grass River Group in the Setting Lake area likely represents the earliest record of collisional tectonics along the Superior boundary zone. This group comprises a lower, upward fining succession of metamorphosed coarse fluvial-alluvial sandstone and conglomerate and an overlying upward coarsening arkosic arenite to felsic tuffaceous sandstone (Zwanzig, 1997, 1998). Gravelly cross bedding, 'floating' pebbles in sandstone, ripped-up shale drapes and upward fining groups of beds indicate alluvial, fluvial, and sheet-flood deposition (**Fig. 5.5**). Fining and sediment transport in the coarse lower units (Gc, Gh) that contain mafic and chert clasts was to the north. Their hornblende content and slightly more mafic composition is probably related to the erosion of their basaltic substrate. Detrital zircon spectra indicate a juvenile Paleoproterozoic source (i.e., the approaching internal zone of Trans-Hudson Orogen, as yet, lying outboard of the TNB). The units form short, thick sequences, with high northward taper, and were probably deposited near syn-depositional faults. The upper formations (units Gb, Gs and Gs2) thicken considerably to the west. They have the felsic composition and probable component of tuff and intercalated rhyolite that suggest an affinity with the late successor arc in the Flin Flon and southern Kisseynew domains. The preliminary detrital zircon spectrum (**Section 10.3.2.2**) is consistent with the age of the correlative Missi Group and indicates coeval deposition and emplacement of the 1836 Ma Bucko quartz monzonite during closure of the basin that separated the internal zone of the Trans-Hudson Orogen and the Superior craton. Abundant, large-scale cross bedding and magnetite placers in unit Gs indicate continued subaerial deposition. Little sediment onlap occurred; the TNB probably stood high, but had a mafic volcanic cover that supplied no detrital zircons.

5.6.2 Stratigraphic Relationships Between Mafic and Ultramafic Rocks in the TNB

The previous interpretation that the ultramafic sills in the Ospwagan Group acted as feeders for the Bah Lake (previously Ospwagan Formation) mafic rocks (Peredery, 1979; Bleeker, 1990b) is not supported by the geochemical data generated in this study (**Sections 8.4**, **8.5** and **8.8.2**). Although there are a few crustally-contaminated and chalcophile element-depleted rocks in the Bah Lake assemblage and a few crustally uncontaminated and chalcophile-element unenriched rocks in the ultramafic sills (**Section 8.4.4**), the majority of the rocks in the Bah Lake assemblage are uncontaminated and undepleted in chalcophile elements (**Section 8.5.2**), which means that they could not have been derived from the crustally-contaminated and locally mineralized residues represented by the ultramafic sills. Although many elements have been mobile during metamorphism, our detailed studies of element mobility indicate that the key elements on which these characteristics are defined (Th, Nb, Ni, and Ir) have not been systematically mobilized in either the Bah Lake mafic rocks or the ultramafic sills.

We have considered the possibility that the ultramafic sills may have originally contained greater abundances of mafic components and that the mafic and ultramafic portions became separated owing to different rheological responses during the prolonged and complex deformation in the TNB, but this would require the contaminated, chalcophile-element depleted product of the ultramafic sills to have been separated from the rest of the Bah Lake. It seems that the only way that the ultramafic sills could have acted as feeders for the Bah Lake volcanic rocks is if the Bah Lake magmas passed through them without forming a cumulate component and if the sills were subsequently filled with cumulate rocks for which no volcanic product was preserved, which makes the relationship irrelevant.

