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Low-pressure regional amphibolite-facies to granulite-facies metamorphism of the Paleoproterozoic Thompson Nickel Belt, Manitoba

Chris G. Couëslan and David R.M. Pattison

Abstract: The Thompson Nickel Belt is a ca. 35 km × 400 km northeast-trending segment of the northwest margin of the Archean Superior craton in Manitoba, bounded to the west by the Paleoproterozoic Reindeer Zone. The belt was metamorphosed and deformed during the Trans-Hudson orogeny (ca. 1.9–1.7 Ga). Mineral assemblages in metamorphosed pelite, aluminous greywacke, mafic igneous rock, iron formation, and ferruginous wacke define regional metamorphic domains, separated by mineral isograds, that are subparallel to the strike of the belt and to regional-scale D3 structures. An elongate, ca. 5 km × 73 km, central zone of middle amphibolite-facies rocks is characterized by the following: muscovite-bearing mineral assemblages in pelites containing combinations of staurolite, andalusite, and sillimanite; muscovite-free, staurolite + cordierite + garnet-bearing mineral assemblages in greywackes; hornblende-bearing mineral assemblages in mafic metagneous rocks; and grunerite-bearing mineral assemblages in iron formation. Pressure–temperature (P–T) conditions of the middle amphibolite-facies zone are ca. 550–620 °C and 3.0–5.0 kbar (1 kbar = 100 MPa), with pressure increasing to the northeast. The middle amphibolite-facies zone is bordered to the east and west by an upper amphibolite-facies zone, ca. 5 km wide on the east and ca. 3–5 km on the west. The upper amphibolite-facies zone is characterized by variably migmatitic K-feldspar + sillimanite-bearing mineral assemblages in pelites; migmatitic, garnet + cordierite + sillimanite-bearing mineral assemblages in greywackes; orthopyroxene-free, hornblende-bearing mineral assemblages in mafic rocks; and orthopyroxene-bearing mineral assemblages in iron formations. Pressure–temperature conditions of the upper amphibolite-facies zone are ca. 640–710 °C and 3.0–5.5 kbar in the southeast, and 675–755 °C and 4.5–6.0 kbar in the northwest. The outermost metamorphic zone is of the granulite facies, characterized by migmatitic garnet + cordierite + K-feldspar-bearing assemblages in pelites and greywackes, orthopyroxene + clinopyroxene + garnet-bearing mineral assemblages in mafic rocks, and orthopyroxene + K-feldspar-bearing mineral assemblages in iron formation in which biotite is unstable. Pressure–temperature conditions of the granulite-facies zone are ca. 775–830 °C and 5.0–7.0 kbar. The P–T paths in the Thompson Nickel Belt appear to be broadly clockwise, except for some domains where they are close to isobaric. The peak P–T conditions, combined with local but widespread development of andalusite, imply relatively steep geothermal gradients of ca. 33–51 °C/km during metamorphism. Regional bathozones (domains of uniform peak-metamorphic pressure) correspond in general but not in detail with the metamorphic-facies zones. They reveal an increase in pressure towards the northeast, suggesting greater degrees of postmetamorphic exhumation in that region. Microstructural analysis suggests that peak metamorphism coincided with, and possibly outlasted, the D2 deformation event. Metamorphic isograds were deformed by D3–D4 structures. These features are consistent with a tectonic model in which the Superior craton moved in a northwest or west-northwest direction relative to the Reindeer Zone, with greatest convergence and tectonic burial occurring at the Thompson promontory.

Résumé : La ceinture nickélifère de Thompson est un segment de la bordure nord-ouest du craton Supérieur (Archéen), au Manitoba; elle est de tendance nord-est et mesure environ 35 km sur 400 km; elle est limitée à l’ouest par la zone Reindeer (Paléoprotérozoïque). La ceinture a été métamorphisée et déformée durant l’orogénèse Trans-Hudson (~1,9 à 1,7 Ga). Les assemblages minéralogiques dans des pelites métamorphisées, des grauwackes alumineux, des roches ignées mafiques, des formations de fer et des wackes ferrugineuses définissent des domaines métamorphiques régionaux, séparés par des isograds minéralogiques qui sont subparallèles à la direction de la ceinture et aux structures D3 d’échelle régionale. Une zone centrale allongée, d’environ 5 km sur 73 km, formée de roches de faciès amphibolite, est caractérisée par : des assemblages minéralogiques à muscovite dans des pelites contenant diverses combinaisons de stauroïde, d’andalousite et de sillimanite; des assemblages dans des grauwackes, sans muscovite, mais comportant de la stauroïde + de la cordiérite et des grenats; des assemblages minéralogiques comportant de la hornblende dans des roches mafiques mété-ignées et des assemblages minéralogiques à grunerite dans une formation de fer. Les conditions de température et de pression dans la zone de faciès...
amphibolite sont d’environ 550 à 620 °C et 3,0 à 5,0 kbar (1 kbar = 100 MPa); la pression augmentant vers le nord-est. La zone de faciès amphibolite moyen est limitée à l’est et à l’ouest par une zone de faciès amphibolite supérieur d’une largeur d’environ 5 km du côté est et de 3 à 5 km du côté ouest. La zone de faciès amphibolite supérieur est caractérisée par des assemblages minéralogiques migmatiques variables de feldspath K + sillimanite dans des pelites; des assemblages minéralogiques migmatiques de grenat + cordiérite + sillimanite dans des grauwackes; des assemblages minéralogiques à hornblende, sans orthopyroxène, dans des roches mafiques et des assemblages minéralogiques à orthopyroxène dans des formations de fer. Les conditions de température et de pression dans la zone de faciès amphibolite supérieur sont d’environ 640 à 710 °C et 3,0 à 5,5 kbar dans le sud-est et de 675 à 755 °C et 4,5 à 6,0 kbar au nord-ouest. La région métamorphique la plus externe est de faciès granulite; elle est caractérisée par des assemblages de granat migmatique + cordiérite + feldspath K dans des pelites et des grauwackes, des assemblages minéralogiques d’orthopyroxène + clinopyroxène + grenat dans des roches mafiques et des assemblages minéralogiques à orthopyroxène + feldspath K dans une formation de fer dans laquelle la biotite est instable. Les conditions de température et de pression de la zone de faciès granulite sont d’environ 775 à 830 °C et 5,0 à 7,0 kbar. Les courbes T–P dans la ceinture nickélifère de Thompson semblent en général dans le sens des aiguilles d’une montre, sauf pour quelques domaines où les courbes tendent vers des isobares. Les conditions de pointe de T–P, combinées au développement localisé mais largement distribué d’andalousite, impliquent des gradients géothermiques plutôt abrupts d’environ 33 à 51 °C/km durant le métamorphisme. Les bathozones régionales (domaines de pointe uniforme de pression métamorphique) correspondent en général, mais pas dans les détails, aux zones de faciès métamorphique. Ces bathozones révèlent une augmentation de pression vers le nord-est, suggérant plus d’exhumation post-métamorphique dans cette région. Une analyse microstructurale suggère que le sommet du métamorphisme ait coïncidé avec l’événement de déformation D2, se prolongeant possiblement au-delà de l’événement. Les isogradés métamorphiques ont été déformés par des structures D2–D4. Ces caractéristiques concordent avec un modèle tectonique selon lequel le craton du Supérieur s’est déplacé vers le nord-ouest ou vers l’ouest-nord-ouest par rapport à la zone de Reindeer; le point de plus grande convergence et d’enfouissement tectonique se produisant au promontoire Thompson.

[Traduit par la Rédaction]

Introduction

The Thompson Nickel Belt (TNB) forms a segment of the Superior Boundary Zone of Manitoba (Bell 1971; Bleeker 1990). It occurs on the northwestern margin of the Archaean Superior craton, which was tectonically reworked during the Trans-Hudson orogeny by collision with the Paleoproterozoic arc-derived terranes of the Reindeer Zone (Fig. 1; Bleeker 1990; Ansdell 2005). The TNB trends 030° and has a width of 30–40 km and a strike length of almost 400 km; however, the southern one-third to half of the belt is covered by Paleozoic limestone (Burnham et al. 2009).

The Trans-Hudson Orogen represents one of the most extensively studied Paleoproterozoic orogens (Lewry and Stauffer 1990; Hajnal et al. 2005). The TNB portion has been subject to a number of regional mapping, stratigraphic, structural, isotopic, and ore-deposit studies (Fuiten and Robin 1989; Bleeker 1990; Gapais et al. 2005; Macek et al. 2006; Böhm et al. 2007; Zwanzig et al. 2007; Burnham et al. 2009; Machado et al. 2011a, 2011b). However, a belt-wide study of regional metamorphism has been lacking, and the latter is necessary to assess geological gradients and depth of tectonic burial in relation to the deformation events that affected the terrane.

This paper consists of three main sections. The first section describes the mineral assemblages observed in rocks of various bulk compositions from which three main metamorphic-facies domains, separated by isograds, are defined. The second section estimates peak metamorphic conditions within these domains using equilibrium assemblage diagrams. The third section discusses the distribution of the metamorphic domains and isograds in relation to metamorphic depth zones (bathozones). The paper finishes with a discussion of the tectonic implications of these findings.

Regional geology

The TNB is largely underlain by reworked Archaean gneiss of the Superior craton (Fig. 2). The gneiss is interpreted to be derived from the Pikwitonei Granulite Domain (Hubregtse 1980). Although the Archaean gneisses are traditionally thought to be orthogneiss, a possibly Archaean supracrustal sequence has been recognized on Paint and Wintering lakes (Böhm 2005; Couëslan 2009). The entire package of Archaean gneiss was subjected to amphibolite- to granulite-facies conditions from ca. 2.72 to 2.64 Ga (Mezger et al. 1990; Heaman et al. 2011). Temperature and pressure estimates based on geothermobarometry for Pikwitonei granulite near the TNB margin vary from 700 to 900 °C and 8 to 12 kbar (1 kbar = 100 MPa) (Paktunc and Baer 1986; Mezger et al. 1990; Heaman et al. 2011).

