

CHAPTER 7 METAMORPHISM

7.1 Introduction

The Archean gneisses in the Pikwitonei domain east of the TNB record a complex polyphase metamorphic history that culminated in Kenoran granulite-grade metamorphism, with P-T estimates for the peak of metamorphism in the range 700-850° C and 8.9-9.5 kbar (Paktunç and Baer, 1986). As the eastern margin of the TNB is approached, however, the granulite facies assemblages and E-W trending structures of the Pikwitonei show progressive overprinting by amphibolite facies assemblages and NE-SW trending structures that record deformation and metamorphism of both the basement and Ospwagan supracrustal rocks during the Trans-Hudson Orogeny (Hubregtse, 1980; Bleeker, 1990b; Fueten, 1990).

The Hudsonian metamorphism in the exposed TNB is characterized by a single, albeit complex P-T loop, with peak metamorphic conditions ranging from lower to upper amphibolite facies. In the region between Pipe II pit and Mystery Lake, lower grade mineral assemblages (muscovite + quartz \pm staurolite) are generally preserved in the core of the TNB, whereas higher-grade assemblages (sillimanite + garnet + K-feldspar) are preserved on the margins (**Fig. 7.1**). Garnet-biotite thermometry on metapelites in this region indicates that temperatures were ~530-635°C in the Ospwagan Lake and Pipe pit areas in the core of the TNB, ~680-735°C in the eastern Kisseynew and Birchtree areas along the western margin of the TNB, and ~740-780°C in the Thompson area along the eastern margin of the TNB (**Fig. 7.1**). Metamorphic pressures in the same area have been estimated to be between 5 and 7 kbar (Bleeker, 1990).

Because the metamorphism affected the compositions and textures of almost all rocks in the region, it is integral to the discussion of the stratigraphy, structure, and geochronology of the belt. As a consequence, virtually all of the various elements of this project included a metamorphic component and most of the new observations regarding the influence of metamorphism on the rocks of the TNB are included, along with their implications, in the other sections of this report (**Chapters 5, 6, 10 and 11**), rather than being compiled as a separate chapter. However, owing to the importance of geochemical studies of the TNB ultramafic bodies in the construction of petrogenetic and metallogenic models for the belt, and the potential mobility of elements during metamorphic processes, a detailed study of the effects of metamorphism on TNB ultramafic bodies was undertaken as part of a MSc project carried out by D. Layton-Matthews, the results of which are summarised in this chapter.

7.2 Ultramafic Rocks

7.2.1 Introduction

Most magmatic Ni-Cu-(PGE)-sulfide deposits are interpreted to have formed from sulfide-undersaturated mafic or ultramafic magmas by the incorporation of crustal S via melting or devolatilization of the adjacent country rock, resulting in sulfide-saturation and the formation of an immiscible sulfide liquid (e.g., Leshar, 1989; Naldrett, 1989, 1999; Keays, 1995). As a result of such processes and the distinctive, yet complimentary, compositions of magmas derived by mantle melting relative to typical continental crustal rocks, the host rocks of many magmatic Ni-Cu-(PGE) sulfide deposits exhibit major and trace element compositions that

are indicative of magma-crust interaction (in particular, enrichment in LREE and selected highly incompatible high-field strength elements, e.g., Th, and U: Leshner et al., 1999, 2001). Because 1) most of the ultramafic bodies in the TNB have undergone variable degrees of metasomatism and/or regional metamorphism that may have modified their primary igneous chemical compositions, and 2) previous studies of the trace element compositions of the TNB ultramafic bodies have indicated that many of the elements most commonly used for the recognition of crustal assimilation associated with mineralization may have been mobile during alteration (Burnham et al., 1998), the effects of metamorphism on the major and trace element compositions of the ultramafic bodies were investigated in detail prior to their use in the petrogenetic and metallogenic models presented in later chapters of this report.

7.2.2 Alteration

The rocks in the Thompson Nickel Belt have experienced variable degrees of post-magmatic deuteric alteration and/or regional metamorphic alteration. As discussed by Leshner and Stone (1996), high field-strength elements (HFSE: HREE³⁺, Y³⁺, Zr⁴⁺, Hf⁴⁺, Nb⁵⁺, Ta⁵⁺, and Th⁴⁺), which have high charges and small ionic radii, are normally immobile, because they do not form stable complexes with the larger, lower-charged ligands (e.g., OH⁻, CO₃²⁻, HS⁻, Cl⁻) that dominate most hydrothermal and metamorphic fluids and because they are normally housed in alteration-resistant accessory phases. Transition metals (Ti⁴⁺, Sc³⁺, V³⁺, Cr³⁺/Cr²⁺, Mn²⁺, Fe³⁺/Fe²⁺, Mg²⁺, Co²⁺, Ni²⁺) are commonly relatively immobile because they are housed in relict igneous phases such as chromite, olivine, and pyroxene and/or are readily accommodated in metamorphic ferromagnesian minerals such as amphibole and chlorite. Calc-alkalic elements (Ca²⁺, Sr²⁺, Ba²⁺; also Eu²⁺) may be relatively stable in clinopyroxenites, but are normally systematically depleted in orthopyroxenites, peridotites, and dunites, as they are not accommodated in serpentine, and may be enriched in carbonated or rodingitized rocks. Alkali elements (Cs⁺, Rb⁺, K⁺, Na⁺) are systematically depleted in pyroxenites, peridotites, and dunites, but Na may be enriched during spilitization of glassy or plagioclase-bearing rocks and K-Rb-Cs may be enriched during alkali metasomatism of rocks intruded by granitoids. Silica is mobile to varying degrees, especially in pervasively serpentinized and carbonated peridotites and dunites. Cu, Zn, Au, and Pd-group PGE (PPGE: Pt, Pd, Rh), which are housed primarily in sulfides and discrete minerals, may be mobile to varying degrees (generally Au > Cu > Zn > PPGE), whereas Ir-group PGE (IPGE: Ru, Ir, Os) are potentially less mobile, as they are also housed in alloys, chromite, and olivine. Sulfur is mobile, but Se appears to be somewhat less mobile.

The best way to evaluate whether a particular element has been mobile is to compare how it varies with other elements of similar geochemical affinity in a known system. For example, in a series of rocks where petrographic data indicate that they are related only by olivine fractionation or accumulation (see below), all elements should define trends that extrapolate to the composition of olivine on MgO variation diagrams (see **Chapter 8**). Departures from such trends indicate mobility and/or the involvement of other phases or processes. Distinguishing inherently complex and/or variable geochemical processes from alteration is difficult and it is commonly necessary to integrate geochemical and volcanological relationships to make an interpretation (Barnes et al., 1995; Leshner and Arndt, 1995).

How the mobilization of a few elements will influence the geochemical trends of the remaining elements depends on the abundances of the elements involved, their geochemical

affinities, and the type of geochemical plot. Removal or addition of trace elements will not significantly affect the absolute abundances of other elements, but because of closure effects (Chayes, 1949), addition or removal of major elements will significantly dilute or concentrate the abundances of other elements. For this reason, whole-rock geochemical analyses of mafic-ultramafic rocks, many of which are assumed to have originally contained negligible H₂O or CO₂, are normally recalculated volatile-free to 100%. Ratio plots utilizing common denominators (Pearce, 1968) have been used to evaluate elemental mobility in komatiites (Beswick, 1982; 1983; Beswick and Soucie, 1978) and to test petrogenetic processes in these and other systems (Russell and Stanley, 1990; Stanley and Madiesky, 1993). Several authors have noted that such diagrams tend to enhance or generate spurious statistical correlations related to closure (Butler, 1986; Rollinson and Roberts, 1986), but this is only a problem if the denominator has a coefficient of variation larger than that of the numerator. If used carefully, such diagrams may enhance and facilitate discrimination of some petrogenetic processes. However, from an exploration standpoint, if a petrogenetic process is not evident on simple bivariate plots, it is probably irrelevant.

Different elements may be mobile on different scales. For example, olivine, which contains negligible Al, is sometimes pseudomorphed by chlorite, which contains Al, implying that Al, which is normally immobile on the scale of a hand specimen, may be mobile on the scale of a thin section. The enrichment of Ca in the upper, amphibole-rich parts of some differentiated komatiite/peridotite and pyroxenite/peridotite units, indicated by anomalously high Ca/Al and Ca/Ti ratios, and the corresponding depletion of Ca from the lower olivine-rich cumulate zones of the same units, indicated by anomalously low Ca/Al and Ca/Ti ratios, suggests that Ca has been mobile on the scale of an individual unit. The complete loss of Na and K from all parts of individual units indicates that those elements have been mobile on an even larger scale. The point of all this is that each element and each sample must be evaluated separately to determine whether there has been any geochemical mobility.

