CHAPTER 11 SUMMARY AND DISCUSSION

The purpose of this chapter is to summarize the principal results of this project and to interpret them within the context of exploration for Ni-Cu-(PGE) deposits in the TNB and in other areas.

11.1 Summary of Principal Results

The principal results and interpretations of this project can be summarized as follows:

- **Stratigraphic Continuity**

  Observation: The stratigraphy of Ospwagan Group, as established by the TNB Working Group[1], appears to be valid over the entire length of the TNB.

  Significance: Stratigraphy can be used to establish structural position and to guide mineral exploration (e.g., to locate Op target horizon).

- **Coherent Stratigraphy**

  Observation: The stratigraphic sequences within major structures throughout the TNB are chronologically continuous and coherent.

  Significance: This is consistent with isoclinal, recumbent folding, but not with thrusting or nappe structures.

- **TNB Structure**

  Observations: The structure of the TNB appears to be dominated by one or more megascopic recumbent westward or westward-verging folds. These have been strongly modified by superimposed southeast-side-up transpression, resulting in a steeply-dipping NNE-SSW foliation and associated conjugate ductile shear zones at all scales. The overall pattern reflects principal sub-vertical stretching, intermediate along-strike stretching, and subhorizontal ESE-WNW shortening. The same strain field is observed from partial melting to greenschist facies conditions.

  Significance: The observed deformation patters are consistent with an early phase of westward-directed compression followed by a later phase of westward-directed transpression. It is not consistent with east-verging nappe emplacement, which would require parts of the sequence to be beheaded. Importantly, it provides a continuity of tens of kilometres for units containing potential Ni deposits and a three-dimensional model (HZ, in progress) for exploration. The deformation appears to represent underthrusting of Paleoproterozoic crust of the Trans-Hudson Orogen below the Archean Superior craton margin (TNB).

- **Duration of Transpression**

  Observation: The bulk kinematics (i.e., transpressive strain patterns) remained the same for at least 100 Ma (~1850 Ma to ~1750 Ma).

  Significance: The transpressive event was a major, protracted event, not a minor, late event, as previously thought.

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[1] The Thompson Nickel Belt Working Group is based at the Manitoba Geological Survey and during the course of this project included J. Macek, T. Corkery, P. Lenton, M. Pacey, D. Peck, P. Theyer, and H. Zwanzig.

- **Diachronous Deformation**

  Observation: Deformation stopped at ~1800 Ma in the easternmost part of the TNB, ~1770 Ma at Thompson, and ~1750 Ma at Pipe.

  Significance: The westward-verging deformation appears to have been diachronous.

- **Ore Localization**

  Observation: Most of the ore deposits appear to be located in zones where deformation lasted until ~1770-1750 Ma. This may reflect the greater susceptibility of sulfides to accommodate deformation at lower temperatures (greenschist facies).

  Significance: Shear zones represent a regional scale exploration target and may be recognizable on the basis of distinctive structural fabrics and/or retrograde mineral assemblages.

- **Lithophile Element Mobility**

  Observation: Many elements were mobile in the ultramafic host rocks during metamorphism and deformation, but Th, Nb, Ta, Zr, Hf, Ti, HREE, Al, and Cr appear to have been immobile in many cases.

  Significance: Th, Nb, Ta, Zr, Hf, Ti, HREE, Al, and Cr may be used to evaluate magma sources, petrogenesis, and contamination processes.

- **Bah Lake Petrogenesis**

  Observation: Sampled Bah Lake volcanic rocks are depleted in highly incompatible lithophile elements (HILE) and undepleted in highly chalcophile elements (HCE), whereas the ultramafic sills within the Ospwagan Group are enriched in HILE and enriched in HCE.

  Significance: The sampled Bah Lake volcanic rocks are not petrogenetically related to the ultramafic sills. The volcanic products of the sills have not been identified, but should have had a volume at least 4x greater than that of the sills.

- **Ore Genesis**

  Observation: The abundances of Ni and platinum-group elements (PGEs) in mill feed from the Birchtree and Thompson mines (representing the best estimate of bulk ore composition) are consistent with equilibration with a komatiitic magma and show no evidence of metal fractionation (magmatic, metamorphic, or hydrothermal) on the scale of the mined ore zones.