The Pikwitonei granulites were exhumed prior to the deposition of the Paleoproterozoic supracrustal rocks of the Ospwagan Group (Scoates et al. 1977; Bleeker 1990; Zwanzig et al. 2007). The Ospwagan Group metasedimentary sequence consists of a fining upward siliciclastic sequence (Manasan Formation), grading into calcareous metasedimentary rocks of the Thompson Formation. The Thompson Formation is overlain by deeper basin siliciclastic and chemical metasedimentary rocks of the Pipe Formation. The Thompson Formation is coarsening upward siliciclastic package. The Setting Formation is finally capped by a thick sequence of mafic to ultramafic metavolcanic rocks of the Bah Lake Assemblage (Bleeker 1990; Zwanzig et al. 2007). Paleoproterozoic detrital zircon grains have been extracted from the Manasan and Setting formations, yielding maximum ages for deposition of 2235 ± 45 and 1974 ± 50 Ma, respectively (Bleeker and Hamilton 2001; Burnham et al. 2009; Machado et al. 2011a). A minimum age for the Ospwagan Group is
provided by amphibitized dykes interpreted to be part of the Molson dyke swarm, and the possibly co-genetic nickel ore-bearing ultramafic sills, which intruded the Ospwagan Group supracrustals at all stratigraphic levels at ca. 1880 Ma (Bleeker 1990; Burnham et al. 2009; Heaman et al. 2009; Scoates et al. 2010).

During the Trans-Hudson orogeny, the Ospwagan Group was affected by four main deformational events. The D1 event predates the intrusion of the ca. 1880 Ma mafic magmatism; however, the resulting deformation is poorly defined. It has been interpreted as an east-verging, nappe-forming event (Bleeker 1990), or a more upright folding event (Burnham et al. 2009). The F1 folds can only be observed where suitable markers are present. The D2 event postdates the intrusion of the Molson dykes and caused refolding and tightening of the F1 folds and resulted in either east-verging (Bleeker 1990; White et al. 2002), or southwest-verging (Burnham et al. 2009), isoclinal to recumbent F2 folds. The D2 event is considered coincident with peak metamorphic conditions of middle amphibolite to granulite facies in the TNB, as demonstrated by the following: the wholesale reorientation of almost all pre-existing fabrics into regionally penetrative S2 and L2 fabrics; the isoclinal to recumbent nature of the regional ductile folding (Bleeker 1990; Burnham et al. 2009); and microstructures (more later in the text). The main regional foliation (S2) is subparallel to S0 layering of Ospwagan Group rocks and the highly attenuated Archean gneissosity (S0) (Paktunc and Baer 1986; Bleeker 1990; Zwanzig et al. 2007; Burnham et al. 2009). The D3 event was likely related to the collision of the Superior craton with the allochthonous Kisseynew Domain of the Reindeer Zone at ca. 1840–1800 Ma (Ansdell 2005; Burnham et al. 2009). The D3 event resulted in tight, vertical to steeply southeast-dipping isoclinal F3 folds (Fig. 3). Infolded Archean gneiss and Ospwagan Group rocks typically form elongate chains of northeast-trending, doubly plunging F3 synforms and antiforms (Bleeker 1990; Burnham et al. 2009). Mylonite zones with subvertical stretching lineations parallel many of the F3 fold limbs (Bleeker 1990). The D3 event is generally considered to be accompanied by retrograde, greenschist-facies metamorphism (Bleeker 1990); however, recent investigations suggest peak metamorphic conditions locally prevailed into D3 (ca. 1770–1760 Ma, Zwanzig 1998). The D3 deformation event is attributed to northwest–southeast shortening and regional, southeast-side-up, sinistral transpression (Bleeker 1990; Burnham et al. 2009). The isoclinal nature of F2 and F3 resulted in a coplanar relationship between S2 and S1 along F3 fold limbs. Tightening of F2–F3 structures continued during D4, which was accompanied by localized retrograde greenschist metamorphism along mylonitic and brittle cataclastic shear zones commonly indicating southeast-side-up, sinistral movement (Bleeker 1990; Burnham et al. 2009). An alternative tectonic model has been presented that promotes long-lived transpressional tectonics from ca. 1850 to 1750 Ma, possibly as late as 1720 Ma (Gapais et al. 2005; Burnham et al. 2009; Machado et al. 2011a). The new metamorphic results of this study have implications for these models.

Thirty years of metamorphic studies of various parts of the TNB have provided a range of temperature estimates for Hudsonian metamorphism from 530 to 575 °C in the Ospwagan Lake area to 600–750 °C elsewhere in the belt, and pressure estimates ranging between 4 and 7 kbar (Russell 1981; Paktunc and Baer 1986; Bleeker 1990; Burnham et al. 2009). Fueten et al. (1986) estimated metamorphic conditions of 575–625 °C and 2.5–5.75 kbar at Pipe II mine based on the metapelitic mineral assemblage quartz (Qtz) + sillimanite (Sil) + biotite (Bt) + muscovite (Ms) + plagioclase (Pl) ± garnet (Grt) and the presence of earlier relict andalusite. Granulite underlying the Paint Lake area has been interpreted as either preserved Archean, Pikwitonei-type granulite (Russell 1981; Paktunc and Baer 1986) or as a Hudsonian granulite-facies overprint (Fueten and Robin 1989; Bleeker 1990). Pressure and temperature estimates for these rocks range from 700 to 900 °C and from 9 to 10 kbar (Russell 1981; Paktunc and Baer 1986; Bleeker 1990).

The adjacent Kisseynew Domain is part of the Reindeer Zone. It represents either a back-arc or fore-arc basin underlain by predominantly turbidite derived, metagreywacke of the Burntwood Group (Ansdell et al. 1995; Zwanzig et al. 1997, 2007). The Grass River Group is a shallow-water clastic sequence of metaconglomerate to arkosic metasandstones that is present along the eastern margin of the Kisseynew Domain. It is believed to be contemporaneous with the deposition of the Burntwood Group (ca. 1.86 to <1.83 Ga; Percival et al. 2005; Zwanzig et al. 2007). The boundary
between the Kisseynew Domain and the TNB is no longer well defined. Structural domes up to 60 km west of the TNB, in the eastern Kisseynew Domain, are cored by Archean gneisses and an Ospwagan Group-like cover sequence with zircon populations typical of Superior craton rocks (Percival et al. 2006; Zwanzig et al. 2006). Interleaving between Osp-
wagan Group and Burntwood Group rocks in the northern part of the TNB suggests early thrusting from the Kisseynew Domain onto the TNB along a low-angle $D_2$ fault (Zwanzig et al. 2006, 2007; Böhm et al. 2007). The TNB and adjacent parts of the Kisseynew Domain therefore likely have a shared tectonic history starting with the $D_2$ event (Zwanzig and Böhm 2002; Percival et al. 2006; Zwanzig et al. 2006).

Peak metamorphic conditions in the adjacent Kisseynew Domain have been estimated at 700–800 °C and 4.5–6.8 kbar, with peak metamorphic assemblages in the Burntwood Group containing Qtz + Pl + K-feldspar (Kfs) + Bt + Grt + cordierite (Crd) + Sil + spinel (Spl) (Gordon 1984, 1989; Growdon et al. 2006). More recent studies have suggested higher temperatures and pressures of ca.
Table 1. Modal percentage of rock, forming minerals in samples discussed in the text.

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Note: Mineral abbreviations are from Kretz (1983). Row headings: Zone, metamorphic-facies zone; MA, middle amphibolite-facies zone; UA, upper amphibolite-facies zone; G, granulite-facies zone; Strat. unit, stratigraphic unit; Op, Ospwagan Group, Pipe Formation; Bw, Burntwood Group; Os, Ospwagan Group, Setting Formation; Om, Ospwagan Group, Manasen Formation; Gr, Grass River Group; Md, Molson Dyke; Pt, Paint Lake sequence; Composition; pel, pelite; grwk, greywacke; spel, semipelite; ark, arkose; diab, diabase; IF sif, silicate-facies iron formation; Fe-wk, ferruginous wacke; tr., trace amounts present; —, not present.

*From Couëslan et al. (2011).*

**Interpreted to be a retrograde phase.**
Table 2. Summary of mineral analyses from samples discussed in the text.

<table>
<thead>
<tr>
<th>Zone:</th>
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<th>MA</th>
<th>MA</th>
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<th>UA</th>
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<td>Op</td>
<td>Op</td>
<td>Bw</td>
<td>Pt</td>
<td>Md</td>
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<tr>
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<td>0.356</td>
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<td>0.10</td>
<td>0.17</td>
<td>0.10</td>
<td>0.13</td>
<td>0.18</td>
<td>0.41</td>
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<td>0.04</td>
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<td>n.p.</td>
<td>n.p.</td>
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<td>0.026</td>
<td>n.p.</td>
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</table>

Note: Mineral abbreviations are from Kretz (1983). Row headings: Zone, metamorphic-facies zone; MA, middle amphibolite-facies zone; UA, upper amphibolite-facies zone; G, granulite-facies zone; Strat. unit, stratigraphic unit; Op, Ospwagan Group, Pipe Formation; Os, Ospwagan Group, Setting Formation; Bw, Burntwood Group; Md, Molson Dyke; Pt, Paint Lake sequence; Composition; pel, pelite; grwk, greywacke; spel, semipelite; diab, diabase; IF sif, silicate-facies iron formation; Grt (r), garnet rim analyses; Grt (c), core analyses; Al, cations per formula unit assuming six oxygen; Ca, cations per formula unit assuming six oxygen; Mg#, Mg/(Mg + Fe); Zn#, Zn/(Zn + Fe<sup>2+</sup> + Mn + Mg). n.p., not present; n.z., no zonation; n.a., not analyzed.

*From Couëslan et al. (2011).
### Table 3. Whole-rock geochemical analyses of samples discussed in the text.