7.2.3 Petrography

Almost all of the ultramafic rocks in the TNB have been pervasively hydrated, carbonate-altered, and/or K-metasomatized, resulting in significant changes in their mineral assemblages (**Table 7.1**)

Table 7.1 Primary and alteration mineral assemblages present in TNB ultramafic bodies

	Dunite	Protolith Peridotite	Pyroxenite
Igneous	olivine ± pyroxene ± chromite	olivine – pyroxene – chromite	pyroxene ± chromite
Serpentinization	serpentine ± magnetite ± brucite	serpentine – tremolite – chlorite ± magnetite	tremolite – chlorite ± magnetite
K-metasomatism	serpentine ± phlogopite ± magnetite	serpentine – tremolite – phlogopite/biotite ± magnetite	tremolite – biotite – dolomite ± magnetite
Talc-carbonatization	talc – magnesite ± chlorite ± magnetite	talc – magnesite – chlorite ± magnetite	tremolite – chlorite – dolomite ± magnetite

The alteration and metasomatism in the TNB ultramafic bodies appears to have occurred on both a regional and local scale. Whereas regional alteration and metasomatism occurred in

ultramafic bodies throughout the TNB, and appears to have been controlled by regional metamorphism and fluid flow, local alteration and metasomatism are restricted to structural features or the margins of pegmatite veins located within the intrusions or along their contacts.

7.2.3.1 Regional Alteration

Serpentinization

Three

broad textural styles of serpentinization have been identified from petrographic examination of the ultramafic bodies:

- 1) Pseudomorphic pervasive serpentinization
- 2) Non-pseudomorphic pervasive serpentinization
- 3) Fracture-controlled serpentinization

In many cases, all three styles of serpentinization have been identified in a given ultramafic body, with a transition from partial serpentinization through complete pseudomorphic serpentinization to complete non-pseudomorphic serpentinization. Although the relative proportions of the different alteration phases varies with the original proportions of olivine, pyroxene, and trapped melt, the degree of serpentinization does not appear to exhibit any systematic correlation with the size, geographic location, or major element composition of the ultramafic body. Each type is described in more detail below.

Pseudomorphic Pervasive Serpentinization

Pseudomorphic serpentinization of TNB ultramafic bodies is characterized by replacement of primary igneous olivine by fine-grained serpentine and magnetite along grain boundaries and fractures such that the original cumulus olivine grain shapes are preserved (**Fig. 7.2**). During pseudomorphic serpentinization, the serpentine species is dominantly lizardite¹, which forms mesh and rare hourglass textures. Pseudomorphic serpentinization in the TNB ultramafic bodies is similar to the classic mesh textures (Type 3) of Wicks and Whittaker (1977), in which α -lizardite forms serpentine hydration rims at the margins of olivine grains and a penetrative network within the grains. The mesh texture appears to be controlled by hydration along olivine grain boundaries and by fractures within olivine grains and forms textures in which serpentine is oriented perpendicular to the margins of olivine grains or fracture margins. Magnetite is localized along grain boundaries and along fractures.

A very fine-grained mineral with low relief and low birefringence often resides in the inter-pseudomorphic grain boundaries in pseudomorphic serpentinized rocks in the TNB. Although the very fine grain-size of the mineral precluded optical identification or quantitative chemical identification using wavelength-dispersive X-ray emission spectrometry on an electron probe microanalyzer, energy-dispersive X-ray emission spectrometry using a scanning electron microscope indicated that Mg is a major cation and

¹ The identities of the various serpentine polymorphs were established optically on the basis of their textures and optical characteristics (Wicks & Whittaker, 1977). X-ray diffraction techniques are more precise, but much more difficult to implement.

the mineral contains negligible Si. There are several possible identities for this mineral, including magnesite (MgCO_3), brugnatellite ($\text{Mg}_6\text{Fe}(\text{OH})_{13}(\text{CO}_3)(\text{H}_2\text{O})_4$), and pyroaurite ($\text{Mg}_6\text{Fe}_2(\text{OH})_{16}(\text{CO}_3)(\text{H}_2\text{O})_4$). However, based on the discussion in O'Hanley (1996) and the low CO_2 contents of many of these samples, this mineral is tentatively interpreted to be brucite ($\text{Mg}(\text{OH})_2$).

The degree of serpentinization in many ultramafic bodies in the TNB increases outwards from the centres of the ultramafic bodies and the principal control on the degree of serpentinization appears to be proximity to their margins. This is evident in a section through the Mid Lake ultramafic body (DDH 86291), in which relict accumulative olivine is preserved in the core and the degree of serpentinization increases to 100% toward the margins.

Non-Pseudomorphic Pervasive Serpentinization

Non-pseudomorphic textures are characterized by complete recrystallization of serpentine, in which pseudomorphic α -lizardite has recrystallized to elongate interpenetrating needles and blades of antigorite (**Figs. 7.2a and b**). The recrystallization of lizardite to antigorite is generally accompanied by recrystallization of associated magnetite into discrete grains and veinlets that no longer define original olivine grain boundaries.

A group of textures that are transitional between the pseudomorphic and non-pseudomorphic types have been identified in samples with high magnetite or pyroxene contents (or their alteration products) (**Figs. 7.2c and d**). In transitional textures, magnetite normally outlines both the original mineral grains and mesh-textures (**Fig. 7.2d**). These transitional textures appear pseudomorphic in plane-polarized light (i.e., maintain ovoid olivine shapes and pseudo-mesh textures), but under cross-polarized light, hourglass and mesh textures are clearly recrystallized to lizardite \pm antigorite \pm brucite.

Fracture-Controlled Serpentinization

Fracture-controlled serpentinization occurs as veins and veinlets that crosscut all primary and metamorphic mineralogy and fabrics. Multiple generations of oriented antigorite veinlets have been identified in several unaltered to serpentinized ultramafic bodies in the northern TNB (e.g., Brostrom Lake, Spur South, and Mid Lake), in which the antigorite forms blades, branching blades, and massive grains that clearly crosscut primary mineralogy and early serpentine textures (**Figs. 7.3a and b**). Magnetite occurs along vein margins in the late veinlet style of serpentinization.

Pale green to white chrysotile veins occur in several ultramafic bodies in the TNB, most notably in the northern TNB. The veins at Pipe pit appear to be concentrated near the western margin of the ultramafic body and form relatively continuous millimetre- to decimetre-wide vein sets. These veins crosscut all fabrics within the ultramafic body and magnetite is concentrated along vein margins (**Figs. 7.3c and d**). Whittaker and Zussman (1956) showed that serpentinized dunites and harzburgites contain exclusively clinochrysotile veins, whereas serpentinized marbles contain exclusively orthochrysotile. As such, then the chrysotile in the veins at Pipe pit may be clinochrysotile.

Alkali-Carbonate Metasomatism

Many of the ultramafic bodies in the TNB contain alkali-rich hydrous and/or carbonate minerals, consistent with subsolidus interaction of the ultramafic rocks with a CO_2 -bearing,

hydrous, alkalic, LILE-enriched fluid. It is inferred from the overgrowth textures and chemistry of the alteration minerals that this fluid infiltrated the ultramafic bodies during the late stages of metamorphism and alteration.

Alkali Alteration

Because they formed by high-degree partial melting of depleted mantle, most komatiitic rocks have low K contents (<0.9 wt%: Arndt and Nisbet, 1982). Because most of the K is concentrated in the glassy or fine-grained interstitial mesostasis, it is particularly susceptible to loss during low-grade metamorphism (see discussion by Leshner & Stone, 1996). However, K can also be added in significant amounts during mild to moderate metasomatism (Beswick, 1982). Potassic alteration in komatiitic rocks of the TNB is generally expressed as a modal increase in phlogopite (in Mg-rich rocks) or biotite (in more Al- and Fe-rich rocks), which may be present in the form of either subhedral porphyroblasts that cross-cut existing serpentinization fabrics (**Fig. 7.4a**) or fine (<5 μm) biotite-serpentine intergrowths in antigorite porphyroblasts. Importantly, phlogopite is only present in serpentinized rocks and is absent in rocks that contain little or no serpentine (i.e., contain only anhydrous magmatic minerals), indicating that it is not a relict igneous phase and is related to alkali metasomatism.

Carbonate Alteration

Carbonate alteration is present in many of the ultramafic rocks of the TNB and appears to represent the youngest alteration style in the bodies. Unlike the potassic alteration described above, however, it appears to be unrelated to the degree of serpentinization. The dominant carbonate alteration mineral in TNB ultramafic bodies is magnesite, although minor amounts of calcite may also be present. Because calcite and magnesite cannot exist in an equilibrium assemblage (Goldsmith, 1983), it is possible that calcite represents a later alteration phase. At Pipe pit, late cream-coloured magnesite veins crosscut all primary and secondary fabrics, including the late chrysotile veining (**Fig. 7.4b**). In unaltered to partially altered ultramafic lithologies, magnesite commonly forms anhedral grains that crosscut primary olivine and secondary α -lizardite (**Fig. 7.4c**). Talc is commonly associated with magnesite and forms a 'feathery-textured' core to many of the anhedral magnesite grains (**Fig. 7.4d**).