  Significance: The ores did not fractionally crystallize Fe-Ni-(Cu) monosulfide solid solution (MSS) during cooling. Ni and PGEs were not lost from the ore zones during deformation and metamorphism.

- **Metal Mobilization**

  Observation: Massive and semi-massive ores from Birchtree and Thompson are depleted in Au, Pt, and Cu relative to the compositions expected from magmatic processes. Mill feed from the same mines is essentially undepleted in Pt and only slightly depleted in Au and Cu. Disseminated ores from Birchtree are not depleted in any metals relative to the compositions expected from magmatic processes.

Significance: Pt appears to have been mobile in massive ores during deformation and/or metamorphism on a scale smaller than mining widths, but greater than that of hand samples, whereas Au and Cu appear to have been mobile on a scale greater than mining widths.

- **Magmatic Ore Chemistry**

  Observation: Thompson "magmatic" massive and semi-massive ores have slightly fractionated chalcophile element abundances (except Pt) consistent with equilibration with a komatiitic magma at relatively low magma:sulfide ratios (R factors). Birchtree and Pipe "magmatic" massive and semi-massive have lower Pd/Ir ratios that cannot be produced via differences in R factor. Birchtree and Pipe are located in Op1, whereas Thompson is located in Op2.

  Significance: Birchtree and Pipe magmatic ores were derived from a different magma than those which produced the Thompson magmatic ores and/or contain different contributions from assimilated country rocks.

- **Sedimentary Ore Chemistry**

  Observation: Barren massive sedimentary sulfides are strongly depleted in Ni-IPGE relative to PPGE-Cu. Thompson massive and semi-massive sedimentary ores are moderately to slightly depleted in IPGE relative to PPGE-Cu, but are anomalously enriched in Ni (as previously reported by W. Bleeker).

  Significance: Thompson massive and semi-massive sedimentary ores formed via a process that involved greater enrichment in Ni than IPGE. The relative roles of physical mobilization, solid-state diffusion, and hydrothermal mobilization are not known.

11.2 Geological Interpretations

11.2.1 Environment of deposition of the Ospwagan Group

The sequence from lower orthoquartzites (Om1) through semi-pelites (Om2) to chemical sediments (Ot and Op1) is consistent with deposition onto a stable shelf, most likely a passive margin. However, the subsequent deposition of turbidites (Os) and mafic volcanic rocks (Ob) is consistent with deposition into a tectonically-active basin, most likely a rifting margin.

11.2.2 Sources of Ospwagan Group sediments

The whole-rock Nd isotopic compositions (**Chapter 8**) of and the ages of detrital zircons (**Chapter 10**) in Ospwagan Group metasediments indicate that the sediments were derived from felsic to intermediate Archean (~2.6-3.0 Ga) sources, most likely the western Superior Province.

The chemical compositions of metasediments (**Chapter 8**) through the Manasan (Om) and Pipe (Op) Formations suggest an increasing mafic component with time. This trend is reversed in the Setting Formation.

11.2.3 Timing of emplacement of ultramafic sills into the Ospwagan Group

It is not certain exactly when the ultramafic sills in the Ospwagan Group were emplaced. The ultramafic compositions of the sills make them difficult to date absolutely, as they do not contain primary minerals suitable for radiometric dating. The only intrusion that has been dated is a differentiated ultramafic-mafic body at Setting Lake, which yielded a U-Pb zircon age of 1880±2 (Hulbert et al., 1998).

No thermal aureoles are recognizable in the metasediments adjacent to the sills. However, hey appear to have experienced most phases of deformation (Bleeker, 1990b), therefore they must be older than the 1850 Ma age of the oldest granitoids (**Section 10.3.3.1**). Thus, the absence of identifiable thermal aureoles may simply mean that they have been obscured by subsequent deformation and metamorphism.

The ultramafic bodies occur throughout the lower and central parts of the Ospwagan Group stratigraphy up to the lower member of the Setting Formation (Os1). This may indicate that they were emplaced during the deposition of Os1 *or* that their emplacement was limited to lower levels for physical reasons (buoyancy, rheology, and/or tectonics). This suggests that they must be younger than the 2.6 Ga age of the youngest detrital zircon in the Setting Formation (**Section 10.2.1.1**).