<table>
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<th>Zone:</th>
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<th>G</th>
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<td>spel</td>
<td>ark</td>
<td>pel</td>
<td>pel</td>
<td>grwk</td>
<td>grwk</td>
<td>diab</td>
<td>Fe-wk</td>
<td>grwk</td>
<td>If sif</td>
<td>pel</td>
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<tr>
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<td>100.01</td>
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<td>101.02</td>
<td>99.70</td>
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<td>—</td>
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<td>—</td>
<td>—</td>
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<tr>
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<td>0.35</td>
<td>0.30</td>
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<td>0.44</td>
<td>0.41</td>
<td>0.29</td>
<td>0.38</td>
</tr>
</tbody>
</table>

**Note:** All constituents are reported in wt%. Total Fe is reported as Fe$_2$O$_3$. Row headings: Zone, metamorphic-facies zone; MA, middle amphibolite-facies zone; UA, upper amphibolite-facies zone; G, granulite-facies zone; Strat. unit, stratigraphic unit; Op, Ospwagan Group, Pipe Formation; Bw, Burntwood Group; Os, Ospwagan Group, Setting Formation; Om, Ospwagan Group, Manasan Formation; G, Grass River Group; Md, Molson Dyke; Pt, Paint Lake sequence; avg. Op, average Pipe Formation pelite (sample size $n = 16$, Table S6$^1$); avg. Bw, average Burntwood Group aluminous greywacke ($n = 11$, Table S7$^1$); Composition; pel, pelite; grwk, greywacke; spel, semipelite; ark, arkose; diab, diabase; Fe-wk, ferruginous wacke; If sif, silicate-facies iron formation; Mg#, Mg/(Mg + Fe). —, not analyzed; bdl., below detection limit.

$^1$From Couëslan et al. (2011).
850 °C and 8 kbar for orthopyroxene-bearing Burntwood Group rocks (Growdon 2010).

**Analytical methods**

Metamorphic mineral assemblages were identified in outcrop and diamond drillcore, and by more detailed petrographic microscopy studies (Table 1). From these, 12 samples were selected for mineral chemical analysis. Mineral analyses were obtained on the JEOL JXA-8200 Superprobe at the University of Calgary Laboratory for Electron Microbeam Analysis (UCLEMA), Calgary, Alberta. A summary of key mineral chemical parameters is presented Table 2. Complete analyses of representative minerals, along with
analytical details, are found in supplementary Tables S1–S5.‡ Fourteen samples were sent to Activation Laboratories Ltd., Ancaster, Ontario, for whole-rock geochemical analysis (Table 3). Major elements were analyzed by lithium metaborate–tetraborate fusion – inductively coupled plasma (ICP). Total S and C were analyzed by infrared spectroscopy using an induction furnace.

Mineral assemblages and metamorphic domains

Three distinct metamorphic facies are recognized in the TNB: middle amphibolite, upper amphibolite, and granulite. The metamorphic facies are oriented subparallel to the regional strike of the TNB (Fig. 4). The mineral assemblages that define these facies are presented in the following text, grouped according to protolith. Protoliths include pelites, aluminous greywackes, mafic igneous rocks, iron formations, and ferruginous wackes (although all the rocks are metamorphosed, the prefix “meta” has been omitted from rock names to improve readability). All mineral abbreviations in the text are from Kretz (1983).

Pelite and semipelite bulk compositions

The majority of pelite and semipelite samples are from the Manasan, Pipe, and Setting formations of the Paleoproterozoic Ospwagan Group. Metamorphic assemblages must therefore be the result of Paleoproterozoic metamorphism. The exceptions to this are the samples from the Pipe Lake area, which are part of a metasedimentary sequence of uncertain age. Because the Paint Lake sequence does not correlate to any of the known Paleoproterozoic supracrustal groups in the region, Couëslan (2009) suggested a tentative Archean age for the metasedimentary package. All rocks of pelite and semipelite bulk composition contain in their assemblage Qtz + Pl + Bt + Ms (at lower grade) or Kfs (at higher grade). Accessory phases commonly include pyrrhotite (Po), graphite (Gr), ilmenite (Ilm), apatite (Ap), tourmaline (Tur), and monazite (Mnz).

Middle amphibolite facies

Pelitic and semipelitic rocks containing the assemblage Qtz + Ms + Bt + Pl, with or without Grt, Sil, andalusite (And), and staurolite (St), are amongst the lowest metamorphic grade rocks in the TNB and indicate middle amphibolite-facies conditions. Porphyroblasts are typically wrapped by, and contain inclusion trails parallel to, the S2 foliation. The S2 foliation is locally folded by F3 folds and crosscut by a S3 foliation defined by reoriented muscovite and local biotite. Retrograde chlorite is locally observed. It typically occurs as a replacement of biotite and, along with muscovite, as a replacement of staurolite. The chlorite is commonly randomly oriented; however, it can define a weak S3 foliation.

At the city of Thompson, pelite of the Pipe Formation contains porphyroblasts of staurolite and garnet, and knots of fibrous sillimanite. The staurolite is commonly xenoblastic with rims of randomly oriented medium- to coarse-grained muscovite. The muscovite rims commonly retain the poikiloblastic texture of the original staurolite. The sillimanite knots locally retain the outlines of prisms and are likely pseudomorphs after andalusite (Fig. 5a). The sillimanite may be radial or randomly oriented at the cores of the knots, but is typically oriented parallel to S2 at the rim.

At Ospwagan Lake, pelite of both the Pipe and Setting formations contain porphyroblasts of staurolite and garnet. Staurolite porphyroblasts are wrapped by the S2 foliation. The garnet locally forms inclusions in the staurolite, and rare idioblastic garnet crystal faces overgrow the S2 foliation, suggesting protracted growth of garnet. Quartz veins are locally present in pelite of the Pipe Formation. Pinch-and-swell structures are a common characteristic of the quartz veins which are oriented parallel to, and are wrapped by, the S2 foliation. Coarse-grained, idioblastic andalusite is commonly present within the quartz veins (Fig. 5b), but has not been observed in the groundmass of the schist.

At the Pipe II mine, an eastward transition occurs from pelite containing the mineral assemblage Qtz + Ms + Bt + Pl + Sil, with or without St, And, and Grt, to pelite containing Qtz + Bt + Sil + Kfs + Pl, with or without Grt (Couëslan et al. 2011). This transition indicates a change from middle amphibolite-facies to upper amphibolite-facies peak metamorphic conditions, with the metamorphic grade increasing towards the east as outlined in Couëslan et al. 2011 (Fig. 4). Porphyroblasts of andalusite are common in the middle amphibolite-facies rocks, and are wrapped by the S2 foliation that typically contains fine-grained fibrous sillimanite. Staurolite is locally observed as inclusions in andalusite.

Upper amphibolite facies

Ospwagan Group pelitic and semipelitic rocks containing the assemblage Bt + Qtz + Pl + Sil + Kfs, with or without Grt, are indicative of upper amphibolite-facies conditions. The rocks are generally migmatitic; however, nonmigmatitic,

‡Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/e2012-029.
Kfs + Sil-bearing pelite is present in the Pipe mine area and north of Setting Lake. In nonmigmatitic rocks, the K-feldspar forms equant, xenomorphic porphyroblasts. Combined with the absence of leucocratic segregations in these rocks, the K-feldspar is interpreted to have grown from muscovite breakdown under subsolidus conditions. The highest grade semipelites from...
the Pipe mine contains Qtz + Bt + Pl + Sil + Kfs; leucosome is prominent in both outcrop and thin section, suggestive of partial melting (Couéslan et al. 2011).

In migmatitic rocks, migmatitic layering and irregular patches of leucosome are typically foliated and wrapped by S2 and are interpreted as syndeformational; however, examples of massive leucosome transecting the S2 fabric do occur.

Garnet porphyroblasts are generally subidiomorphic to xenomorphic and wrapped by S2. K-feldspar occurs in the groundmass and leucosome. It can be partially overprinted by myrmekite, fine-grained white mica, randomly oriented muscovite, and skeletal quartz–muscovite or rarely quartz–biotite intergrowths (Fig. 5c). Fibrous to fine-grained prismatic sillimanite occurs intergrown with biotite and locally forms dis-
continuous laminae; it also occurs as discrete flattened knots and as elongate masses with a shape locally reminiscent of andalusite (Fig. 5d). Sillimanite may be partially replaced by retrograde muscovite and fine-grained white mica. Retrograde muscovite can also occur as matrix grains that are randomly oriented or oriented along S3. S3 muscovite is locally associated with chlorite.

**Granulite facies**

Migmatitic pelites containing the mineral assemblage Qtz + Bt + Kfs + Crd + Pl + Grt + Sil are characteristic of metamorphism at granulite-facies conditions. The subassemblage Kfs + Grt + Crd is commonly used to define the granulite facies in metapelites (e.g., Pattison et al. 2003). Staurolite and spinel, along with rare rutile, occur as inclusions.
in Grt. The S$_2$ foliation wraps around porphyroblasts of garnet, which in turn, contain inclusion trails that parallel S$_2$. The leucosome is typically parallel to, and weakly wrapped by, the S$_2$ foliation. Grains of biotite located within the leucosome may be randomly oriented. Antiperthite is locally present and occurs most commonly in the leucosome. Cordierite occurs in several forms: as aggregates rimming garnet; as enveloping grains and aggregates enclosing sillimanite with or without spinel; and lining the contacts between melanosome and leucosome (Fig. 5e).

Fine-grained intergrowths of quartz + cordierite, plagioclase + biotite, and quartz + cordierite are common at the grain boundaries of garnet. Skeletal quartz–biotite intergrowths are also a common replacement of K-feldspar (Fig. 5f). $S_1$ biotite and chlorite is associated with pinitic alteration in cordierite.

A sample of pelite from Paint Lake contains very coarse-grained garnet porphyroblasts rimmed by leucosome. The melanosome is composed dominantly of biotite, cordierite, garnet, and sillimanite. The sillimanite occurs as monocrystalline and polycrystalline pseudomorphs after andalusite (Figs. 5g, 5h), and as scattered fine-grained inclusions, parallel to $S_2$, in cordierite. The sillimanite pseudomorphs are completely enclosed, and partially replaced, by granoblastic cordierite. Garnet is characterized by inclusion-free cores, locally with euhedral outlines, inclusion-rich annuli, and inclusion-free rims. Inclusions consist dominantly of sillimanite, quartz, staurolite, spinel–sillimanite symplectite, replacing staurolite, rutile, ilmenite, and pyrrhotite. Both the garnet and the pseudomorphed andalusite are wrapped by $S_2$. Local $S_3$ shear zones are associated with pinitic alteration of cordierite, chlorite alteration of biotite, and the presence of myrmekite along K-feldspar grains. The rock’s foliation is oriented parallel to the Paleoproterozoic north-northeast D$_2$–D$_3$ fabric of the TNB rather than the regional east–west-trending foliation (S$_0$) of gneisses in the adjacent Superior craton. The presence of $S_3$ sillimanite inclusions in cordierite, and presence of pseudomorphed andalusite, suggests that the preserved foliation and prograde assemblage likely developed as part of the Paleoproterozoic Hudsonian metamorphism.