7.2.3.2 Localized Metasomatism

Although it has been recognised that the ultramafic bodies in the TNB have been intruded by numerous pegmatite veins (Coats, 1966; Bliss, 1972; Good, 1985), no systematic studies have been done to determine the effect of these veins on the ultramafic rock compositions. Because serpentine + brucite dehydrate to olivine at temperatures in excess of $\sim 400^\circ\text{C}$ (Spear, 1995), the serpentinization and carbonatization of the ultramafic bodies must represent a low-temperature, post-peak metamorphic processes. In contrast, because the pegmatite veins are interpreted to have formed during near-peak metamorphic conditions (Bleeker, 1990), the metasomatic alteration fronts around the veins may be inferred to be high temperature metasomatic features. In order to study the effects of pegmatite emplacement on the compositions of the ultramafic bodies, samples of veins and their wall-rocks were taken from surface outcrops and diamond drill core from UM bodies in both the northern and central regions of the TNB, including those in the William Lake W-56 body (DDH WL96-166 and WL97-179), Brostrom Lake area (DDH 89239), Birchtree area (DDH 86288), and Pipe pit area.

The geochemical and petrographic data indicate a clear link between mineralogy and metasomatism, and exhibit systematic geochemical trends that are independent of the degree of serpentinization of the ultramafic rocks, but coincide with well-defined mineral reaction zones. Metasomatic alteration zones grade from a biotite-chlorite zone near the pegmatite margin through anthophyllite-gedrite and tremolite zones, to a talc-carbonate zone near the UM contact (**Figs. 7.5 and 7.6**).

Biotite-Chlorite Zone

A 1 to 20 cm thick ‘blackwall’ of dominantly biotite-chlorite marks the visible pegmatite margin. Biotite is usually the first mineral in the metasomatic sequence and forms randomly oriented idiomorphic plates with abundant inclusions of metamict zircon (**Fig. 7.6a**). The biotite zone often (but not always) grades into a thin chlorite-rich band with textures similar to the biotite zone (**Fig. 7.6b**). Zircon is present in both zones and decreases in grain size away from the pegmatite margin, grading from ~1 mm near the pegmatite to less than 0.1 mm in the chlorite zone.

Amphibole Zone

The transition into the amphibole zone from the pegmatite blackwall is sharp, with a pronounced increase in amphibole content at the contact (**Fig. 7.6c**). This indicates that the rate of mineral reaction exceeded the rate of fluid infiltration (Brady, 1977). The amphibole zone comprises interpenetrating, randomly oriented grains of ortho- and clinoamphibole in a groundmass of chlorite and biotite. There is a progressive change across the zone from medium-grained, predominantly Al-rich orthoamphibole (gedrite) near the biotite-chlorite contact to fine-grained, mostly calcic amphibole (tremolite) and minor Al-poor orthoamphibole (anthophyllite) near the contact with the talc-carbonate zone (**Fig. 7.6d**).

Talc-Carbonate Zone

The contact between the amphibole and talc-carbonate zones is gradational over 5-10 cm and is characterized by the replacement of talc + magnesite by tremolite + anthophyllite, such that close to the contact with the host ultramafic rock, no amphibole is present and the metasomatic mineral assemblage is predominantly massive talc-magnesite. The gradational contact indicates that the rate of fluid infiltration exceeded the rate of mineral reaction (Brady, 1977). The talc-magnesite forms a distinctive vermicular intergrowth texture that coarsens towards a sharp contact with the host ultramafic rock (**Fig. 7.6e**). Beyond this contact, minor carbonate veins penetrate up to 1-3 cm into the ultramafic rock (**Fig. 7.6f**).

In the rare cases where the ultramafic rock hosting the pegmatite vein is un-serpentinized (e.g., parts of the W-56 South body in the William Lake area), a thin (<5cm) band of serpentine marks the talc-carbonate-ultramafic rock contact. The absence of pervasive serpentinization adjacent to the pegmatite veins indicates that the veins were not responsible for the majority of the serpentinization in the ultramafic rocks.

7.2.4 Alteration Geochemistry

7.2.4.1 Regional Alteration

General Trends

The ultramafic rocks of the TNB show a distinct trend of increasing loss-on-ignition (LOI) with increasing MgO (**Fig. 7.7a**) that is consistent with a correlation between the degree of serpentinization and initial olivine content. Samples that plot below this trend either contain unserpentinized olivine (e.g., samples from William or Brostrom Lake) or represent pyroxenitic rocks, in which chlorite \pm amphibole are the main alteration minerals. Although the high LOI of most samples that plot above the serpentine control line may be attributed to the presence of carbonate minerals (primarily magnesite), some samples with high LOI (up to 18-20 wt%) do not have correspondingly high CO₂ (**Fig. 7.7b**), indicating that an additional phase that is more hydrous than serpentine (e.g., brucite) must be present.

Major Elements

Whereas the volatile-free TiO₂, Al₂O₃, and FeO contents of the TNB ultramafic bodies form well-defined trends on plots against their MgO contents (**Figs. 8.12 to 8.14**), consistent with fractionation and accumulation of olivine \pm orthopyroxene \pm clinopyroxene \pm chromite, their SiO₂, K₂O, and Na₂O contents all show considerable scatter around the inferred fractionation and accumulation trends, indicating that these elements have been mobile during alteration. Whereas the addition of Si and K is characteristic of potassic alteration and reflects modal increases in phlogopite or biotite contents, the apparent addition of Na, up to 1-2 wt% Na₂O in some samples (**Figs. 8.12 to 8.14**), is more problematic because no metasomatic phase that contains Na has been identified in the TNB ultramafic rocks. Because the increase in Na appears to correlate with an increase in the degree of serpentinization, it is inferred to have occurred during hydration. O'Hanley (1996) has shown that elevated sodium contents in many serpentinite bodies may be attributed to the presence of saline (~4-22 wt% NaCl) fluid inclusions within the serpentine grains.

To examine the effect of alteration on the major and minor element compositions of ultramafic rocks from the TNB, principal component analysis (**Appendix 7**) was applied to a subset of 176 ultramafic samples collected by the Laurentian researchers during the project and characterized by Layton-Matthews. In order to filter for ultramafic lithologies and to avoid errors introduced by discretization of data at low concentrations, the subset included only samples with MgO >20 wt% and for which all the elements of interest were present at levels well above the limits of detection. The variables were selected to represent those expected to vary during magmatic (Al₂O₃, Cr₂O₃, MgO, CaO, Ni, HFSE, HREE, LILE), mineralization (Ni, Cu, S), and alteration processes (H₂O, CO₂, K₂O, LILE, LREE). Before the analysis was performed, LOI data were corrected for contributions by S and CO₂, so that they reflected only the H₂O contents of the samples.

The analysis produced 7 components that controlled ~86% of the total variation in the major and minor element contents of the ultramafic rocks (**Table 7.2**). Although many statisticians recommend that only components with greater than unit eigenvalues should be retained (such that the variance of each component is greater than that of the original standardized variables), two extra components (6 & 7) with less than unit eigenvalues were retained in the analysis because they corresponded to lithological variations in the sample suite.

Component 1 accounts for 34% of the total variance and has large positive loadings for Al, Ca, Sm, Yb, and large negative loadings for Mg and H₂O. It also has small positive loadings for Ce, Nb, and Sr and a small negative loading for Ni. Because most of the elements with negative loadings² are concentrated in olivine, whereas most of those with positive loadings are concentrated in the magmatic liquid, this factor is interpreted to reflect accumulation of olivine. The absence of strong positive loadings for K, Nb, Th, La, Ce, Rb, and Sr indicates that other processes exert a stronger influence on these elements. The relatively high positive loading for H₂O is inferred to reflect the general trend of increasing serpentinization with increasing MgO content.

Component 2 accounts for 14.5% of the total variance and has large positive loadings for Nb, Th, La, and Ce, and small positive loadings for Sm, Yb, and Al. All other elements have negligible loadings (< 0.2). Although the loading for Nb is slightly higher and the loading for Th slightly lower than expected for crustal contamination, which should show enrichments in the order Th > La > Ce > Nb ~ Ta > Sm, the La contents may be influenced by La mobility (see below) and this is the only factor that can be attributed to crustal contamination.

Component 3 accounts for 12.5% of the total variance and has large positive loadings for Ni, Cu and S, but negligible loadings for all other elements. This component is interpreted to represent magmatic sulfide mineralization.