Thus, the only constraints on the absolute age is that they may have been emplaced some time between 2.6 and 1.85 Ga. However, given the magnitude of magmatism indicated by the prevalent 1880-1890 Ma mafic-ultramafic "Molson" dikes in the adjacent Superior Province, it seems possible that the ultramafic sills were emplaced during this event.

A differentiated mafic body in the Winnipegosis Belt has yielded a U-Pb zircon age of 1864 Ma (Hulbert et al., 1994), suggesting that this belt may be younger.

11.3 Petrogenetic Interpretations

As discussed in **Chapter 8**, the results of this part of the study have important implications for the interpretation of the volcanic/subvolcanic architecture of the magmatic system that formed the TNB. It does not appear that the mineralized ultramafic intrusions were feeders to the overlying Bah Lake (formerly "Ospwagan") volcanic rocks. However, because of limitations in exposure and other uncertainties, it is not clear 1) whether the mineralized ultramafic units were emplaced after deposition of the lower part of the Setting Formation and that their volcanic products were eroded before deposition of the upper part of the Setting Formation (**Fig. 8.54a**), 2) whether the mineralized ultramafic units were emplaced after the Bah Lake Formation and that their volcanic products eroded (**Fig. 8.54b**), or 3) whether the volcanic products of the mineralized ultramafic units were emplaced outside of the volume of preserved section and faulted in or out of the section (**Fig. 8.54c**).

We found no clear evidence for the mode of emplacement (e.g., replacement vs. dilation) of the mineralized (or non-mineralized) ultramafic bodies in the TNB. Any transgressive contacts, syn-emplacement deformation of country rocks, or local contact metamorphic effects appear to have been destroyed by subsequent deformation and/or regional metamorphism. There is also no *direct* physical record of any assimilation processes in the ultramafic bodies in the TNB, in the form of xenoliths, xenocrysts, silicate xenomelts, or restites of partial-melting. Nevertheless, the Ni-Cu-(PGE) ores are interpreted to represent sulfide xenomelts because the amount of sulfide in the deposits is much greater than could have dissolved in and then quantitatively removed from the magma (even after allowing for the systems being dynamic).

There is *indirect* chemical evidence of contamination and the composition of the contaminant is consistent with it being Ospwagan Group sediments. However, because the trace element compositions of both mineralized and non-mineralized bodies may exhibit up to 40% contamination, it is clear, here as in other areas (see Lesher et al., 2001), that contamination alone was not sufficient to induce sulfide saturation and produce Ni-Cu-(PGE) mineralization.

Taken together, the stratigraphic, lithogeochemical, sulfide geochemical, S isotopic, and S-Se data reinforce previous interpretations that the associated sulfide facies iron formations were the principal source of S in the Ni-Cu-(PGE) deposits in the Thompson Nickel Belt.

11.4 Tectonic Interpretations

Different approaches have led to different interpretations of the TNB structure and its tectonic history. Structural mapping using stratigraphic markers (e.g., Bleeker, 1990a,b; Zwanzig, this study) suggests that the structure is dominated by upright folds superposed on westward-verging isoclinal recumbent folds, whereas strain and kinematic analysis of shear zones supported by U-Pb ages of syn-kinematic pegmatite intrusions (e.g., Fueten and Robin, 1989; Potrel et al., this study) suggests that the structure is dominated by NNE-trending reverse shear zones (southeast-side-up) in a transpressional tectonic zone.

Most of the discrepancies can be resolved by recognizing the progressive, polyphase nature of the deformation, in which earlier stages may have been dominated by horizontal tectonics and folding, whereas the later stages may have been dominated by vertical tectonics and transpression. In this respect, the style of deformation in the TNB is similar in many respects to the style of deformation in many Archean greenstone belts (see e.g., Condie, 1981, 1994; Windley, 1995). Nevertheless, there remain some inconsistencies between the two models, so they are discussed below independently.

11.4.1 Fold-nappe model

The age of formation and direction of tectonic transport in the refolded fold-nappe[2] model are still uncertain, but recent structural mapping in the Setting Lake – Brostrom Lake area suggests that one or several large recumbent folds-nappes were transported west or southwest and refolded by major northeast-trending upright folds. The emplacement of these small nappes occurred during high-grade metamorphism and involved the Archean basement and the Ospwagan Group supracrustal rocks and their contained ultramafic intrusions. Structural analysis indicates that sheet-like structures of the Ospwagan Group and possible ultramafic intrusions, refolded like the Thompson nappe, exist in the Kisseynew Domain adjacent to the TNB.