Metamorphic assemblage zones

The pelite and semipelite assemblages described in the preceding section define four metamorphic assemblage zones (Figs. 6, 7). The lowest grade assemblages contain Ms + St ± And and define a low-grade subzone in the core of the middle amphibolite-facies zone in the Pipe mine–Ospwagan Lake area, and near the city of Thompson. Staurolite-absent, Ms ± Sil-bearing assemblages define a higher grade subzone of middle amphibolite-facies metamorphism. Variably migmatitic Kfs + Sil assemblages define upper amphibolite-facies conditions. The highest grade pelitic assemblages, representative of granulite-facies conditions, are characterized by Kfs + Crd + Grt.

Aluminous greywacke bulk compositions

All occurrences of aluminous greywacke are interpreted to be from the Paleoproterozoic Burntwood Group. Burntwood Group rocks are present only along the west margin of the TNB. All assemblages contain Qtz + Pl + Bt + Grt, and are free of Ms. K-feldspar is present only at the highest metamorphic grades. Common accessory minerals include Gr, Ilm, Po, Ap, Tur, Mnz, and zircon (Zrn).

Middle amphibolite facies

Greywacke characterized by the assemblage Bt + Qtz + Pl + Grt + Crd + Sil, with or without St, indicates middle amphibolite-facies peak metamorphic conditions. White leuocratic, layer parallel segregations containing predominantly quartz with minor plagioclase are wrapped by $S_2$. The leuocratic segregations give the rock a migmatic appearance, but they are interpreted as subsolus segregations (cf. Gordon 1984; Sawyer and Robin 1986). Larger segregations locally contain porphyroblasts of cordierite. Staurolite occurs as rare porphyroblasts, locally enclosed by granoblastic cordierite (Fig. 5a), and more commonly as fine-grained inclusions in garnet, plagioclase, and rarely cordierite (Fig. 5b). Garnet porphyroblasts are wrapped by the $S_2$ foliation; however, both garnet and cordierite commonly contain biotite inclusions oriented parallel to $S_2$. Cordierite is common in the groundmass where it is locally wrapped by shear bands containing biotite and very fine-grained fibrous sillimanite. The shear bands locally merge with, and tighten, the dominant $S_2$ foliation. It is unclear if the shear bands developed as part of the $S_3$ fabric, or represent a later, subparallel $S_1$ foliation. Chlorite replacement of biotite and pinitic alteration of cordierite is commonly present along the bands, suggesting that they were at the least reactivated during $D_3$. 

Upper amphibolite facies

Greywacke containing Bt + Qtz + Pl + Grt + Sil + Crd is characteristic of the upper amphibolite-facies metamorphism. Two types of leuocratic segregations are present: (i) quartz-rich segregations (similar to those described in the preceding subsection), and (ii) quartz–plagioclase segregations. The generally seriate texture of the type ii segregations, along with the increased plagioclase content, suggest that they may be the result of partial melting. Both varieties of segregation
are wrapped by $S_2$ biotite and sillimanite. Garnet porphyroblasts are also wrapped by the $S_2$, but together with cordierite typically contain inclusion trails oriented parallel to the foliation. Sillimanite is more abundant than at middle amphibolite facies and also occurs as discrete fibrous knots. Staurolite occurs as rare inclusions in garnet and plagioclase.

**Granulite facies**

Granulite facies greywacke containing the assemblage Qtz + Pl + Kfs + Bt + Crd + Grt, with or without Sil, indicate granulite-facies peak metamorphic conditions and is the same mineral assemblage observed in pelites at this grade. The leucosome is typically plagioclase-rich with subordinate quartz and K-feldspar,
and the plagioclase is locally antiperthitic. The foliation is typically tightened along leucosome margins. Porphyroblasts of cordierite and garnet are typically wrapped by the foliation. S2 sillimanite occurs as relict clusters of needles at the cores of cordierite porphyroblasts and is locally accompanied by fine-grained spinel. Fine-grained intergrowths of quartz + cordierite (Fig. 8c), and plagioclase + biotite with or without quartz, are common at the margins of garnet grains. Skeletal intergrowths of quartz + biotite are also common and appear to be a replacement of K-feldspar and possibly cordierite. S2 shear planes are locally developed and associated with chloritization of biotite, pinitization of cordierite, and replacement of plagioclase and cordierite by very fine-grained white mica.

**Metamorphic assemblage zones**

Three metamorphic assemblage zones can be defined for rocks of aluminous greywacke bulk composition (Fig. 9), corresponding to the three metamorphic facies. The first assemblage zone (middle amphibolite facies) is characterized by the presence of porphyroblastic stauriolite and quartz-rich leucoxenitic segregations. With increasing metamorphic grade (upper amphibolite facies), stauriolite disappears or is present only as small relict inclusions in plagioclase, garnet, and cordierite; plagioclase-rich leucoxenitic segregations are observed, and sillimanite becomes more abundant. In the highest grade zone (granulite facies), the greywacke contains Kfs + Crd + Grt and Kfs-bearing leucoxenitic segregations as observed in pelitic rocks at this grade.

**Mafic bulk compositions**

Most samples of metamorphosed mafic igneous rocks were collected from amphibolitized dykes and sills hosted by Ospwagan Group supracrustal rocks, or from volcanic rocks of the Bah Lake assemblage at the top of the Ospwagan Group sequence. Exceptions to this are the mafic rocks sampled at Wintering and Paint lakes, which represent amphibolitized dykes that intruded Archean gneiss. Accessory titanite (Ttn), Ilm, Po, and Ap are common.

**Middle and upper amphibolite facies**

Mafic rocks containing a high-variance assemblage of hornblende (Hbl) + Pl, with or without Bt, Qtz, Grt, cummingtonite (Cum), and clinopyroxene (Cpx), are typical of middle and upper amphibolite-facies metamorphic conditions.

At Wintering Lake, situated near the eastern boundary of the TNB (Fig. 2), Molson dykes are locally undeformed and only partially affected by Hudsonian metamorphism. The dykes retain an ophtic texture, and plagioclase and relict clinopyroxene and orthopyroxene are characterized by oscillatory zoning (Fig. 8d). Both clinopyroxene and orthopyroxene have thick rims of hornblende. Preservation of the primary ophtic texture and oscillatory zoning of minerals suggest the dykes are Paleoproterozoic and postdate the Archean granulite-facies metamorphic event.

At the transition from the amphibolite facies to the granulite facies, several samples of mafic rock contain orthopyroxene without clinopyroxene. These rocks may represent low-Ca mafic rocks, where the orthopyroxene formed from a reaction involving cummingtonite.

**Granulite facies**

Mafic rocks with the assemblage Hbl + Pl + orthopyroxene (Opx) + Cpx + Qtz + Bt, with or without Grt and magnetite (Mag), are characteristic of granulite-facies metamorphism. Some rocks contain leucoxenitic segregations of quartz and plagioclase with local antiperthite and orthopyroxene porphyroblasts. Metamorphic pyroxenes typically have partial rims of hornblende with or without wormy intergrowths of quartz.

Rare weakly deformed diabase dykes (Fig. 8e) with preserved chilled margins are present at Paint Lake. They are medium grained and granoblastic with hornblende and two pyroxenes defining a weak S2 foliation. Grains of plagioclase and pyroxene are relatively homogeneous chemically, with the exception of diffuse zoning in the plagioclase, and the presence of cryptic exsolution lamellae, visible in back-scatter electron images, in both the plagioclase and clinopyroxene (Fig. 8f). Diffuse zoning in the plagioclase appears to be related to the presence of adjacent Ca-bearing phases such as hornblende, clinopyroxene, and garnet. Garnet occurs as fine-grained, idioblastic inclusions in plagioclase. The weakly deformed nature of the dykes in otherwise strongly deformed Archean gneiss suggests that they are Paleoproterozoic (likely Molson dykes), or at least, postdate the Archean metamorphic events. Incipient boudinage of one of these dykes, which is wrapped by S2, suggests it intruded prior to, or during, D2.

**Metamorphic assemblage zones**

Three metamorphic assemblage zones are recognized for mafic bulk compositions (Figs. 10, 11). Rocks subjected to middle and upper amphibolite-facies conditions do not contain orthopyroxene. Orthopyroxene first appears in clino-pyroixene-free, Ca-poor mafic rocks, in the transition zone between the upper amphibolite-facies and granulite-facies domains. Mafic rocks of the granulite facies contain both clinopyroxene and orthopyroxene.

**Iron-formation bulk compositions**

All iron-formation samples are from the Pipe Formation of the Ospwagan Group. Mineral assemblages vary broadly according to whether the protolith was dominated by iron oxides, carbonates, sulphides, or silicates. For comparative analysis of metamorphic grade, samples rich in iron silicates were chosen that contained no carbonate, and minimal amounts of iron sulphides and oxides. Accessory phases include Ap and Mnz, and rare Pl.

**Middle amphibolite facies**

The mineral assemblages observed in iron formations vary considerably from one layer or lamination to the next, but assemblages containing Qtz + Bt + grunerite (Grü) + Hbl + Mag + Po, with or without Grt, are typical of middle amphibolite-facies peak metamorphic conditions (Couëslan et al. 2011). Exsolution lamellae of hornblende within grunerite, and grunerite within hornblende are common. Mineral assemblages of iron formation subjected to middle amphibolite-facies conditions are best observed in the Pipe mine area and are described in greater detail in Couëslan et al. (2011).
Upper amphibolite facies

Assemblages consisting of Qtz + Opx + Bt + Hbl + Po + Mag, with or without Grt and Kfs, are characteristic of iron formation metamorphosed at upper amphibolite-facies conditions. In more foliated samples, orthopyroxene and garnet are elongate parallel to, and wrapped by, S₂. Potassium feldspar occurs as rare porphyroblasts, typically along metachert laminations. Retrograde grunerite is common as optically continuous overgrowths on hornblende, fine-grained intergrowths with biotite, pseudomorphs after orthopyroxene, and as aggregates associated with locally developed S₃ foliation planes. Prograde hornblende with exsolution lamellae of gru-
nerite is present; however, grains of retrograde grunerite do not contain exsolution lamellae of hornblende.