Component 4 accounts for 10.4% of the total variance and has large positive loadings for K and Rb, a small positive loading for Nb, and negligible loadings for all other elements, including the indices of hydrous and carbonate alteration (H₂O and CO₂). Thus, this component is interpreted to reflect alkali metasomatism. Whereas a correlation between K and Rb would be expected for potassic alteration, the weak correlation of Nb with these elements is unexpected. On a plot of Nb vs. K₂O (not shown), the majority of samples exhibit negligible correlation between the two elements, but a few Nb-rich samples possess high K₂O contents, which heavily influences the apparent correlation. The trace element compositions of the anomalous samples appear normal in other respects.

Component 5 accounts for 5.6% of the total variance and has large positive loadings for Sm, Yb and Sr, small positive loadings for Al, Ca, and Ce, and a small negative loading for Mg. Whereas the positive loadings for Sr, Al, and Ca may indicate the influence of plagioclase in this component, the positive loadings for the MREE and HREE suggest that this component represents accumulation of clinopyroxene. The small amount of the total variation accounted for by the component indicates that clinopyroxene accumulation was not an important process in TNB ultramafic bodies.

Component 6 accounts for only 5.0% of the total variance and is characterized by a high loading for only CO₂, indicating that it represents the effects of carbonate alteration. The absence of any correlation between CO₂ and the other elements indicates that their variations are more strongly controlled by processes other than carbonate alteration and that, with the exception of the addition of a volatile component, carbonate alteration may have been essentially isochemical.

² The *magnitudes* of the loadings are proportional to their influence in defining the component, but the absolute *signs* of the loadings are arbitrary and have no petrogenetic significance (see **Appendix 7**).

Table 7.2 Results of principal component analysis of whole rock major, minor and trace element contents of ultramafic rocks from the TNB

	Component							Communality
	1	2	3	4	5	6	7	
Al₂O₃	0.841	0.319	-0.170	0.118	0.199	-0.030	-0.049	0.894
Cr₂O₃	-0.092	-0.131	0.083	-0.141	-0.058	0.032	0.957	0.972
MgO	-0.825	-0.187	0.114	-0.166	-0.243	-0.100	0.043	0.827
CaO	0.916	0.048	-0.155	-0.017	0.201	0.064	-0.104	0.921
K₂O	0.182	-0.019	0.010	0.897	0.045	-0.057	-0.046	0.846
CO₂	0.012	-0.067	0.054	-0.058	0.021	0.984	0.030	0.980
H₂O	-0.755	0.105	-0.138	-0.140	0.057	0.053	-0.020	0.627
Ni	-0.293	-0.166	0.874	-0.028	-0.059	0.004	-0.011	0.882
Cu	0.005	0.142	0.866	0.077	-0.034	0.011	-0.051	0.780
Nb	0.199	0.738	-0.039	0.286	0.102	0.018	-0.182	0.711
Th	-0.027	0.897	0.048	-0.015	-0.108	0.029	-0.111	0.833
La	0.079	0.947	-0.013	-0.063	0.098	-0.066	0.017	0.922
Ce	0.224	0.891	-0.056	-0.074	0.235	-0.087	0.049	0.917
Sm	0.585	0.423	-0.127	-0.044	0.592	-0.105	0.025	0.901
Yb	0.656	0.308	-0.118	-0.012	0.606	-0.120	-0.035	0.922
Rb	0.056	0.047	0.019	0.961	-0.021	-0.007	-0.100	0.939
Sr	0.234	0.025	-0.058	0.041	0.890	0.078	-0.064	0.863
S	0.013	-0.045	0.892	-0.029	-0.060	0.050	0.167	0.833
Variance accounted for	34.1%	14.5%	12.5%	10.4%	5.6%	5.0%	4.6%	
Interpretation	Olivine Accum	Contam-ination	Mineralization	Alkali Metasom.	Cpx Accum.	Carbon-ation	Chr Accum.	

Notes: Number of samples: 176. Extraction method: principal component analysis with Varimax rotation and Kaiser normalization. Loadings with magnitudes greater than 0.5 or less than -0.5 are indicated in bold.

Component 7 accounts for only 4.6% of the total variance and is characterized by a high positive loading for only Cr. This component is interpreted to reflect variations in the olivine:chromite ratios of the rocks owing to differences in the Cr-saturation state of the parental magmas.

It should be noted that no transformation was applied to the data in order to compensate for either the non-normal distribution of the element concentrations or the frequently overlooked fact that compositional data, in particular those involving major elements, are constrained to sum to 100% and may contain false correlations resulting from changes in a single variable (e.g., for non-volatile corrected data, the concentrations of all elements will decrease with increasing H₂O content in isochemically-altered rocks). Under such circumstances, components should be calculated using “constrained principal component analysis”, rather than conventional principal component analysis, starting with either the centred log-ratio covariance matrix (if all the available variables are considered) or the uncentred log-ratio covariance matrix (if only a sub-set of the total number of variables is used). A full

discussion of the reasoning behind this and its methodology may be found in Aitchison (1986) and Reymont and Jöreskog (1993). Although the results of such analyses are statistically more rigorous, they are significantly more complicated to perform and, in this case, produced results that were qualitatively similar to those obtained from the principal component analysis that was employed.

Trace Elements

Previous studies of the ultramafic bodies of the TNB have demonstrated that most (but not all) of the bodies are significantly enriched in incompatible elements and exhibit trace element signatures that resemble those of the pelitic country rocks. Although such enrichment clearly indicates that the majority of the ultramafic bodies have interacted with an upper crustal component, this interaction may have occurred either through wall-rock assimilation during emplacement or as a result of metasomatic alteration by fluids that may have originated from the wall rocks. Because the assimilation of sulfide-bearing country rocks may either bring the magma to sulfide-saturation through dissolution of the sulfides by the magma, or produce an immiscible sulfide liquid with which the magma can interact to form magmatic sulfide ores (see discussion in **Chapter 9** and Lesher & Burnham, 2001), whereas metasomatic alteration should be unrelated to the production of magmatic sulfide ores, the discrimination between contamination and metasomatic enrichment of the TNB ultramafic bodies is critical in the identification of mineralization signatures.

Potassium

Komatiitic rocks possess K_2O contents that are generally at or below the limits of detection for major elements by WD-XRF techniques and rarely contain potassic phases. Consequently, the high K_2O contents and presence of phlogopite and biotite in many (but not all) ultramafic rocks in the TNB clearly indicates that K has been added to these rocks. Because the addition of potassium is commonly accompanied by the addition of other LILE (Beswick, 1982; Kerrich and Wyman, 1996; Lesher and Stone, 1996), the presence of such minerals may indicate the addition of other trace elements. This is confirmed on a mantle-normalized, multi-element plot of phlogopite-bearing samples from the TNB ultramafic bodies (**Fig. 7.8**), in which modal increases in phlogopite (characterized by highly positive K-anomalies) coincide with increases in Cs, Rb, and Ba, but negligible change in either the REE or HFSE compositions of the rocks.

Lanthanum

Although there is a clear relationship between the mobilization of the LILE (Cs, Rb, K, Ba, and Sr) and potassic-alteration and/or carbonatization of the ultramafic rocks of the TNB, the effects of serpentinization on other trace element contents of the ultramafic bodies is less clear. There is a broad trend of increasing mantle-normalized La/Sm ratio with increasing H_2O in the serpentinized ultramafic bodies, which indicates a relationship between serpentinization and LREE (and in particular La) enrichment. However, such a relationship may arise in a number of different ways:

- 1) LREE enrichment may have been synchronous with hydrous alteration and the hydrating fluids introduced La to the ultramafic bodies,
- 2) Previously hydrated rocks may have been more susceptible to subsequent LREE enrichment,

3) LREE enriched rocks may have been more susceptible to hydrous alteration.

Whereas the first and second possibilities are probably valid processes, the third can be dismissed because both LREE-enrichment and LREE-depletion occur in serpentinized ultramafic rocks of the TNB (**Fig. 7.9**).

Transport of REE in metamorphic or hydrothermal fluids for any distance requires the initial stabilization and eventual destabilization of carbonate, fluoride, chloride, or sulfate complexes (Humphris, 1984). Studies by Wendlandt and Harrison (1979) and Taylor and Fryer (1983, 1987) have shown that the LREE are mobile in CO₂-rich fluids, whereas Flynn and Burnham (1978) and Campbell et al. (1984) have demonstrated that both LREE and MREE are mobile in chloride-rich fluids. Martin et al. (1978) and Humphris (1984) suggested that under these circumstances the LREE would be less stable than the MREE or HREE, leading to preferential adsorption of LREE onto existing mineral phases or incorporation into secondary minerals. If LREE *have* been mobile in the TNB ultramafic rocks and this involved either CO₂- or Cl-bearing fluids, then the order of LREE mobility and precipitation should be $\text{La}^{3+} > \text{Ce}^{3+} > \text{Pr}^{3+} > \text{Nd}^{3+} > \text{Sm}^{3+}$. Under oxidizing conditions Ce may be transported as Ce⁴⁺, leading to a decoupling of Ce from the trivalent LREE. Under reducing conditions Eu may be transported as Eu⁺², leading to a decoupling of Eu from the trivalent MREE.

