Abstract

Alteration zones around a volcanogenic Cu–Zn–Au massive sulfide deposit in the Paleo-Proterozoic Trans-Hudson Orogen at Photo Lake, near Snow Lake, Manitoba, and in the Kisseynew Domain experienced multiple stages of metamorphism and metasomatic alteration during the deformation events. In the Snow Lake area, F₁ produced a chlorite-grade schistosity. During F₂, pressure increased by 1–2 kbar, and temperature increased by 10–50°C, up to approximately 5 kbar and 550°C, at which time most of the F₂ strain occurred, destroying most evidence of S₁. This was followed by a continued temperature increase of 10–20°C. Peak metamorphic, syn-F₂ assemblages in the altered volcanic rocks include staurolite + garnet + biotite, and kyanite + chlorite. F₃ produced a crenulation of S₂, along with minor chloritization at 400–450°C. In alteration zones in the Kisseynew Domain, S₁ is obscure, but garnet grew prior to, during, and after the development of the S₂ fabric, as is the case at Snow Lake. Likewise, metamorphic conditions during F₃ were similar to those at Snow Lake during F₂. However, rocks in the Kisseynew Domain were heated another 100–150°C after growth of the garnet, as shown by the assemblage sillimanite + garnet + biotite and geothermometry. They also acquired a gneissic fabric at or near the thermal peak of metamorphism. Garnet + cordierite assemblages and geobarometry suggest that metamorphic pressures during the thermal peak were similar to those at garnet grade. The final heating event occurred after F₂ deformation, and requires a source of heat localized under the Kisseynew Domain. Likely scenarios include emplacement of plutons in and under the Kisseynew Domain during F₂.

Keywords: Snow Lake, Trans-Hudson Orogen, Kisseynew Domain, metamorphic petrology, P–T paths, Manitoba.

Sommaire

Les zones d’altération entourant un gisement volcanogénique de sulfures massifs à Cu–Zn–Au de la ceinture orogénique paléoproterozoïque de Trans-Hudson, au lac Photo, près du lac Snow, au Manitoba, et dans le domaine adjacent de Kisseynew, ont subi plusieurs stades de métamorphisme et d’altération métasomatique lors des événements de déformation. Dans la région du lac Snow, F₁ a produit une schistosité dans le champ de stabilité de la chlorite. Au cours de F₂, la pression a augmenté de 1 à 2 kbar, et la température, de 10 à 50°C, jusqu’à un seuil d’environ 5 kbar et 550°C; c’est à ce stade que la plupart de la déformation F₂ a affecté ces roches, oblitérant par le fait même les signes de S₁. Cet épisode a été suivi par une augmentation continue en température de 10 à 20°C. Parmi les assemblages typiques du paroxysme métamorphique, formés pendant F₂ dans les roches volcaniques altérées, figurent les associations staurolite + garnet + biotite, et kyanite + chlorite. F₃ a produit un plissement de S₂, avec une légère chloritisation à 400–450°C. Dans les zones d’altération du domaine de Kisseynew, S₁ est obscur; en revanche, le garnet s’est formé avant, pendant, et après le développement de S₂, tout comme c’était le cas au lac Snow. De même, les conditions du métamorphisme au cours de F₂ étaient semblables à celles dans la région du lac Snow. Par contre, les roches du domaine de Kisseynew ont été réchauffées environ 100 à 150°C après la croissance du garnet, comme le témoignent les assemblages à sillimanite + garnet + biotite et la géothermométrie. Ces roches ont de plus acquis une gneissosité lors du maximum thermique. Les assemblages à garnet + cordiérite et la géobarométrie font penser que la pression atteinte lors du maximum thermique ressemblait à celle dans le faciès à garnet. L’événement thermique final a eu lieu après la déformation F₂, et requiert une source de chaleur en dessous du domaine de Kisseynew. Il est probable que la mise en place de plutons dans et sous ce socle au cours de F₂ en soit la cause.