The fold-nappe model suggests that the stratigraphy and chains of ultramafic intrusions extend continuously southwest along the limbs of the large folds and may differ across their axial surfaces or across strike. It implies that the major, late, upright folds do not define the main structural and kinematic framework in the TNB, but that they only modify (albeit strongly) the earlier subhorizontal structures. In this model, the major shear zones are interpreted as accommodation structures that developed in the tighter limbs of the late folds and transferred strain from one structure to the next. The shear zones are interpreted to post-

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[2] A *nappe* (from the French *nappe de recouvrement*) is a recumbent, isolincally-folded sheet of rock that has been transported over adjacent strata as a result of overthrusting; it may or may not be detached from the root of the fold.

date the intrusion of ultramafic rocks and development of Ni mineralization and serve only to modify the shape of existing ore bodies or cause their local mobilization.

If the fold-nappe model for the TNB is correct, it suggests the possible existence of blind structures containing the Ospwagan Group and its intrusions.

11.4.2 Transpression model

This transpression model suggests that the TNB consists of a network of anastomosing shear zones resulting from westward-verging, east-side-up transpressional tectonics. It has been shown that granitoid intrusions and pegmatite emplacement may have been controlled by shear zones and that the same tectonic constraints were present from partial melting conditions to low temperature retrogression. Age dating reveals that the tectonic constraints were active from ~1850 Ma to ~1750 Ma (possibly to ~1720 Ma), and that on a regional scale there is a general younging of structures to the west. However, in detail, the generation of small volumes of pegmatite melts as well as metamorphism are rather irregularly distributed. The picture that emerges is that as transpression progresses new shear zones develop and propagate while older ones reactivate. Shear zones can act as sinks for melts and the progressive increase in connectivity can trigger melt migration. Given the very intense vertical stretching and the anastomosing shear array, melt migration may also be aided by shifting of shear-bounded domains. Pegmatites preferentially emplaced along shear bands may be deformed during later reactivation of these deformation zones whilst new melts may be collected elsewhere in the same zone. The dynamics of shear zone arrays portrayed here will have a significant impact on mineral exploration. The generation and development of shear zones will depend not only on the regional tectonic constraints but also on the nature and rheology of different formations. The dismembering of mineralized bodies by the shear zone arrays is to be expected. Unfortunately, it was not possible to carry out a detailed investigation of the relationships between timing of structure generation and ore occurrence and metal migration-fractionation.

The results obtained for this work also contribute to elucidate the regional tectonic framework of the TNB. One refers to the observation that at least two generations of Archean crust are present in the TNB, one dated at 2.6-2.8 Ga and the other older that 3.2 Ga. More recent work has documented the presence of ca. 3.6 Ga gneisses in a sector of the Kisseynew Domain adjacent to the northern TNB (Böhm et al., 1999). For simplicity, the younger gneisses are referred to as Pikwitonei-type and the older gneisses as Assean-type. Interestingly, the available U-Pb data indicate that Assean-type gneisses were not affected by 2.6-2.7 Ga metamorphism characteristic of Pikwitonei crust. This leads to the interesting possibility that the evolution of the TNB may have been controlled at least in part by boundaries between Archean domains. This aspect merits further study.

The other aspect refers to the timing of collision between the Reindeer Zone (RZ) and the Superior craton. Briefly, the oldest magmatic activity recorded in the TNB, dated at ~1880 Ma, is represented mainly by emplacement of mafic dykes. It is coeval with arc formation and accretion in the RZ, but its significance in relation to the evolution of the RZ is still enigmatic. It may represent either the final stages of extensional tectonics responsible for the formation of the basin occupied by the Ospwagan Group on the Superior margin or may it may be related to the interaction between this margin and the RZ.

The 1851-1836 Ma magmatism in the TNB is coeval with the formation of the Wathaman batholith and continental sedimentation in the RZ and marks the major episode of formation of continental crust associated with collisions between the RZ and the Sask and Hearn cratons. It can now be stated that oblique collision with the Superior craton also started at ~1850 Ma.