Several of the REE patterns of ultramafic rocks from the central TNB ultramafic rocks are enriched in La relative to Ce in a manner that is inconsistent with crustal contamination (**Fig. 7.10**), but that suggests selective enrichment of La, possibly by preferential adsorption during metasomatism (Humphris et al., 1978). When $[\text{La}/\text{Ce}]_{\text{mn}}$ is plotted as a function of LOI (**Fig. 7.11**), all samples with anomalously high $[\text{La}/\text{Ce}]_{\text{mn}}$ also have high LOI. This, coupled with a near zero correlation of $[\text{La}/\text{Ce}]_{\text{mn}}$ with $[\text{K}/\text{K}^*]$, CO₂, or $[\text{Eu}/\text{Eu}^*]$, and the positive association of La enrichment with increased H₂O (**Fig. 7.11**), suggest that serpentinization, rather than K-metasomatism or carbonatization was the mechanism for La addition in these samples.

The enrichment of La by metasomatic fluids may be distinguished from crustal contamination by comparing $[\text{La}/\text{Yb}]_{\text{mn}}$ and $[\text{Nb}/\text{Yb}]_{\text{mn}}$. Increases in $[\text{La}/\text{Yb}]_{\text{mn}}$ can be attributed to either the assimilation of crustal material during emplacement or to the addition of La during metasomatism. However, because Nb and Yb should be less mobile during alteration, but may be present in crustal assimilants in non-mantle proportions, only contamination should affect the $[\text{Nb}/\text{Yb}]_{\text{mn}}$ ratio. It is clear from **Figure 7.12** that many ultramafic samples from the central TNB exhibit an increase in $[\text{La}/\text{Yb}]_{\text{mn}}$ without a corresponding increase in $[\text{Nb}/\text{Yb}]_{\text{mn}}$, consistent with the addition of La by a metasomatic process. Although the majority of the samples that are anomalously enriched in La are totally serpentinized and possess non-pseudomorphic recrystallized textures (indicating that La mobility was caused by a late thermal/fluid event), not all recrystallized serpentinized rocks show elevated $[\text{La}/\text{Ce}]_{\text{mn}}$ and recrystallization alone appears to be insufficient to cause mobility of La.

Other Trace Elements

In order to assess the effect of serpentinization on the other trace elements, principal component analysis was applied to several trace element ratios that represent indices of either alteration or crustal contamination. These were:

- 1) $[\text{Th}/\text{Nb}]_{\text{mn}}$, a ratio that is commonly used as an indicator of crustal input during crustal assimilation,
- 2) $[\text{Ce}/\text{Sm}]_{\text{mn}}$, a ratio used as an indicator of LREE enrichment as a result of either source enrichment, crustal assimilation or metasomatism (Ce was chosen over La owing to the apparent mobility of La in the TNB),
- 3) $[\text{K}/\text{K}^*]_{\text{mn}}$, an indicator of K-alteration, where $\text{K}^*_{\text{mn}} = ([\text{Th}]_{\text{mn}} + [\text{Ce}]_{\text{mn}})/2$,
- 4) $[\text{Sr}/\text{Sr}^*]_{\text{mn}}$, an indicator of Sr mobility during alteration of pyroxene (may also reflect plagioclase fractionation, but this may be ignored in ultramafic rocks), where $\text{Sr}^*_{\text{mn}} = ([\text{Ce}]_{\text{mn}} + [\text{Sm}]_{\text{mn}})/2$,
- 5) $[\text{Eu}/\text{Eu}^*]_{\text{mn}}$, an indicator of Eu mobility during alteration, where $\text{Eu}^*_{\text{mn}} = ([\text{Sm}]_{\text{mn}} + [\text{Gd}]_{\text{mn}})/2$ (Owing to its smaller charge to ionic radius ratio, Eu^{2+} is considerably more mobile than the adjacent trivalent MREE, especially in the absence of plagioclase or pyroxene.).

Trace element ratios were utilised in order to 1) avoid the problems inherent in a constrained database (see discussion in Reymont and Jöreskog, 1993), 2) maximize the amount of data in the analysis, and 3) minimize the number of variables in the analysis. To avoid spurious correlations resulting from low element concentrations and restrict the analysis to ultramafic samples, the samples were filtered to include only those with >0.04 ppm Th, > 0.04 ppm Nb, > 0.02 ppm Ce, > 0.02 ppm K, > 0.4 Sr, > 0.02 ppm Eu, > 0.02 ppm Sm, > 0.02 ppm Gd, and > 18 wt% MgO. The results of the analysis are summarized in **Table 7.3**.

Table 7.3 Results of principal component analysis of trace element ratios in ultramafic rocks from the TNB

	Component		Communalities
	1	2	
$[\text{Th}/\text{Nb}]_{\text{mn}}$	0.738	-0.048	0.518
$[\text{Ce}/\text{Sm}]_{\text{mn}}$	0.764	0.028	0.656
$[\text{K}/\text{K}^*]_{\text{mn}}$	-0.396	0.459	0.424
$[\text{Sr}/\text{Sr}^*]_{\text{mn}}$	-0.148	0.854	0.534
$[\text{Eu}/\text{Eu}^*]_{\text{mn}}$	0.210	0.852	0.625
Variance accounted for	29%	25%	
Interpretation	Crustal Contamination	Alteration	

Notes: Number of samples: 190. Extraction method: principal component analysis with Varimax rotation and Kaiser normalization.

Two factors account for 54% of the total variance in the trace element ratio data

Component 1 accounts for 29% of the variance, has high positive loadings for $[\text{Th}/\text{Nb}]_{\text{mn}}$ and $[\text{Ce}/\text{Sm}]_{\text{mn}}$, but low loadings for the three indices of alteration, and is interpreted to reflect crustal assimilation.

Component 2 accounts for 25% of the variance and has high positive loadings for all three indices of alteration, but negligible loadings for $[\text{Th}/\text{Nb}]_{\text{mn}}$ and $[\text{Ce}/\text{Sm}]_{\text{mn}}$, indicating that the degree of alteration is independent of the amount of prior crustal assimilation.

The absence of a strong correlation between $[\text{Th}/\text{Nb}]_{\text{mn}}$ and $[\text{Ce}/\text{Sm}]_{\text{mn}}$, and the three indices of alteration suggests that Th, Nb, Ce, and Sm were relatively immobile during alteration and may record primary magmatic processes. These results indicate that although the high La/Ce ratios in the ultramafic rocks of the TNB may be a product of serpentinization and recrystallization, the enrichment in the remaining LREE is probably a product of primary magmatic contamination by crustal rocks.

A confirmation of the immobility of the high field-strength elements (including Th, Nb, and Ti) was obtained by a study of the compositions of mafic and ultramafic rocks intersected by diamond drilling in the Mystery Lake area of the northern TNB (DDH 89225, 89234, and 89236: **Fig. 7.13**). Because at least one of these holes (DDH 89234) intersected a large dunitic body that exhibits a range of serpentine and carbonate alteration and is closely associated with a thick sequence of mafic to ultramafic volcanic rocks, it is possible to examine the behaviour of different elements under a range of conditions.

Trace element data for the samples collected from DDH 89234 indicate that both the cumulate ultramafic rocks of the ultramafic body and the adjacent non-cumulate rocks are highly enriched in incompatible elements, but that the degree of incompatible element enrichment decreases with Mg content such that the lowermost basaltic and komatiitic rocks are depleted in incompatible elements. Although this change in trace element chemistry may be accounted for by the lower susceptibility of the less magnesian rocks to metasomatic alteration owing to their higher initial trace element contents, the decrease in incompatible element enrichment is more likely to represent a primary magmatic feature such as a progressive decrease in the degree of country rock assimilation and/or a change in the composition of the source magma with decreasing olivine content. This may be demonstrated by a plot of $[\text{Th}/\text{Nb}]_{\text{mn}}$ and $[\text{Ce}/\text{Sm}]_{\text{mn}}$ as a function of Yb content (**Fig. 7.13d**). Because the Yb contents of most crustal assimilants are similar to those of the inferred ultramafic magma and because the HREE appear to have been relatively immobile during metamorphism of the ultramafic bodies, neither contamination nor alteration should change the Yb contents of the ultramafic cumulates substantially and they should remain an accurate index of their original trace element contents. In **Figure 7.13d**, neither Th/Nb nor Ce/Sm correlates with Yb, indicating that the incompatible trace element enrichment is independent of the amount trapped melt. A second plot, using Nb/Ti and Th/Ti ratios (**Fig. 7.13c**), gives similar trends to **Figure 7.13d**, suggesting that Ti was also immobile during alteration and that HFSE and LREE ratios that exclude La may retain evidence of magmatic processes, despite subsequent metasomatic alteration.