**Granulite facies**

Iron formation containing the assemblage Opx + Qtz + Bt + Grt + Kfs + Po with or without Mag is typical of granulite-facies metamorphic conditions. Perthitic grains of K-feldspar appear interstitial and are rarely associated with myrmekite. In one sample, the myrmekitic plagioclase also forms a fine-grained intergrowth with orthopyroxene. Orthopyroxene is locally elongate parallel to $S_2$ and commonly contains inclusions of $S_2$ biotite. Grains of orthopyroxene and K-feldspar are commonly partially replaced by fine-grained, skeletal intergrowths of quartz + biotite with or without garnet.

**Fig. 11.** Prograde mineral-assemblage map of the south half of the Thompson Nickel Belt for mafic bulk compositions. Solid black lines define indicated assemblage-zone boundaries, dashed lines define inferred boundaries, and dotted lines indicate limits of data. The numbered sample location is referred to in the text. The unfilled symbols in the Kisseynew Domain are from Growdon et al. (2006). Abbreviations as in Figs. 5, 6, and 8. Cum, cummingtonite.
This texture suggests local back-reaction of K-feldspar and orthopyroxene to form biotite + quartz, a common retrograde feature of granulite-facies migmatitic rocks (Waters 2001; Sawyer 2008).

**Metamorphic assemblage zones**

Three metamorphic assemblage zones are recognized (Figs. 12, 13). Grunerite is the dominant Fe-silicate in iron formation metamorphosed at middle amphibolite-facies conditions. Orthopyroxene first appears at the transition between middle amphibolite- and upper amphibolite-facies conditions and becomes the dominant Fe-silicate in upper amphibolite-facies rocks. At the highest metamorphic grade, the presence of Opx + Kfs, combined with evidence for the incongruent breakdown of biotite, suggests granulite-facies metamorphic conditions.
**Ferruginous wacke bulk compositions**

The ferruginous wacke differs from iron formation in that it is likely of clastic, rather than chemical, sedimentary origin, and is typically interbedded with psammitic horizons rather than chert. Although it is Fe-rich, it does not contain the extreme Fe-enrichment present in iron formation (Table 3). The ferruginous wacke is part of the metasedimentary sequence of uncertain age. In all outcrops, the bedding and dominant foliation of the wacke parallels the north-northeast regional $S_2$ foliation of the TNB, rather than the east–west $S_A$ preserved in the adjacent Superior craton. Accessory minerals include Ap, Po, Zrn, Mnz, and Ilm.
Upper amphibolite facies

Ferruginous wacke containing the assemblage Qtz + Pl + Bt + Grt is characteristic of upper amphibolite-facies metamorphic conditions. The rock typically contains discontinuous leucocratic segregations parallel to the bedding and S₂. Subidioblastic garnet has locally overgrown S₂ biotite, but is in turn weakly wrapped by S₂. Chlorite occurs as a replacement of biotite along locally observed S₃ cleavage.

Granulite facies

Ferruginous wacke containing Qtz + Pl + Bt + Opx + Grt + Kfs with or without Hbl, Cpx, and Po is characteristic of granulite-facies metamorphic conditions. The rocks are typically migmatitic, with orthopyroxene-bearing leucosome. The leucosome typically parallels S₂ and locally pools in D₂ boudin necks; however, the leucosome also locally forms massive discordant pools (Fig. 8h). Antiperthitic plagioclase
is relatively common in both the matrix and leucosome. Potassium feldspar is most common in the leucosome, but it occurs locally in the matrix where it is associated with both myrmekite and skeletal quartz + biotite intergrowth. Orthopyroxene in the leucosome is randomly oriented and idiomorphic, whereas in the matrix it is typically xenomorphic and elongate parallel to S2. Orthopyroxene is locally replaced by skeletal quartz + biotite intergrowth, garnet, or chlorite. Garnet is typically anhedral and weakly wrapped by the foliation. Pooling of the leucosome into D2 structures, and the local occurrence of apparently post-D2 leucosome, suggests at least a portion of the orthopyroxene-bearing leucosome is Paleoproterozoic.

Metamorphic assemblage zones

A scarcity of recognized ferruginous wacke in the majority of the TNB hampers efforts to define assemblage zones and also limits the usefulness of this bulk composition. Where found, the combination of orthopyroxene + K-feldspar leucosome, antiperthite, and skeletal quartz + biotite intergrowths, is indicative of granulite-facies metamorphism (Fig. 14).

Phase equilibria modelling

Equilibrium-assemblage diagrams were calculated using the Theria-Dominio software package (de Capitani and Brown 1987; de Capitani and Petrakakis 2010), using the updated 2003 ds5.5 thermodynamic dataset of Holland and Powell (1998). The activity models used are those outlined in Tinkham and Ghent (2005), Pattison and Tinkham (2009), and Couëslan et al. (2011). Samples were modelled in the chemical system MnO–Na2O–CaO–K2O–FeO–MgO–Al2O3–SiO2–H2O–TiO2, with C and P2O5 omitted from the whole-rock analysis, and projected from pyrrhotite. The chemical system was oversaturated with a pure H2O fluid phase below the solidus. For calculating melt-bearing systems above the solidus, the H2O content was limited to that contained in hydrous phases immediately below the solidus.

For estimating P–T conditions, mineral assemblages of individual bulk compositions commonly provide tight P–T estimates. In a number of situations, however, the P–T constraints provided by individual rocks were so broad as to be of little value. In these situations, a particularly useful approach was the use of overlapping P–T domains from two or more bulk compositions in the same metamorphic domain, which in many cases provided tight P–T estimates.

Sample selection

Samples of various lithologies from throughout the TNB were examined under petrographic microscope to look for suitable, low-variance assemblages. The extensive use of drillcore for this study often resulted in a limited sample size, not suitable for bulk geochemical analyses. As a result, samples available for geochemical analyses were restricted to those collected from outcrops, at mine sites, or from continuous, relatively homogeneous units from drillcore. Under these restrictions, samples were selected to cover the largest areal extent along strike within each metamorphic-facies zone.

Bulk geochemical analyses were obtained for 40 samples consisting of pelites, semipelites, aluminous greywackes, mafic rocks, iron formations, and ferruginous wackes. Equilibrium assemblage diagrams were calculated for each of these bulk compositions, and of these, 15 were selected which provided well-constrained P–T conditions for the observed mineral assemblages present in the rock.

Middle amphibolite facies

Three samples, spanning a distance of ca. 73 km, were selected from the elongate middle amphibolite-facies zone. Aluminous greywacke sample MY-07-03A from the Burntwood Group at Mystery Lake contains the assemblage Bt + Qtz + Pl + Grt + Crd + Sil + Ilm + St. The equilibrium-assemblage diagram for this sample is shown in Fig. 15a. This assemblage defines a narrow field in P–T space of ca. 610–620 °C and 4.4–5.0 kbar; however, this assemblage may not represent equilibrium. Although porphyroblasts of staurolite are present, staurolite more commonly occurs as fine-grained inclusions in garnet, plagioclase, and cordierite, suggesting it may no longer have been stable in the matrix. If so, the upper P–T limit could be as high as ca. 680 °C and 5.5 kbar as constrained by the solidus.

Pelite sample OP-06–27C from the Pipe Formation at Ospwagan Lake contains the prograde assemblage Qtz + Ms + Bt + Pl + St + Grt + Ilm. The phase-diagram section generated for this sample is given in Fig. 15b. Although the assemblage defines an area in P–T space of roughly 550–650 °C and 3.25–6.25 kbar, the presence of andalusite-bearing, syn-metamorphic quartz veins suggest P–T conditions within the field of stable andalusite. This constrains the P–T conditions at ca. 550–585 °C and 3.2–4.1 kbar.

Samples PP-08-08B and PP-06-28C (see next section) are from the Pipe II mine and were previously presented in Couëslan et al. (2011). The Pipe II mine is situated at the boundary between the middle amphibolite-facies zone and upper amphibolite-facies zone. Pelite sample PP-08-08B from the Pipe Formation contains the middle amphibolite-facies assemblage Qtz + Bt + Ms + Pl + St + And + Sil + Grt. This assemblage defines a short univariant line at ca. 585 °C and 3.9 kbar in the calculated equilibrium assemblage diagram (Fig. 15c). Textural evidence suggests that staurolite and andalusite may be metastable relics, in which case the metamorphic conditions could have been as high as 585–600 °C and 3.7–3.9 kbar. Overall, there appears to be a north-east increase in pressure from the Pipe mine – Ospwagan Lake area to the Mystery Lake area within the middle amphibolite-facies zone.

Upper amphibolite facies

Seven samples were selected from the upper amphibolite-facies zone: four from the eastern domain (samples SL-07-29C, PP-06-28C, TM-06-14A2, SP-02-01; Figs. 6, 7) and three from the western domain (samples MN-07-17A, CC-771, CC-786; Figs. 6, 9).

Arkose sample SL-07-29C from the Grass River Group at Setting Lake contains the prograde assemblage Qtz + Pl + Bt + Kfs + Sil + Ilm. This defines a field in P–T space of ca. 660–680 °C and 3.3–4.5 kbar in the calculated equilibrium-assemblage diagram (Fig. 16a).