The relative quiescence in magmatic-metamorphic activity observed in the TNB between 1836-1800 Ma is correlative with a similar one in the Kisseynew Domain (KD), although the oldest metamorphic ages in the latter are 18-15 m.y. older than equivalent ages in the TNB (1800 Ma). The period of decreased magmatic-metamorphic activity was marked, however, by the emplacement of an intrusive suite in the KD and the Wintering Lake granite in the TNB at ca. 1825 Ma.

Continuing convergence between the Sask and Hearn cratons led to inversion of the KD basin which is marked by peak metamorphism in the KD at 1815-1810 Ma and regional high-grade metamorphism until ca. 1780 Ma. Younger U-Pb ages are seldom found in western KD indicating that major regional metamorphism was finished by that time. Metamorphism in the TNB lasted from 1800 Ma to 1750 Ma and thus outlasted metamorphic activity in the KD by at least. 30 m.y. since ages as young as 1720 Ma are found sporadically.

This summary shows that transpression in the TNB started during the major collisional episode in the RZ and was coeval with it for about 20 m.y. until ~1780 Ma. Transpression in the TNB continued for another 30 m.y. indicating that the latest tectonic activity on the western THO was concentrated along the Superior margin and is coherent with the predominance of ~1750 Ma ages in this area.

11.5 Ore Genetic Interpretations

Previous workers (e.g., Bleeker, 1990b) have demonstrated an empirical association of mineralization with ultramafic sills and sulfide-facies iron-formations and the work done by the TNB Geology Working Group and in this project has only strengthened this observation. The TNB Geology Working Group has shown that the Bucko deposit, which was previously interpreted to be located with Archean basement gneisses, actually occurs within highly deformed paragneisses of the Pipe Formation. This may also apply to the Manibridge deposit. This means that all of the known Ni-Cu-(PGE) deposits in the TNB occur within the Op1 (Birchtree, Bucko, Manibridge, and Pipe) or Op2 (Thompson and Soab) members of the Pipe Formation of the Ospwagan Group. This, coupled with systematic variations in the Se/S ratios and $\delta^{34}S$ of the ores, which trend from the compositions of barren Pipe sulfidic sediments toward mantle values (Eckstrand et al., 1989), clearly indicates derivation of the majority of the S in the ores from the sulfidic sediments.

The similarity of the compositions of the disseminated and net-textured ores in the TNB (e.g., Birchtree, Halfway Lake, Pipe, and William Lake) to those expected to have formed by equilibration of a sulfide melt with an komatiitic magma of a composition inferred from the petrologic studies (see above), supports the interpretation that the majority of the metals in these ores were derived from the komatiitic magma. Variations in the absolute and relative abundances of metals may be accounted for by variations in the proportions of silicate magma and sulfide (R factors) in different areas and in different parts of the same area. However, systematic differences in the Pd/Ir ratios of Thompson and Birchtree-Pipe ores suggest that these two groups of deposits formed from slightly different magma compositions.

The abundances of Co, Ni, Cu, PGE, and As in disseminated and net-textured ores correlate positively with each other indicating that all of these elements are housed in sulfides. The overall trends are consistent with most of the Co, Ni, Cu, and PGEs being derived from the magma, and with most of the S, Se, As, etc. being derived from the sediments.

Massive and semi-massive ores generally have lower metal tenors than disseminated and net-textures ores, consistent with equilibration under lower R factors, but they are also variably depleted in Au, Cu, and Pt. We have considered the possibility that this may reflect lower initial abundances of those elements in the magma, but this would require the magma to be abnormally depleted in those elements relative to other PGEs and there is no evidence of this in the silicate rocks. Thus, the lower abundances of these elements are interpreted to reflect variable mobilization during deformation and metamorphism. Comparisons of the compositions of grab samples with corresponding mill feed indicates that Pt was preferentially lost from massive and semi-massive ores on a scale greater than that of individual grab samples, but less than that of mining widths. In contrast, Au and Cu appear to have been preferentially lost on a scale greater than the mining widths. Too few samples of mill feed are available to estimate accurately the amount of metal "missing" from the ore zones, as the mill feeds average material from multiple stopes in different parts of the mines and the degree of mobilization may vary considerably from area to area. However, the Cu and Au contents of mill feed samples appear to be ~40-60% and 40-70% lower than expected, respectively. If these elements have been mobilized and dispersed beyond the ore zones, they and other elements that may also have been mobilized with them (e.g., semi-metals and volatile metals) may be useful pathfinders in exploration.