7.2.4.2 Localized Metasomatism

In order to investigate the behaviour of elements during pegmatite-related metasomatism, mass balance calculations were carried out using the method of Gresens (1967). The results are shown in **Figure 7.14**. Compositional changes are expressed as the ratios of the volumes of elements in one assemblage (obtained by dividing the mass abundances for each element by the densities of the samples) to their volumes in the preceding assemblage. Elements are arranged into groups with similar geochemical characteristics and plotted along the X-axis.

The diagrams illustrate relative enrichments or depletions of different elements, from which volume changes may also be interpreted. Whereas immobile elements should maintain a ratio of 1 during alteration at a constant volume, volume changes during alteration will lead to immobile element ratios that are either greater than 1 (volume decrease) or less than 1 (volume increase).

The marked contrast of Cr values in the biotite-chlorite ‘blackwall’ (>90 ppm) with that of the amphibole zone (>900 ppm) is inferred to mark the original pegmatite-ultramafic contact (**Fig. 7.5**). Cr, and to some extent Al, exhibit relatively constant interelement ratios and are therefore interpreted to have been least mobile in the alteration zones. Whereas alteration of the ultramafic rock to talc + carbonate (+ biotite ± chlorite) is accompanied by an apparent decrease in Cr and Al, suggesting a minor volume gain, alteration of talc + carbonate to gedrite + anthophyllite ± tremolite (+ biotite ± chlorite), shows no change in Cr values, but a large positive change in Al, suggesting there was negligible change in volume during this reaction, but that Al was added.

The results of the mass balance calculations indicate that alteration of the ultramafic rock to talc + carbonate involved a loss of MREE, Zr, and Hf, and a gain of K, Ba, and Sr, CO₂, and H₂O (**Fig. 7.14a**). Although the REE all show negative changes during alteration (indicating that all were lost to some degree), the greater loss of the MREE compared to LREE and HREE suggests that the MREE were significantly less compatible in the talc-carbonate assemblage than the other REE and that small amounts of the MREE may have been mobilized into either the ultramafic rock, or more likely, the amphibole zone near the pegmatite.

The reactions to produce anthophyllite from talc + carbonate involve partial devolatilization accompanied by the liberation of silica (Koons, 1981). In the presence of K and Al, the excess SiO₂ and H₂O would likely be incorporated into biotite, as suggested by the presence of biotite in the groundmass. The decreasing abundances of gedrite and biotite away from the pegmatite contact suggest that the source of K and Al is likely the pegmatite. Based on mass balance calculations, the alteration of the talc + carbonate (+ biotite ± chlorite) to gedrite + anthophyllite ± tremolite involved an addition of Si, Al, Cs, Rb, Ba, Zr, and Hf, and the loss of Sr, Ca and Mn (**Fig. 7.14b**), as well as a loss of CO₂.

7.2.5 Timing of Alteration

Serpentinization

There are three possible timings for serpentinization in the TNB:

- 1) Pre-metamorphic serpentinization through auto-serpentinization caused by the intrusion of hot ultramafic rocks into cold wet sediments, or through fluid ingression during prolonged exposure to wet sediments or seawater
- 2) Prograde serpentinization, through the introduction of fluids derived by dehydration of the sedimentary country rocks
- 3) Retrograde serpentinization, through interaction with either any fluids remaining after metamorphism, or connate and/or meteoric waters

It is unlikely that the regional serpentinization of the bodies occurred prior to deformation or peak metamorphism. Not only should any existing serpentine have been unstable under peak

metamorphic conditions and have decomposed to either $Ol \pm Tlc \pm Tr \pm Chl$ (amphibolite facies) or $Ol \pm Opx \pm Cpx \pm Sp$ (granulite facies), but the boudinage of the ultramafic bodies during the ductile, high temperature phase of deformation indicates that the bodies behaved relatively competently during metamorphism and so are unlikely to have contained large amounts of (incompetent) serpentine. As a consequence, the serpentinization in the TNB ultramafic bodies is interpreted to post-date peak metamorphism.

Based on 1) the observed decrease in the degree of serpentinization with increasing depth from surface, 2) the presence of hypersaline fluids in fractures in the mine environment, and 3) the determination of a strong correlation between latitude and the D/H ratios in lizardite- and/or chrysotile-rich serpentinites located elsewhere in North America that indicated recent interaction between the serpentinites and meteoric waters (Wenner & Taylor, 1974), it has been suggested that the serpentinization of the TNB ultramafic bodies may have not only post-dated metamorphism, but may be relatively recent (J.P. Golightly, pers. comm., 2001). Although interactions between fluids and the ultramafic bodies may have continued or been reactivated long after metamorphism in the TNB, the pervasive regional serpentinization found in the samples adjacent to the pegmatite veins does not appear to have affected the biotite-chlorite assemblage in the associated alteration zones, indicating that serpentinization must predate vein emplacement and probably occurred during retrograde metamorphism. Although the D/H and $\delta^{18}O$ values for the lizardite- and chrysotile-dominated samples from the serpentinite bodies studied by Wenner & Taylor (1974) correlated with latitude, a similar correlation was absent in samples wholly composed of antigorite, chlorite, and/or talc from the same bodies, suggesting that “deep-seated” or metamorphic fluids were involved in the initial serpentinization of these bodies and that serpentinization occurred during the early stage of retrograde metamorphism.

Pegmatite-Related Metasomatism

The metasomatic fronts at the intrusive contacts between the pegmatites and unserpentinized ultramafic rocks in the TNB preserve a sequence of temperature-dependent reactions that end with either talc + magnesite or serpentine alteration of the ultramafic rock. Although pegmatite intrusion was interpreted by Bleeker (1990) to represent near-peak metamorphic conditions ($\sim 530 - 635^{\circ}C$ in the Pipe pit, Oswagan Lake, and William Lake areas, and $740 - 780^{\circ}C$ in the Thompson area), the presence of talc and/or serpentine-bearing assemblages at the pegmatite-ultramafic rock contacts in otherwise unaltered dunites, and the preservation of high-temperature biotite-chlorite zones along the margins of pegmatites hosted by totally serpentinized ultramafic bodies, indicates that the pervasive regional serpentinization must pre-date pegmatite emplacement and that the pegmatites were introduced into ultramafic bodies already below $\sim 500 - 550^{\circ}C$ (the approximate breakdown temperature of forsterite + talc to antigorite at 2 – 5 kbar: Spear, 1995).

Alkali and Carbonate Metasomatism

Many of the ultramafic bodies in the TNB contain alkali-rich hydrous and/or carbonate minerals, consistent with subsolidus interaction of the ultramafic rocks with a hydrous, alkaline, LILE-enriched fluid. The porphyroblastic textures of alteration minerals indicate that alkali and carbonate alteration postdates serpentinization, and it is inferred that fluid infiltrated these bodies during the late stages of metamorphism and alteration. The crosscutting relationship of potassic minerals by carbonate minerals in ultramafic rocks that

have both alteration types suggests that carbonate alteration also post-dates alkali metasomatism and is therefore the youngest alteration type in the TNB.