Semi pelite sample PP-06–28C from the Setting Formation at the Pipe II mine site contains the upper amphibolite-facies assemblage Qtz + Bt + Kfs + Pl + Sil. The outcrop contains
Fig. 15. Equilibrium-assemblage diagrams for samples from the middle amphibolite-facies zone (Figs. 4, 6, 8). The dashed grey lines indicate the aluminosilicate stability fields in the system $\text{Al}_2\text{O}_3$–$\text{SiO}_2$–$\text{H}_2\text{O}$, as defined by Holland and Powell (1998) based on Pattison (1992). The observed metamorphic assemblage for each sample is circled. (a) Greywacke MY-07-3A, from the Burntwood Group, Mystery Lake. The narrow grey field represents the observed metamorphic assemblage containing staurolite, cordierite, and sillimanite. (b) Pelite OP-06-27C, from the Pipe Formation, Ospwagan Lake. The grey field represents the peak metamorphic conditions as indicated by the observed staurolite-bearing metamorphic assemblage and the presence of andalusite-bearing quartz veins. (c) Pelite PP-08-08B, from the Pipe Formation, Pipe II mine (data from Couëslan et al. 2011). The grey field represents the peak metamorphic conditions as indicated by the observed metamorphic assemblage (see text for details). Whole-rock compositions can be found in Table 2. 1 kbar = 100 MPa. Abbreviations as in Figs. 5 and 8. Chl, chlorite; Cz, clinozoisite; Ilm, ilmenite; Ky, kyanite; Pg, paragonite; Rt, rutile; St, staurolite; Ttn, titanite.

Middle Amphibolite Facies
no leucosome, and the K-feldspar occurs as relatively equant porphyroblasts distributed throughout the matrix. These textures suggest the K-feldspar crystallized under subsolidus conditions. The observed assemblage indicates metamorphic conditions of 640–660 °C and 3.0–3.6 kbar (Fig. 16b; Couëslan et al. 2011).

Pelite sample TM-06-14A2 from the Pipe Formation at the Thompson mine contains the prograde assemblage Bt +
Qtz + Pl + Sil + Kfs + Grt + Ilm. Significant amounts of muscovite are present in this sample; however, it occurs as a retrograde replacement of sillimanite and as skeletal intergrowths of quartz + muscovite after K-feldspar. The prograde assemblage for this sample defines a rather large field in the calculated equilibrium assemblage diagram (Fig. 16c) of ~655–800 °C and 3.5–8.0 kbar. Better pressure and temperature constraints are obtained from semipelitic sample SP-02-01 from the Manasan Formation at the Thompson mine (Fig. 16d). The semipelite contains the prograde assemblage
Bt + Qtz + Kfs + Pl + Sil + Ilm. The prograde assemblage defines a $P$–$T$ field of roughly 670–710 °C and 3.5–5.5 kbar. These lower pressures are in agreement with the sillimanite pseudomorphs after andalusite in adjacent parts of the Thompson structure (Fig. 5d).

Several samples of aluminous greywacke from the Burntwood Group and a sample of pelite from the Pipe Formation were collected in the upper amphibolite-facies zone west of Thompson (Figs. 6, 9). All samples of greywacke contain the same peak metamorphic mineral assemblage of Bt +...
Qtz + Pl + Grt + Cord + Sil + Ilm. Sample MN-07-17A defines a $P-T$ field of 4.4–5.8 kbar and 675–755 °C (Fig. 17a), whereas sample CC-771 defines $P-T$ conditions of 5.0–5.9 kbar and 680–760 °C (Fig. 17b). The pelite sample CC-786 contains the mineral assemblage Bt + Pl + Qtz + Sil + Grt + Kfs + Ilm. This assemblage defines a $P-T$ field of ca. 5.3–7.5 kbar and 720–790 °C (Fig. 17c). A better estimate for the $P-T$ conditions of the upper amphibolite-facies zone west of Thompson can be made by overlaying phase equilibrium diagrams for the greywacke and pelite (Fig. 17d). The $P-T$ region of overlap is 5.3–5.9 kbar, 730–755 °C.

Similar to the middle amphibolite-facies zone, there appears to be a northeast increase in pressure across the upper amphibolite-facies zones. The upper amphibolite-facies rocks west of the city of Thompson appear to have been subjected to higher pressure than those east of the city.

**Granulite facies**

Six samples were selected from the granulite-facies zone: three from the eastern belt at Paint Lake (samples 108-09-415, 108-08-226, PT-07-18A; Figs. 6, 10, 14) and three from the western belt (samples HY-06-22A, CC-601, CC-602; Figs. 6, 9, 12).

The metadiabase sample (108-09-415) contains the assemblage Hbl + Pl + Op = Qpx + Qtz + Bt + Ilm + Grt. Local wavy intergrowths of quartz in hornblende, and the ubiquitous rimming of pyroxene by hornblende, suggests that a portion of the observed hornblende is the result of retrograde metamorphism; however, assuming at least a portion of the hornblende is part of the prograde assemblage suggests $P-T$ conditions of at least 6.5–9.9 kbar and 775–825 °C (Fig. 18a).

The ferruginous wacke sample (108-08-226) contains the assemblage Pl + Qtz + Bt + Op = Kfs + Gt + Ilm. The assemblage defines a large area in $P-T$ space from ca. 4 to 9.5 kbar and from 810 to 870 °C (Fig. 18b). However, this likely represents a maximum set of $P-T$ conditions. Most K-feldspar occurs in the leucosome and is only locally present in the groundmass. This suggests that most, and possibly all, of the K-feldspar crystallized out of the coexisting silicate melt. This could expand the area defined by the equilibrium assemblage to lower temperatures and pressures (725–870 °C, <2–9.5 kbar).

The pelite sample (PT-07-18A) contains the prograde assemblage Bt + Qtz + Gt + Cord + Pl + Sil + Kfs + Ilm. The heterogeneous, migmatitic, and coarse-grained texture of the rock precluded obtaining meaningful whole-rock geochemistry or modal analysis. Therefore, the composite Archean pelite composition of Cameron and Garrels (1980) was used to calculate an equilibrium-assemblage diagram for comparison with the observed mineral assemblage in the Paint Lake pelite (Fig. 18c). This composite was compiled from 406 samples of Archean shale collected from the Superior craton, which were variably, but weakly, metamorphosed. Isopleths calculated for Ca in plagioclase and garnet, Mg(# (Mg/(Mg + Fe)) of cordierite, biotite, and garnet, and Mn in garnet show a close correspondence between the composition of minerals analyzed in sample PT-07-18A and the predicted mineral compositions from the equilibrium-assemblage diagram, recognizing that this diagram is suitable only for a general comparison between the observed mineral assemblage in sample PT-07-18A and the calculated assemblage diagram.

Although sillimanite is present in the prograde assemblage, it is typically partially overprinted by cordierite. Assuming the sillimanite is a relict prograde phase, the assemblage defines a broad $P-T$ field of 2.7–7.0 kbar and 715–840 °C, the upper pressure limit corresponding to the maximum pressure for the assemblage Kfs + Cord + Ilm. This ~7.0 kbar limit is remarkably consistent amongst the pelite compositions modelled in this study.

The $P-T$ conditions of peak metamorphism in the Paint Lake area can be better constrained by overlapping the three phase equilibria diagrams (Fig. 18d). The minimum temperature and pressure is constrained by the diabase assemblage at 780 °C and 6.5 kbar, the maximum temperature and pressure by the pelite assemblage at 830 °C and 7.0 kbar, giving rise to a combined estimate of 6.5–7.0 kbar, 780–830 °C.

One sample of aluminous greywacke from the Burntwood Group (HY-06-22A), and one sample each of pelite (CC-601) and iron formation (CC-602) from the Pipe Formation were selected from the granulite-facies zone west of Mystery Lake. The greywacke sample contains the peak metamorphic mineral assemblage Qtz + Pl + Kfs + Bt + Cord + Gt + Ilm. This assemblage defines a $P-T$ field of ca. 2.1–7.0 kbar and 720–825 °C in the calculated equilibrium-assemblage diagram (Fig. 19a).

The pelite and iron-formation samples were collected from a single diamond drillhole. The pelite contains the assemblage Qtz + Kfs + Pl + Bt + Cord + Gt + Sil + Ilm. The limited sample size available from the drillcore, together with the heterogeneous, migmatitic nature of the rock precluded obtaining a representative whole-rock geochemical and modal analysis. An equilibrium assemblage diagram was therefore calculated using an average Pipe Formation pelite composition ($n = 16$, supplementary Table S61, Fig. 19b). The observed assemblage plots in a narrow field extending from 660 to 800 °C and from 3.5 to 6.9 kbar.

The iron-formation sample CC-602 contains the prograde metamorphic assemblage Qpx + Qtz + Bt + Gt + Kfs + Ilm, with ubiquitous skeletal quartz–biotite intergrowth overprinted on K-feldspar and orthopyroxene. Potassium feldspar is not a discrete phase in any of the predicted phase assemblages, but it likely represents a component of the crystallized coexisting melt. The K-feldspar and quartz–biotite intergrowth suggests that incongruent melting of biotite had taken place. The upper stability of biotite from the assemblage described in the preceding text would be the maximum conditions for peak metamorphism at 830–875 °C and >5.5 kbar (Fig. 19c); however, the incongruent melting of biotite takes place as a continuous reaction, and it is likely that at least a portion of the biotite present in the observed assemblage is part of the prograde assemblage. Approximately 25% of all biotite in the rock appears to be retrograde (occurring as skeletal intergrowth with quartz). Assuming an equal proportion of biotite had originally reacted to melt, a minimum temperature can be estimated of 780 °C (Fig. 19c).

Overlapping the three-phase equilibria diagrams of samples from the granulite zone west of Mystery Lake provides a better constraint on the peak metamorphic conditions (Fig. 19d). The maximum temperature and pressure are defined by the pelite assemblage at 800 °C and 6.9 kbar, and the minimum temperature and pressure are defined by the iron formation at 775 °C and 5 kbar, giving rise to a
Fig. 19. Equilibrium-assemblage diagrams for samples from the granulite-facies zone west of Mystery Lake. (a) Greywacke HY-06-22A, from the Burntwood Group. The grey field represents the observed metamorphic assemblage. The dashed grey lines indicate the aluminosilicate stability fields in the system Al$_2$O$_3$–SiO$_2$–H$_2$O as defined by Holland and Powell (1998) based on Pattison (1992). (b) Average Pipe Formation pelite (sample size $n = 16$, Table S6), the grey field indicates the observed metamorphic assemblage in pelite CC-601 of the Pipe Formation. The dashed grey lines indicate the aluminosilicate stability fields in the system Al$_2$O$_3$–SiO$_2$–H$_2$O. (c) Iron formation CC-602, from the Pipe Formation. Dashed grey lines indicate the percentage of biotite that has reacted to form melt. The grey field represents the observed metamorphic assemblage (see text for details). (d) The overlapping fields of a–c yield a best estimate for the metamorphic conditions in the granulite-facies zone west of Mystery Lake, as indicated by the long dashed lines (see text for details). Whole-rock compositions can be found in Table 2. 1 kbar = 100 MPa. Abbreviations as in Figs. 5–15 and Table 3. Act, actinolite.
combined estimate of 5.0–6.9 kbar, 775–800 °C. These findings are similar to the 750 ± 50 °C and 5.5 ± 1 kbar estimate of Gordon (1989), and ca. 775 °C and 6.8 kbar estimate of Growdon et al. (2006) for the adjacent Kisseynew Domain, but are lower than the ca. 850 °C and 8 kbar estimate of Growdon (2010).