Some Thompson 1D ores are enriched in As relative to Ni, suggesting that these ores may contain excess (i.e., above and beyond what would have been incorporated from the sediments during ore formation and responsible for the positive correlation between Ni and As in the majority of the data) hydrothermally-transported and deposited Ni and/or As. Ni is immobile in most hydrothermal and metamorphic fluids, but is known to be complexed and transported by As-S and carbonyl complexes, explaining its low abundance in most hydrothermal ore deposits, but higher abundances in As-rich systems like Cobalt (e.g., Berry, 1971) and Carlin (e.g., Hofstra et al., 2003; John et al., 2003) and in reduced black shales in the Yukon (Hulbert et al., 1992) and in China (Coveney et al., 1991, 1992).

A revised ore deposit model for the Thompson Nickel Belt deposits is presented here to account for trends in the texture and the chemistry of the sulfides. The stages listed below represent major events in the history of the deposition and post-magmatic modification of the ores.

11.5.1.1 Intrusion of Ultramafic Sills

Ultramafic magmatism associated with a rifting event led to the intrusion of ultramafic sills into the Ospwagan Group sedimentary rocks. Based on the similarity in Se/S ratios from the Birchtree and Thompson ores, the two deposits may have been generated from a similar magmatic source. However, pentlandite grains disseminated within ultramafic rocks from Birchtree have distinctly low Ni/Co ratios in comparison to Thompson pentlandite grains of similar texture. This distinction in Ni/Co ratios could indicate that: 1) the Birchtree magmas had a different composition from the Thompson magmas, or 2) the Birchtree magmas had a lower *R* factor than the Thompson magmas.

Given the structural, lithological, and chemical similarities in the Birchtree and Pipe deposits, both deposits are considered to have undergone similar magmatic processes. The Pt depletion in massive sulfides from the two deposits, as well as the Thompson deposit, could indicate that the ultramafic magmas that produced the massive ores were intruded in reducing conditions. Such conditions would be encountered in the graphitic units of the Ospwagan Group, thereby indicating that the ores may largely be stratigraphically controlled.

The high Se/S ratios of the William Lake ultramafic bodies, in comparison to the rest of the TNB bodies, suggests that the magmatic source for William Lake may have been more juvenile than the sources that generated the Birchtree, Pipe, and Thompson ores.

11.5.1.2 Folding and Stretching During High-Grade Metamorphism

Upon mobilization of the sulfides from their ultramafic hosts, it is possible that fluids, generated from the metamorphism of the ore zones, mobilized Ni along strike of the ore horizon and away from the base of the ultramafic rocks. These metamorphic fluids may have also caused Pt to partition from the other PGE; how the Pt partitioned, or where the bulk of the Pt is residing in the mines is uncertain.

Birchtree and Pipe massive breccia ores are not as highly metamorphosed, nor mobilized as far from their ultramafic host rocks as the Thompson massive ores. The markedly higher Ni/Co ratios in the Thompson massive ores, in comparison to the Birchtree and Pipe massive ores, may reflect a metamorphic enrichment of Ni in Thompson relative to Birchtree and Pipe. However, these ratios may also reflect 1) a difference in the initial compositions between Thompson and Birchtree/Pipe magmas, or 2) a difference in *R* factor. It is possible that the higher Ni tenor of Thompson ore, relative to Birchtree and Pipe ore, is a result of both primary magmatic processes and metamorphic alteration.

11.5.1.3 Late Stage Ductile-Brittle Deformation

The cooled (or cooling) massive sulfides were locally concentrated into late tension gashes and shear zones, and milled to finer-grained sulfides. Unsheared portions of the massive sulfide horizons remain coarse-grained. In the Thompson 1D ore body, the extent of shearing and brittle deformation appears to be on a mine scale, based on the predominance of fine-grained sulfides in association with extreme brecciation of the host rocks in that part of the mine. The Thompson 1D ore body is interpreted to represent the most remobilized sulfides in the Thompson structure, while the T1 fold nose area hosts the most preserved or least deformed sulfides in the Thompson deposit. The elevated As, Bi, Pd, and Ni concentrations in the Thompson 1D ore body, compared to the rest of the Thompson Mine, suggest that the deposition of these elements is structurally and metasomatically controlled.