7.2.6 Conclusions

- 1) The ultramafic bodies of the TNB have experienced a multistage history of both regional and local alteration and metasomatism, resulting in partial to complete replacement of primary igneous olivine, pyroxene, chromite, and interstitial melt by metamorphic serpentine, magnetite, brucite, magnesite, talc, phlogopite, tremolite, and/or orthoamphibole.
- 2) Temperature-dependent reaction fronts (e.g., biotite-chlorite → amphibole → talc-carbonate → serpentine) along pegmatite-ultramafic rock contacts suggest that although pegmatite emplacement probably post-dates pervasive serpentinization and did not occur under peak metamorphic conditions, pervasive serpentinization probably resulted from interaction with metamorphic fluids during retrograde metamorphism rather than recent interaction with meteoric waters.
- 3) The order of regional metasomatic alteration appears to be, from oldest to youngest, serpentinization, K-metasomatism, and carbonate metasomatism.
- 4) LILE and LREE (in particular La) enrichment in recrystallized serpentinites from the TNB can be attributed to recrystallization of serpentine in the presence of LILE/La-enriched metasomatic fluids. In the absence of an identifiable La-bearing phase, the La enrichment is interpreted to represent preferential La adsorption onto serpentine.
- 5) Pegmatite intrusion was not responsible for the pervasive serpentinization of the ultramafic rocks.
- 6) Fluid infiltration related to either pegmatite emplacement into unserpentinized ultramafic rocks, or regional alteration is hindered by a decrease in permeability caused by serpentinization, which is most likely related to the volume increase during serpentinization.
- 7) In order to study the effects of AFC processes, whole-rock chemical data should be filtered to remove samples with anomalously high SiO₂, K₂O, Na₂O, and/or CaO concentrations compared to the fractionation-accumulation trends expected for an ultramafic magma. Variation in these elements, for the most part, can be attributed to potassic and/or carbonate alteration, both of which can be readily identified by petrographic examination.
- 8) The effects of serpentinization on major and minor elements appear to be minimal once the data are recalculated volatile-free. However, late chrysotile veining should be avoided because these veins are not likely derived locally (i.e., on the hand-sample scale). Samples taken close to (or in) pegmatite alteration zones should also be avoided, because elements generally considered immobile during alteration (e.g., Al), appear to have been mobile in these zones.
- 9) Because La appears to have been mobile during recrystallization of some TNB serpentinites, mantle-normalized La/Sm ratios may be unreliable indicators of LREE-enrichment that resulted from crustal contamination. However, the absence of any correlation between [Ce/Sm]_{mn}, [Th/Nb]_{mn}, [Th/Ti]_{mn}, and [Nb/Ti]_{mn} ratios and several

other indices of trace element enrichment suggests that Ce, Sm, Th, Nb, and Ti may have been less affected by metasomatic alteration and may be reliable indicators of magmatic assimilation processes.

- 10) In order to filter out samples that have experienced significant trace element enrichment during metasomatism, those with anomalously high K, CO₂ or Sr contents (i.e., $[K/K^*]_{mn} \gg 1$, $[Sr/Sr^*]_{mn} \gg 1$, CO₂ > 3wt%) should be removed from the database before further investigation.

7.3 P-T Conditions

As mentioned in the introduction, the Hudsonian metamorphism in the exposed TNB is characterized by a single, albeit complex P-T loop, with peak metamorphic conditions ranging from lower to upper amphibolite-facies. Whereas a number of pressure and temperature estimates have been produced for the northern TNB, especially in the area between Pipe and Mystery Lake (e.g., Pactunc, 1984; Fueten, 1990; Pactunc & Baer, 1986; Bleeker, 1990), at the start of this project there were no estimates of the conditions in the central or southern TNB. As part of the current work, P-T conditions for this region were estimated from metapelitic rocks from the William Lake area, using the garnet-biotite geothermometer and muscovite-plagioclase-garnet-biotite geobarometer. Additional temperature estimates were made on mafic/ultramafic rocks from the same area, using the olivine-spinel geothermometer of Sack & Ghiorso (1991) and orthopyroxene geothermometers of Witt-Eickschen & Seck (1991) and Brey & Koehler (1990). The results of the P-T estimates from the pelitic rocks are consistent with those determined for the northern region of the TNB, particularly those in the Pipe pit area.

7.3.1 Metasediments

Metapelites near the William Lake dome are mineralogically similar to those in the Pipe Formation; they are biotite schists with abundant aluminous porphyroblasts (garnet, staurolite, or sillimanite). The mineralogy of the samples studied is summarised in **Table 7.4**.

Table 7.4 Summary of metamorphic mineral assemblages in metapelitic rocks from the central TNB

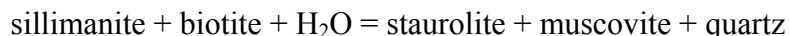
Mineral	Garnet	Biotite	Staurolite	Sillimanite	Muscovite	Quartz	Feldspar
WB09853	X	X			X	X	
WB09866	X	X	X		X	X	
WB09867	X	X	X	X	X	X	X
WB09871	X	X			X	X	

Metapelites in the William Lake area contain two types of garnet porphyroblasts. The first type (Gt1) forms rounded to subhedral porphyroblasts with inclusion-rich cores and inclusion-free overgrowths (similar to Garnet I of Bleeker, 1990) (**Fig. 7.15a**). The inclusion-free rims appear to have formed relatively late and in some cases truncate an earlier foliation. The inclusion population includes quartz, biotite, and feldspar. The second type (Gt2) forms elongated porphyroblasts that appear to have grown within the foliation (**Fig. 7.15b**). This

style of porphyroblast typically contains fewer inclusions (similar to the Garnet II of Bleeker, 1990).

Staurolite appears to be associated only with Gt1 type garnets (i.e., those with overgrowths that form small subhedral grains and overgrow the biotite and quartz matrix: **Fig. 7.15a**). The staurolite in these rocks is interpreted to represent a late metamorphic phase that is in equilibrium with the garnet overgrowths.

Sillimanite, where present, occurs as relict grains, which are variably altered to muscovite + quartz (**Fig. 7.15c**), most likely through the retrograde reaction (Billings, 1937):



Sillimanite was found in only one of the four samples studied (WB09867) and was distinguished from other Al-pseudomorphs on the basis of optical characteristics (positive sign of elongation and high birefringence). The sillimanite in these rocks has been interpreted to represent a peak metamorphic phase that is in equilibrium with the garnet cores.

Based on the interpreted peak metamorphic assemblage (garnet + sillimanite) and the absence of cordierite, spinel, or orthopyroxene, the peak metamorphic grade can be estimated to be <700 °C and <8 kbar (Spear, 1995).

7.3.1.1 Geothermometry

Garnet-biotite thermometry (Ferry and Spear, 1978) was performed on 4 samples from the William Lake area in the central TNB (**Fig. 7.16**), with two samples providing the retrograde garnet overgrowth and matrix staurolite necessary for garnet-staurolite-sillimanite-quartz-H₂O geothermometry (Hutcheon, 1979). The results are presented in **Table 7.5** and **Figure 7.17**; the microprobe data on which the calculations are based are summarized in **Appendix 6 (Table A6.1)**.

Where possible, several garnets and their surrounding matrices were analyzed within each thin section to verify homogeneity on the thin section scale. Each grain was analyzed in several locations to check for homogeneity on the grain scale. All of the analyzed samples displayed compositionally unzoned cores with retrograde zonation confined to grain rims.

Care was taken to analyze garnets that either contained biotite inclusions or occurred in a biotite-dominated environment, so as to minimize the effects of Fe/Mg exchange during retrogression and determine peak metamorphic conditions (Yardley, 1977). However, two samples exhibit retrograde growth of staurolite in the presence of sillimanite (**Fig. 7.15a**). In this case, garnet-staurolite-sillimanite-quartz-H₂O geothermometry was applied to the retrograde garnet rims (overgrowths). These geothermometric analyses are the most accurate minimum estimates for peak and retrograde metamorphic temperatures for the William Lake Area.

Because the temperatures calculated from the garnet-biotite geothermometer will vary as a function of pressure (which was not accurately constrained by the phase assemblages in many of the samples), upper and lower values were calculated assuming pressures of 2 and 10 kbar, respectively. Using the mixing model and calibration of Ferry and Spear (1978), calculated temperatures for the William Lake metasediments (Ospwagan Group metapelites?) range between 600 and 650°C and coincide with peak metamorphic conditions in the Ospwagan Lake and Pipe areas in the northern part of the TNB (Bleeker, 1990). In

samples WB09867 and WB09866, where retrograde temperatures were calculated using the Gt-St-Sil-Qtz calibration of Hutcheon (1979), an estimate of $\sim 570^{\circ}\text{C}$ was calculated using an estimate of 0.1-0.3 for $P_{\text{H}_2\text{O}}$. In this calculation it was assumed that porosity in the TNB metapelites was low and similar to other metapelitic rocks, where $P_{\text{H}_2\text{O}} \gg P_{\text{total}}$ (Cathles, 1976; Norton and Knight, 1977; Ferry, 1980). Although each of the calculations above was performed for pressures conservatively estimated to be within the range 2 - 10 kbar, based on the Al-pseudomorph stabilities determined by Holdaway (1971) and the presence of sillimanite in sample WB09867 at the calculated temperatures, the pressures were likely within the range 5.5 to 2.5 kbar (see below).

7.3.1.2 Geobarometry

Although the presence of sillimanite in sample WB09867 at $\sim 570^{\circ}\text{C}$ implies pressures of 5.5 - 2.5 kbar (Holdaway, 1971), because this sample contains the assemblage Ms + Pl + Gt + Bt, a more precise estimate may be determined using the Ms-Pl-Gt-Bt geobarometer and the calibration and mixing model of Ferry (1980). The results are presented in **Table 7.5** and **Figure 7.17**; the microprobe data on which the calculations are based are summarized in **Appendix 3 (Table A3.1)**.