**Discussion**

**Mineral isograds**

The idealized reactions that correspond to each mineral isograd are summarized in Spear (1995) for amphibolite-facies reactions and Pattison et al. (2003) for granulite-facies reactions, unless otherwise indicated.

Areas of St-bearing pelite and aluminous greywacke, the lowest grade rocks of the TNB, are located in the core of the middle amphibolite-facies zone (Figs. 6, 9). The boundary of these areas defines the St-out isograd for pelite and greywacke, which separates the middle amphibolite-facies domain into lower and upper subzones. The disappearance of staurolite in pelitic rocks is likely the result of the reaction:

\[
\text{Ms} + \text{St} + \text{Qtz} = \text{Bt} + \text{Al}_2\text{SiO}_5\text{Grt} + \text{H}_2\text{O}
\]

The St-out reaction for rocks of pelitic composition is not the same as for rocks of greywacke composition. The absence of coexisting muscovite leads to a different idealized staurolite-consuming reaction in the greywacke in which garnet and cordierite are produced instead of sillimanite and garnet:

\[
\text{St} + \text{Qtz} = \text{Grt} + \text{Crd} + \text{H}_2\text{O}
\]

Bailes and McRitchie (1978)

Reaction [2] is predicted to occur at slightly higher temperatures than reaction [1], ~20 °C higher at 4.5 kbar (cf. Figs. 16c, 17b).

The boundary between zones of Qtz + Ms-bearing pelite and Kfs + Sil-bearing pelite defines the Kfs + Sil-in isograd (Figs. 6, 7), represented by the idealized reaction:

\[
\text{Ms} + \text{Qtz} = \text{Kfs} + \text{Sil} + \text{H}_2\text{O} \quad \text{([MS + Qtz] = Kfs + Sil + H_2O)}
\]

or melt (above ca. 3.5 kbar)

Where possible, this isograd was used to define the boundary between the middle amphibolite-facies and upper amphibolite-facies zones (Fig. 4).

There is a close correlation between the location of the Kfs + Sil-in isograd for pelite and the Opx-in isograd for iron formation (Figs. 12, 13). The Opx-in isograd is located between the zones of Gru-bearing and Opx-bearing iron formation, giving rise to the idealized reaction:

\[
\text{Gru} = \text{Opx} + \text{Qtz} + \text{H}_2\text{O}
\]

Couéslan et al. (2011) found the orthopyroxene-in isograd to occur roughly 20 °C below the Kfs + Sil isograd at 3–4 kbar. This suggests that at low to moderate pressures and in the presence of a H_2O-rich fluid, the orthopyroxene-in isograd can be used to define the beginning of upper amphibolite-facies metamorphism for iron-formation bulk compositions.

At the boundary between upper amphibolite facies and granulite facies, three isograds occur in close proximity: the Kfs + Crd + Grt-in isograd for pelite and greywacke bulk compositions (Figs. 6, 7, 9); the Opx-in and Cpx + Opx-in isograd for mafic bulk compositions (Figs. 10, 11); and the isograd corresponding to the incongruent melting of biotite in iron-formation bulk compositions (Figs. 12, 13). The idealized reactions for the isograds are, respectively:

\[
\begin{align*}
\text{[5]} & \quad \text{Bt + Si} + \text{QtzPl} = \text{Grt} + \text{Crd} + \text{meltKfs} \\
\text{[6]} & \quad \text{Cum} = \text{Opx} + \text{Qtz} + \text{H}_2\text{O} \quad \text{(Spear 1995)} \\
\text{[7]} & \quad \text{Cum} + \text{Hbl} + \text{Grt} + \text{Qtz} = \text{Opx} + \text{Pl} + \text{H}_2\text{O} \quad \text{(Hollocher 1991)} \\
\text{[8]} & \quad \text{Hbl + QtzGrt} = \text{Opx} + \text{Cpx} + \text{meltPl} \\
\text{[9]} & \quad \text{Bt + QtzPl} = \text{Opx} + \text{meltGrtKfs}
\end{align*}
\]

These isograds were used individually or collectively to define the lower limit of the granulite-facies zone.

**Bathozones**

A combination of diagnostic peak-metamorphic mineral assemblages and inferred peak metamorphic P–T conditions were used to identify domains of different metamorphic pressure, or “bathozones” (cf. Carmichael 1978). The lowest pressure bathozone (3–4 kbar) is interpreted to stretch from Ospwagan Lake in the north to Setting Lake in the south (Fig. 20). Pelite assemblages from this zone are characterized by andalusite at middle amphibolite-facies conditions and subsolidus K-feldspar + sillimanite at upper amphibolite-facies conditions (see Fig. 21a). Staurolite-bearing assemblages containing sillimanite pseudomorphs after andalusite at the city of Thompson suggest that this zone could extend farther north.

An intermediate pressure bathozone (4–5 kbar) occurs to the north and east of the low-pressure bathozone (Fig. 20). Semipelites from this bathozone are migmatitic and typically contain sillimanite and K-feldspar but not garnet (Figs. 16b, 16d), indicating pressures typically in the range of 3.5–5.5 kbar. Middle amphibolite-facies aluminous greywackes in the Mystery Lake area contain assemblages with coexisting staurolite, cordierite, and sillimanite that limit pressure to ca. 4–5 kbar (Fig. 21b). Pelites do not contain a diagnostic mineral assemblage for this bathozone.

The highest pressure bathozones occur northwest of the intermediate pressure bathozone and in the Paint Lake area (Fig. 20). Pressures of 5–6 kbar occur west of the city of Thompson – Mystery Lake area where migmatitic greywacke assemblages of the upper amphibolite-facies domain contain coexisting cordierite, sillimanite, and garnet (Fig. 21b). Pressures slightly farther west in the granulite-facies domain are limited to <7 kbar by the presence of K-feldspar, cordierite, and ilmenite in pelite and greywacke bulk compositions (Fig. 21), and to pressure >5 kbar by the presence of garnet and relict sillimanite needles included in cordierite porphyroblasts in aluminous greywacke and coexisting garnet, sillimanite, and cordierite in pelites (Fig. 21). Similar pressures of 5–7 kbar are inferred for the granulite zone at Paint Lake based on pelite assemblages containing K-feldspar, garnet, cordierite, and ilmenite, and phase equilibria calculations

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Fig. 20. Bathozone map of the Thompson Nickel Belt. Solid lines define indicated boundaries, the dashed lines define inferred boundaries, and dotted lines indicate limits of data. The bathozone corresponds to the pressure bands in the phase diagrams in Fig. 21. 1 kbar = 100 MPa. Abbreviations as in Figs. 5, 6, and 15.

Although sillimanite pseudomorphs after andalusite at Paint Lake and the city of Thompson are not indicators of peak pressure, they do imply a relatively shallow $P$–$T$ path for these rocks (see the following text).

There is a broad correlation between the metamorphic-facies domains (Fig. 4) and the bathozone (Fig. 20), consistent with the expected increase in metamorphic grade with increasing pressure. However, the two do not always correspond. For example, the ca. 4 kbar boundary between the low-pressure and intermediate-pressure bathozone cuts across the middle amphibolite-facies zone in the Ospwagan Lake – city of Thompson area, with higher pressures to the
northeast. This pattern implies greater degrees of postmetamorphic uplift of middle and upper amphibolite-facies rocks in the northern part of the TNB compared with the south.

A second example of the noncoincidence of bathozones and metamorphic facies is at the Pipe II mine site, where both middle and upper amphibolite-facies rocks occur in...
the low-pressure, 3–4 kbar bathozone. This pattern implies temperature gradients across the same relatively shallow crustal level, such as may occur due to advection of heat associated with magmas or fluids. This situation is seen in other localities in Figs. 4 and 20.

**Metamorphic P–T paths**

Mineral microtextures allow inferences to be made about the P–T path of metamorphic rocks of the TNB. The lowest grade, middle amphibolite-facies pelite from the Pipe II mine contains staurolite, andalusite, and sillimanite, in which staur- olite is locally observed as inclusions in andalusite and prismatic sillimanite is rarely observed as an overgrowth on andalusite (Couëslan et al. 2011). Fibrous sillimanite is also prevalent in the matrix. A sensibly isobaric metamorphic P–T path can be inferred beginning in the field of stable staurolite, passing into the field of stable andalusite, and finally into the field of stable sillimanite (Fig. 21a). Although a P–T path of increasing pressure is also possible, the nearby occurrence of subsolidus K-feldspar + sillimanite-bearing assemblages, formed at a similar pressure of 3–4 kbar (Couëslan et al. 2011), favours the former. A similar path could be proposed for middle amphibolite-facies pelites in the vicinity of the city of Thompson where staurolite is typically rimmed by muscovite, and fibrous sillimanite has pseudomorphously replaced andalusite.

Middle amphibolite-facies aluminous greywacke from the Mystery Lake area locally contains staurolite porphyroblasts enclosed by cordierite with fibrous sillimanite present in the matrix. This implies a P–T path that passed through the field of stability for staurolite, into the field of coexisting staurolite and cordierite, and reached peak metamorphic conditions in (or possibly slightly beyond) the field of stable St + Crd + Sil (ca. 4.5 kbar, 600–650 °C; Fig. 21b).