The lack of any petrogenetic relationship between the ultramafic sills and the Bah Lake assemblage is consistent with the observed stratigraphic relationships. As noted above, the ultramafic sills have not been identified at any levels higher than the lower member (Os1) of the Setting Formation. It is unlikely that this reflects the level of neutral buoyancy for the ultramafic magma, because some ultramafic magmas were able to erupt through the Setting Formation to form the Bah Lake assemblage. Thus, it seems likely that the ultramafic sills were emplaced during deposition of Os1 and that they therefore predate emplacement of the volcanic component of the Bah Lake assemblage. Because the geochemical characteristics of the intrusive components of the Bah Lake assemblage are consistent with them being related to the volcanic components of the Bah Lake assemblage, but not with the ultramafic sills, it seems likely that the ultramafic sills also predate emplacement of the intrusive component of the Bah Lake assemblage. Thus, the ultramafic intrusions (and associated Ni-Cu-(PGE) mineralization) in the Ospwagan Group may represent an early pulse of voluminous komatiitic magmatism that was selectively intruded into the lower part of the sequence and became contaminated via interaction with pelites and iron-formations, whereas the Bah Lake assemblage may represent a later pulse of less voluminous komatiitic and tholeiitic magmatism that was intruded and extruded at higher levels. Alternatively, the ultramafic components of the Bah Lake assemblage may represent the *parental* magmas to the sills: magmas that were not ponded in the sedimentary sequence. In any case, the absolute ages of the contaminated, mineralized ultramafic sills in the Ospwagan Group and the mafic-ultramafic lavas, sills, and dikes in the Bah Lake assemblage are not well constrained, so any interpretation of the relative timing of their emplacement remains speculative.

Regardless of the timing of emplacement, there is still the problem of where the voluminous, crustally contaminated, and chalcophile element-depleted komatiitic lavas from which the ultramafic sills crystallized were erupted. If the Bah Lake assemblage was deposited autochthonously on top of the Setting Formation and if it is broadly in place, as argued above, then the only possibility is that they were erupted elsewhere in the basin, in or out of the current section (as discussed in **Section 8.8.2**).

5.6.3 Molson Dyke Event

Another important interpretation arising from our studies of the Bah Lake assemblage and associated mafic-ultramafic sills and dykes is the concept of coeval and co-magmatic "Molson" and TNB magmatism. For example, the Grass River intrusion shares many gross similarities to the Cuthbert Lake dyke located 40 km east of the TNB in the Superior Province (Paktunç, 1987) and to weakly differentiated intrusions in the Fox River Belt to the north (Scoates, 1990). Recent field observations on the western shoreline of Cuthbert Lake indicate that the Cuthbert Lake dyke also has a mafic marginal zone that is subordinate to the core peridotite body exposed in the central part of the lake. Recent geochemical studies undertaken by Falconbridge Ltd., the Manitoba Geological Survey, the Geological Survey of Canada, and the University of Manitoba in the Fox River Belt indicate that many of the so-called Lower Differentiated Intrusions (Scoates, 1990) bear a remarkable petrological similarity to the Cuthbert Lake dyke and the Grass River intrusion in terms of the range and proportions of major rock types and arrangement of rock types. All of these intrusions have olivine-rich cores (dunite to peridotite) and marginal units of websterite or orthopyroxenite that locally grade to gabbronorite or norite, all occur in the Superior Boundary Zone, and all are known or inferred to have been emplaced at 1.88 Ga:

1) The Lower Differentiated Intrusions in the Fox River Belt are assumed to be coeval with the 1.88 Ga Fox River Sill (Heaman et al, 1986).
2) The Setting Lake ultramafic body in the TNB has an U-Pb age of 1.88 Ga (L. Hulbert and M. Hamilton, unpubl. data, 1998).
3) The main suite of mafic dykes in the Superior Boundary Zone appears to belong to the 1.88 Ga Molson swarm (Heaman et al., 1986; Toope et al., 2000).

The weight of evidence therefore suggests that the "Molson dyke event" generated most (but not all) of the ultramafic and mafic rocks in the Superior Boundary Zone, including those in the TNB. However, because of the known diversity in mafic rock geochemistry in the TNB and the existence of multiple dyke generations in proximal parts of the northwestern Superior Province (e.g., Heaman et al., 1986), it strongly recommend that future workers abandon the recent trend toward naming all dykes in the TNB "Molson" dykes. Likewise, any future attempts to use mafic dykes as a means for relative dating of TNB structural events must accompanied by high precision geochronology. This is a daunting task given the difficulties encountered by CAMIRO researchers in obtaining primary age dates for these rocks, but is essential in terms of constraining the geological relationships in such a complex environment.