The results suggest that peak metamorphic pressures were between 4 and 7 kbar in the William Lake area. These coincide with Bleeker's (1990) pressure estimates of the northern TNB, but are higher than those estimated by Russell (1981) and Paktunç & Baer (1986) for the northern TNB. The calculated pressure is also consistent with the absence of cordierite and the presence of sillimanite seen within this sample.

Table 7.5 Summary of geobarometric and geothermometric calculations for metasedimentary rocks from the central TNB

Method	Sample	DDH	Temperature ($^{\circ}\text{C}$)		Pressure (bars)	
			T (at P_1)	T (at P_2)	P (at T_1)	P (at T_2)
St-Gt-Sil-Qtz- H_2O^1	WB09867	WL95-111	583	587	2001	10000
	WB09867	WL95-111	584	588	2001	10000
	WB09866	WL95-111	583	586	2001	10000
Gt-Bt ²	WB09871	WL95-110	560	591	2001	10000
	WB09871	WL95-110	580	611	2001	10000
	WB09867	WL95-111	599	631	2001	10000
	WB09867	WL95-111	605	637	2001	10000
	WB09867	WL95-111	590	621	2001	10000
	WB09867	WL95-111	582	613	2001	10000
	WB09866	WL95-111	570	601	2001	10000
	WB09853	WL98-205	599	631	2001	10000
	WB09867	WL95-111	300	700	2484	5816
Ms-Pl-Gt-Bt ³	WB09867	WL95-111	300	700	3108	6876
	WB09867	WL95-111	300	700	3078	6824
	WB09867	WL95-111	300	700	2910	6539
	WB09867	WL95-111	300	700	2910	6539

Notes: ¹ Hutcheon (1979), ² Ferry and Spear (1978), ³ Ferry (1980).

7.3.1.3 Summary of P-T Estimates From Metasedimentary Rocks

Garnet cores from Gt1 and Gt2 garnets, and inclusion biotite and matrix biotite, respectively, yield consistent prograde temperature estimates of $600 \pm 50^{\circ}\text{C}$ between (and within) drillhole

samples. Staurolite and Gt1 garnet rims in samples WB09866 and WB09867 from DDH WL95-111 yield consistent retrograde temperature estimates of $575 \pm 50^\circ\text{C}$.

Garnet cores from Gt1 garnets, inclusion biotite and plagioclase, and matrix muscovite in sample WB09866 from DDH WL95-111 yield a prograde pressure estimate of 5.5 ± 1 kb.

Prograde P-T and retrograde T estimates from the William Lake area are similar to those estimated at the Pipe II pit (Bleeker, 1990). Prograde pressure-temperature estimates correspond to the F₁-F₂ events, whereas the retrograde temperature estimates correspond to the post-F₂ (peak metamorphism) to F₃ events of Bleeker (1990).

In general, the metamorphic conditions in the William Lake area correlate well with the amphibolite metamorphic conditions in the northern region of the TNB, particularly those at Pipe II pit.

7.3.2 Mafic and Ultramafic Rocks

Although most of the ultramafic rocks of the central TNB are either serpentinites or olivine adcumulate rocks and contained retrograde assemblages of serpentine + magnetite + brucite + magnesite \pm talc \pm unaltered olivine \pm chromite that provide little information regarding the P-T conditions in the area, the majority of the mafic amphibolites and metapyroxenites contain metamorphic phases indicative of upper amphibolite-grade metamorphism, including porphyroblastic olivine and/or orthopyroxene, hercynitic spinel, and trace anthophyllite. Typical assemblages are summarized in **Table 7.6**.

Table 7.6 Summary of metamorphic mineral assemblages from mafic and ultramafic rocks from the central TNB.

Drill Core	Sample Number	Description	Olivine	Orthopyroxene	Clinopyroxene	Tremolite	Anthophyllite	Hornblende	Plagioclase	Biotite/ Phlogopite	Spinel
WL95-106	WB02044	Fine grained amphibolite			X			X			
	WB02050	Medium grained picrites with porphyroblastic olivine		X		X		X		X	
	WB02052	Massive pyroxenite		X		X		X		X	
	WB02054	Laminated amphibolite						X	X		
BL93-68	WB02064	Porphyroblastic olivine pyroxenite	X	X			Tr.				
	WB02065	Massive amphibolite		X		X				X	
WL95-151	WB02067	Porphyroblastic metapicrite	X	X		X					X
	WB02077	Porphyroblastic metapicrite	X	X		X					X

Notes: X, > 5%, Tr., < 5%. Ol: olivine, Opx: orthopyroxene, Cpx: clinopyroxene, Tr: tremolite, Anth: anthophyllite, Hb: hornblende, Pl: plagioclase, Bt/Phlg: biotite/phlogopite, Sp: spinel.

In order to estimate the temperature of metamorphism, olivine-spinel pairs were analysed from three samples of metapicrite. Whereas samples WB02067 and WB02077 were collected from DDH WL95-151, which was located 500m west of the William Lake granitoid body,

sample WB02064 was collected from DDH BL93-68 in the Bracken Lake area to the west of the main William Lake area. The olivine porphyroblasts in samples WB02064, WB02067, and WB02077 are both compositionally and morphologically different from the typical relict olivines found in the olivine cumulate rocks that form the majority of the ultramafic bodies in central TNB. In addition to being considerably less magnesian (Fo_{76-82}), they rarely represent more than ~10-20% of the total rock and are typically equant to highly irregular with yellow alteration rims and coronas and/or inclusions of dark green to brown-green spinel and orthopyroxene (**Fig. 7.15d**).

Temperature estimates were calculated for different olivine + spinel intergrowths or orthopyroxene grains in each of the three samples, using the olivine-spinel geothermometer of Sack & Ghiorso (1991) and orthopyroxene geothermometers of Witt-Eickschen & Seck (1991) and Brey & Koehler (1990). From the presence of anthophyllite + spinel in WB02064 pressures were assumed to lie in the range 3 - 5 kbar. The results of the calculations are shown in **Table 7.7**.

Although there is reasonably good agreement between the temperatures calculated using the three different calibrations, the temperatures calculated for the mafic rocks of the William Lake and Bracken Lake areas (680 – 710°C) appear to approach those of the lower granulite-facies and are almost 100°C higher than those estimated for the biotite schists. Although the metapelitic rocks were collected from drill cores collared several kilometres northwest of those that intersected the metapicrites and the difference in temperatures might be attributable to differences in metamorphic grade across the region, the presence of amphibole (either tremolite and or hornblende) in all metabasaltic or picritic samples examined and the absence of mafic or ultramafic samples containing relict ortho- + clinopyroxene and/or garnet + clinopyroxene suggests that the temperatures estimated from the mafic minerals are overestimates. Attempts to apply this system in other areas (e.g., Kambalda) have yielded similar high estimates (CML, unpubl. data).

Table 7.7 Summary of geothermometric calculations for mafic rocks from the central TNB

Sample	DDH	Temperature (°C)		
		Ol-Spl (Mg-Fe Exch.) ¹	Opx (Cr-Al) ²	Opx (Ca) ³
WB02064	BL93-68		710	710
WB02067	WL95-151	690- 710	680	710
WB02077	WL95-151	710 - 720	730	680 -700

Notes: Temperature ranges indicate the variation between results calculated for different olivine –spinel intergrowths of orthopyroxene grains.¹ Sack & Ghiorso (1991), ² Witt-Eickschen & Seck (1991), ³ Brey & Köhler (1990).

7.4 Future Work

Although qualitative estimates have been made of the changing metamorphic grade through different regions of the TNB, there has been no systematic study carried out outside the Pipe-Moak Lake area in order to quantify these changes owing to 1) the commonly discontinuous outcrop pattern of lithologies that may contain appropriately P-T sensitive mineral assemblages, 2) the probable deformation of the early-formed isograds, leading to complex outcrop patterns (e.g., the observed sillimanite-andalusite isograd at Pipe pit), and 3) the

detailed studies that would be required in each area in order to put the P-T estimates into a tectonic framework. However, with the completion of the compilation map of the bedrock geology of the exposed and sub-Paleozoic TNB (TNB Geology Working Group, 2001), it should be possible to re-approach this problem, possibly by tracking the changes in metamorphic grade of a single unit (or package of units) throughout the belt, or by selecting areas where regionally distinctive units have been identified. A more thorough examination of the P-T-t history of the southern and central part of the exposed TNB would not only aid in the differentiation between potentially conflicting interpretations of the tectonic evolution of the belt (**Chapter 6 Parts I and II**), but also help in the identification of the high-strain, steeply-dipping, substantially retrogressed, younger deformation zones that appear to host the economic mineralization in the TNB (**Section 6.10**).