Sillimanite pseudomorphs after andalusite are observed in upper amphibolite-facies semipelite from the Thompson mine area, and relict staurolite was reported as inclusions in plagioclase at the Thompson mine (Bleeker 1990). Estimated peak metamorphic pressures >4 kbar, based on the stability range of Kfs + Sil + Grt in upper amphibolite-facies pelite from Thompson mine, favours a P–T path of increasing pressure (Fig. 21a). Greywacke from the upper amphibolite-facies zone west of Thompson may have followed a similar P–T path as at Mystery Lake, as indicated by the presence of small, round inclusions of staurolite in both plagioclase and garnet, finishing in the field of stable Grt + Crd + Sil + melt (Fig. 21b).

In granulite-facies migmatitic pelites from Paint Lake, staurolite inclusions in garnet and pseudomorphous replacement of andalusite by sillimanite + cordierite suggests a P–T path that began in stability fields of staurolite and andalusite before attaining a peak metamorphic assemblage of Kfs + Crd + Grt (Fig. 21a). It is possible that the P–T path is more complicated that the simple partial loop in Fig. 21a.

Relict fibrous sillimanite at the core of cordierite porphyroblasts in greywacke, from the granulite-facies zone west of Mystery Lake, suggests a path continuing out of the field of stable sillimanite to a peak metamorphic assemblage in the field of stable Kfs + Crd + Grt (Fig. 21b). Garnet rimmed by cordierite is a common feature in rocks of pelite and aluminous greywacke bulk composition from the granulite-facies zones. This textural relationship may indicate decompression near peak metamorphic conditions, implying a clockwise P–T path.

The interpreted P–T paths for the majority of samples are characterized by a segment of increasing pressure and temperature (Fig. 21). Samples from the granulite-facies zones imply an interval of relatively high-temperature decompression (cordierite after garnet) after peak metamorphism. Although individual P–T paths may not be representative of the P–T path of the whole belt, the overall pattern seems to be a broadly clockwise P–T path. In contrast, the samples from Pipe mine in the middle amphibolite-facies zone are suggestive of an isobaric path.

**Geothermal gradients**

Geothermal gradients were calculated for eight locations in the TNB from Setting Lake in the south to Mystery Lake in the north (Fig. 4). Calculations were made using a crustal density of 2.77 g/cm³ (White et al. 2005) and assuming a linear gradient from the surface. The calculated gradients correspond to the instantaneous geothermal gradient at the time of peak metamorphic P–T conditions. The highest geothermal gradients were recorded by the isobarically metamorphosed rocks at Pipe mine where middle amphibolite-facies rocks indicate an average gradient of ca. 47 °C/km, and upper amphibolite-facies rocks an average gradient of ca. 51 °C/km. A slightly lower geothermal gradient of ca. 44 °C/km is suggested by the middle amphibolite-facies rocks at Ospwagan Lake. The geothermal gradient continued to decrease within the middle amphibolite-facies zone towards the north: at Mystery Lake, the geothermal gradient at the time of peak metamorphism was ca. 36 °C/km.

There is also a general decrease in the recorded geothermal gradient towards the north and west in upper amphibolite-facies rocks. At Setting Lake, the rocks indicate a gradient of ca. 45 °C/km. Although the gradient was higher at Pipe Mine (ca. 51 °C/km), it was lower at Thompson Mine (ca. 42 °C/km), and lower still in the upper amphibolite-facies zone west of Thompson (ca. 37 °C/km).

The lowest geothermal gradients are indicated by rocks from the granulite-facies zones. Rocks from the Paint Lake area indicate a geothermal gradient of ca. 32 °C/km, and rocks from the granulite-facies zone west of Mystery Lake indicate a gradient of ca. 36 °C/km. The presence of andalusite pseudomorphs in pelite at Paint Lake suggests an initially steeper geothermal gradient.

Geothermal gradients in the TNB are generally consistent with andalusite-to-sillimanite P–T paths and imply an external input of heat such as magmatism (e.g., England and Thompson 1984). There are few recognized intrusions of significant size that correlate with the timing of peak metamorphism (Zwanzig et al. 2003; Percival et al. 2004, 2005; Burnham et al. 2009; Machado et al. 2011a, 2011b). However, metre- to kilometre-scale, syn-D3 granitoid sheets and dykes occur in abundance throughout the TNB and may have advected heat from zones of crustal melting at greater depths. Metre-scale, syn-D3 to post-D3 granitoid dykes are also relatively common. An analogous mechanism has been proposed for the central Kisseynew Domain where crustal melts from the base of the Burntwood Group sedimentary pile migrated upwards, advecting heat to shallower crustal levels (White et al. 2005).
Fig. 22. A schematic model of the major tectonic phases in the Thompson Nickel Belt. The metamorphic-facies zones of Fig. 4 correspond to the shaded zones in this figure. (a) Thrusting of the Burntwood Group rocks onto the Superior craton margin along early D2 faults. (b) Creation of a thrust and nappe stack, which consists of reworked Archean gneiss and Ospregan Group rocks with intercalations of Burntwood Group rocks, during the main D2 phase. (c) The metamorphic-facies zones were likely established prior to D2 and were deformed by upright F3–F4 folding accompanied by steeply east-dipping mylonite zones that record vertical stretching and sinistral movement. (d) Continued differential uplift along D3–D4 structures lead to the present-day distribution of metamorphic-facies zones as presented in this schematic cross section along line X–X' on Fig. 4.
Timing of metamorphism with respect to deformation

The majority of prograde metamorphic minerals in the TNB are either synchronous with or wrapped by the dominant $S_2$ foliation. Garnet and cordierite commonly contain inclusion trails of minerals oriented parallel to $S_2$, which implies growth during the $D_2$ event. In the granulite-facies zones, cordierite locally overgrows $S_2$, suggesting protracted growth that outlasted $D_2$. Leucosome and leucocratic segregations are typically parallel to and wrapped by $S_2$; however, in the granulite-facies zone at Paint Lake, leucosome locally in-fills $S_2$ boudin necks, and irregular pools have also been noted that crosscut $S_2$ (Fig. 8h). In the upper amphibolite-facies zones, randomly oriented muscovite has locally replaced both K-feldspar and sillimanite, and this unoriented muscovite is in turn crosscut by $S_3$ muscovite, biotite, and chlorite. These observations indicate that prograde metamorphism occurred during and possibly outlasted $D_2$, and was followed by a period of quiescence and some cooling, prior to $D_3$. Greenschist-facies assemblages associated with $S_3$ and later fabrics have been identified in rocks of most bulk compositions throughout the TNB.

Local exceptions to this general pattern are rare occurrences of fibrous sillimanite reoriented parallel to $S_2$ at Pipe II mine (Couéslan et al. 2011) and at Setting Lake (Zwanzig 1998). This texture could be interpreted to indicate that peak metamorphic conditions prevailed into $D_3$, although mechanical reorientation of fine-grained sillimanite in $D_3$ is also a possibility.

Tectonic implications

The parallel spatial relationship between the upright, doubly plunging $F_3$–$F_4$ structures and shear zones, and the metamorphic domains, isograds, and bathozones (Figs. 3, 4, 20) suggests that the isograd surfaces were largely established prior to the $D_3$ event. The metamorphic domains were then deformed into their current positions during the combined folding and faulting of $D_3$–$D_4$. There is locally a strong correlation between the metamorphic domains and $F_3$–$F_4$ fold structures. For example, the middle amphibolite-facies zones appear to correlate with synclines or structural basins north of Setting Lake, and stretching from the Pipe mine to beyond Mystery Lake. In areas such as the upper amphibolite-facies zone between Osowagan and Paint lakes, however, the metamorphic field gradient appears to be developed at a significantly longer wavelength than finely corrugated $F_3$–$F_4$ folding. This may imply that major $D_3$–$D_4$ shear zones had a stronger influence on the distribution of metamorphic domains (Fig. 22).

Mylonite zones with subvertical stretching lineations parallel the limbs of $F_3$–$F_4$ fold structures and indicate substantial vertical movement (Bleeker 1990). Some of the more significant shear zones also correlate with the boundaries between both metamorphic zones and bathozones (Figs. 3, 4, 20, 22). The Superior Boundary Fault along the west shore of Osowagan Lake, and an unnamed mylonite zone along the east shore, correlate with the boundary between the middle amphibolite-facies and upper amphibolite-facies zones as well as the 4 kbar boundary between the low-pressure and intermediate-pressure bathozones. The Burntwood mylonite zone coincides with the boundary between middle amphibolite-facies rocks in the city of Thompson – Mystery Lake area, and upper amphibolite-facies rocks of the Thompson structure, and the Grass River lineament coincides with the west boundary of the Paint Lake granulite domain.

In the southern exposed part of the TNB, there appears to be less variation in metamorphic grade and fewer isograds. Either the vertical deformation that accompanied the $D_3$–$D_4$ event was less intense, or there may have been a change in the metamorphic history of this portion of the belt in which high-grade metamorphism continued during the $D_2$ event (Zwanzig 1998). The later $D_3$ event of Zwanzig (1998) may not have produced enough vertical movement to juxtapose zones of significantly varying metamorphic grade. Another possibility is that occurrences of Osowagan Group rocks and other lithologies that develop useful metamorphic mineral assemblages are less abundant in the southern part of the belt, so that the apparent lack of metamorphic variation could be an artifact of insufficient data.

Although all current tectonic models for the TNB include a period of transpression (Bleeker 1990; White et al. 1999; Burnham et al. 2009), the duration of this transpression event remains in question. The long-lived transpression model of Machado et al. (2011a) predicts that variations in metamorphic grade will not follow a systematic distribution across the belt. In contrast, this study shows that there is a systematic variation in metamorphic grade, with a correlation between the distribution of metamorphic zones and $D_3$–$D_4$ structures of the nappe-tectonics model (Bleeker 1990).

Evolution of the nappe-tectonics model has led to the suggestion that northwest- or west-northwest-directed convergence between the Superior craton and the Reindeer Zone was greatest at the Thompson promontory (Fig. 1; White et al. 1999, 2002; Kuiper et al. 2011). Greater convergence towards the Thompson promontory would explain the apparent plunge of the TNB towards the north, as manifested by the closure of the 3–4 kbar bathozone towards the north, and increasing metamorphic grades towards the north.

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