11.5.1.4 Final Cooling

Fine-grained, milled sulfides that were sampled from late tension gashes in the Thompson deposit show evidence of recrystallization. These observations suggest that a high temperature metamorphic event followed late ductile-brittle deformation of the sulfides. During final cooling of the sulfides from high temperatures, the following processes may have occurred:

1) Crystallization of Ni-enriched pyrrhotite and pentlandite in the most deformed sulfides
2) Crystallization of late paragenetic bismuthotellurides and arsenic-bearing minerals
3) Migration of Cu into stringers at the contacts between massive sulfide horizons and metasedimentary hosts
4) Development of chalcopyrite-pyrite symplectite textures
5) Solid-state diffusion and mechanical mobilization of Ni from massive sulfide horizons into the hosting metasediments

Correlations between structural, stratigraphic, and chemical data are important in assessing potential economic concentrations of sulfides in the Thompson Nickel Belt. High Ni-tenor sulfides are found in the most complexly deformed and sheared parts of the Thompson Mine, i.e. the 1D ore body. These high Ni-tenor sulfides have the highest Ni/Co and Pd/Ir ratios in the Thompson Mine (Ni/Co = 57-113; Pd/Ir = 13-22). These massive sulfides also show elevated concentrations of As, Bi, and Pd (As > 300 ppm, Bi > 25 ppm, Pd > 1100 ppb). These data correlate with the mineralization of late paragenetic Pd-bearing bismuthotellurides and As-bearing sulfides.

Elevated As, Bi, Ni/Co, and Pd/Ir in highly deformed massive sulfide horizons within Ospwagan Group metasediments may indicate the presence of high-grade Ni ore nearby. If this ore is located on a limb of an F_3 fold structure, similar to the Thompson structure, it may be possible to locate large, relatively lower Ni-tenor ores preserved in the fold nose (e.g. T1 Mine). These larger bodies may be more favorable to mine, as they have lower concentrations of deleterious metals (e.g. As and Se) and can be recovered at higher effective grades.

A Pt depletion in massive ores from localities other than the Thompson, Birchtree, or Pipe deposits may indicate ore formation in a reducing environment; such a depletion may indicate that the ore is located in a stratigraphic setting (especially within Ospwagan Group metasediments) that is favourable for an economic deposit to occur. Alternatively, the Pt depletion in massive sulfides may indicate that the sulfides underwent a metamorphic or metasomatic process that allowed Pt to partition differently than the other PGE. Whether stratigraphically controlled or metamorphically controlled, a Pt depletion in a potential deposit may indicate a genetic link between that deposit and the ores of Thompson, Pipe, and Birchtree mines.

According to this study, the Ni halo around sediment-hosted massive sulfide horizons does not exceed a scale of tens of metres. Therefore, testing proximity to ore in the metasediments of the Ospwagan Group using low-resolution exploration drilling data may not be very feasible.

11.6 Applications to Exploration in the TNB

The work by the TNB Working Group and the results of this project have enhanced the view that mineralized ultramafic bodies are restricted to the Op1 and Op2 members of the Pipe Formation, which contain abundant sulfide-facies iron-formation. This is consistent with the interpretation that an external source of S is required to generate magmatic Ni-Cu-(PGE) sulfide deposits and reaffirms the importance of that part of the stratigraphic sequence as an exploration target.

The localization of the ores in the TNB within or near ultramafic boudins and the compositions of the ores suggest that the ores are magmatic and related to the ultramafic rocks. This is consistent with the interpretation that these bodies represent a source of heat (for melting sedimentary S) and the principal source of metals for the ores. Although often tectonically-disrupted from the ores, these bodies still represent an important exploration target.

Although many TNB ores have relatively low Ni contents (~5% Ni in 100% sulfides), the magmas had the capacity to generate more metal-rich ores (up to ~15% Ni). Recognizing that the rocks in the ultramafic sills formed after the original stratiform massive ores, exploration should focus on more dynamic, longer-lived (more magnesian, less differentiated) systems that would be characterized by higher R factors and therefore higher metal tenors.

Late (retrograded) shear zones containing ultramafic boudins with talc-carbonated margins and associated ductile massive Fe-Ni-Cu sulfides may have focussed late-stage deformation. They may be recognizable on the basis of distinctive structural fabrics and greenschist-facies mineral assemblages.

The metals in TNB ores appear to have been mobilized in the order Au > Cu >> Pt >> Ni >> Pd-Rh-Ru-Co-Ir >> Cr. Because this appears to have occurred during deformation and metamorphism and because the principal stretching direction is subvertical, this raises the possibility that Au, Cu, and Pt may be dispersed upwards along shear zones defining halos that may be used to vector toward mineralization.

11.7 Applications to Exploration in Other Areas

This project has confirmed the importance of heat and metal source (UM magma) and local S source in the genesis of Ni-Cu-(PGE) deposits, as previously deduced for most other deposits of this type (Lesher, 1989; Naldrett, 1989) and previously suggested for the TNB (Bleeker, 1990b). Although some workers continue to argue for a mantle S source on the basis of the non-radiogenic to weakly-radiogenic Os isotopic signature of some Ni-Cu-(PGE) ores (e.g., Lambert et al., 1998a,b, 1999; Arndt et al., 2003), most, if not all, of the discrepancies can be explained to result from the facility with which the radiogenic Os signatures of crustal isotopic systems are diluted in highly dynamic systems (Lesher and Stone, 1996; Lesher and Burnham, 1999, 2001). S isotopes and S/Se ratios are much more robust and much more direct indicators of the source of S in magmatic sulfide deposits. This is not simply an academic issue, as this work suggests that a robust exploration model for deposits of this type should include not only thick, MgO-rich intrusions (heat and metal source), but also an association with sulfidic sediments (S source).

The absence of any geochemical relationship between the mineralized ultramafic sills and the Bah Lake Group in the TNB highlights the danger of using the geochemistry of volcanic rocks to predict the mineralization status of subvolcanic intrusions. As discussed by Lesher et al. (2001), such relationships can also be influenced by the stratigraphic architecture of the system (i.e., thickness and accessibility of potential contaminants) and may vary with time and location in the volcanic-subvolcanic system. Indeed, Arndt et al. (2003) point out that the stratigraphic-geochemical relationships at Noril'sk-Talnakh may be much more complicated than previously thought. Clearly, lithogeochemical information must be interpreted within the context of the geological architecture of the system.

Although the results of this project suggests that ores in the TNB have been mobilized only locally, this can be attributed at least in part to the *transpressional* nature of the deformation, which involved a large component of pure shear (flattening). Ore mobilization may be greater in zones with greater component of simple shear (strike-slip or dip-slip) deformation (e.g., Perseverance: Libby et al., 1998). It is possible that the chromatic dispersion of metals in other areas may be different than observed in the TNB, because of i) differences in the original abundances of the metals in the ores, ii) differences in metal solubilities and diffusion constants as a function of pressure, temperature, fluid/rock composition, fluid/rock ratio, fO_2, and fS_2, and iii) differences in the nature of the metal transport process (physical mixing vs. diffusion vs. infiltration: see **Fig. 9.50**).

11.8 Follow-Up Work

The following work, some of which was planned and some of which follows from the results of this project, is recommended:

1) SIMMS analyses of the major sulfide minerals would help constrain the mass balance of metals in the ores.
2) Structural mapping between Soab Lake and Joey Lake would aid in completing the structural analysis of the TNB.
3) More detailed Sm-Nd work on mafic flows in the Ospwagan Lake and Setting Lake areas would aid in understanding the nature and degree of contamination of the magmas that formed those rocks.
4) A regional and mine-scale structural and metamorphic analysis of TNB, focusing on shear zones to define their scale (crustal vs. local), rheology (brittle vs. ductile), and style (wet vs. dry), would aid in establishing which types of shear zones are preferentially associated with mineralization and which are not.
5) A detailed structural, mineralogical, and geochemical analysis of deformed ores in the TNB would aid in determining how metals fractionate in shear zones and whether metal ratios of more mobile metals can be used as vectors to mineralization.