(Mots-clés: lac Snow, ceinture orogénique Trans-Hudson, domaine de Kisseynew, pétrologie métamorphique, tracé P–T, Manitoba.)

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INTRODUCTION

The Flin Flon greenstone belt and the Kisseynew gneiss domain in northern Manitoba (Fig. 1) have been the focus of recent lithological and structural mapping, geochronology, geochemistry, and geophysics undertaken during collaborative efforts by geologists involved with the Lithoprobe Trans-Hudson Orogen Transect, the Geological Survey of Canada's Shield Margin Project, and the Manitoba Energy and Mines. The resulting explosion of new data and interpretations provides an ideal framework for studies of metamorphic petrology focused on understanding the tectonic history of the region. In this paper, we present detailed

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Fig. 1. Geology of the Snow Lake area, with location of samples marked by asterisks (Bailes 1996). Inset shows location of Lithoprobe seismic lines (Lucas et al. 1994, Kraus & Williams 1993). In the Snow Lake area, the Kisseynew Domain is interleaved with the Flin Flon Belt along the marked faults. HLGD: Herblent Lake gneiss dome, RLP: Reed Lake pluton, WLP: Wekusko Lake pluton.
results on the metamorphic petrology of a few samples from the Flin Flon Belt at Snow Lake and from the Kisseynew Domain to the north, and use those results to interpret the regional tectonic evolution.

REGIONAL SETTING

The Snow Lake area straddles the boundary between the Flin Flon greenstone belt to the south and the Kisseynew gneiss domain to the north (Fig. 1). Volcanic rocks of the Flin Flon belt at Snow Lake are mainly of island-arc affinity, with minor units of ocean-floor rocks (Bailes 1988, Stern et al. 1995, Bailes & Galley 1996). The Kisseynew gneisses at Snow Lake consist mainly of the Burntwood Group metaturbidites and correlative Missi Group fluvial-deltaic metasandstones (Froese & Moore 1980).

Lithoprobe seismic reflection lines 5 and 7, which cross the Flin Flon Belt and the southern part of the Kisseynew Domain (Fig. 1), have been interpreted by Lucas et al. (1994) to show isoclinal folding and thrust faulting of the Kisseynew Domain southward over the Flin Flon Belt (Fig. 2). We interpret this to be our F2 event at Snow Lake. Figure 2 was constructed from seismic data, and hence displays fewer and different units than the geological map in Figure 1. The thrust sheets and fault slices have an apparent thickness of ca. 4 km below the present erosion-surface. However, the total thickness of overthrusting is ambiguous because of the effects of erosion and the possibility of stacking of repeated thrusts and isoclinal fold sheets.

GEOLGY OF SNOW LAKE

Stratigraphy and structure

Stratigraphic units and F1–F2 structures in the Snow Lake area have recently been mapped by Bailes (1996), Bailes & Galley (1992), Bailes & Simms (1994), and Kraus & Williams (1993, 1994, 1995). Volcanic rocks and synvolcanic tonalites were emplaced at approximately 1.89 Ga (Machado & David 1992, David et al. 1996). Sedimentary rocks of the Missi Group are younger than 1845 Ma (Ansdell et al. 1992) and broadly correlative with sedimentary rocks of the Burntwood Group in the Kisseynew Domain (David et al. 1996).

At Snow Lake, rocks of the Kisseynew Domain and Flin Flon Belt were structurally interleaved during F1 and F2 deformation, producing a zone that is characteristic of the “south flank” of the Kisseynew Domain (Kraus & Williams 1994). F2 produced tight to
isochemical cleavage and a muscovite cleavage in the Snow Lake area (Froese & Moore 1980, Kraus & Williams 1994) prior to emplacement of the 1840–1834 Ma Wekusko granite (Gordon et al. 1990, David et al. 1996), which cross-cuts F1 folds (Bailes 1992, Kraus & Williams 1995). F2 folds at Snow Lake area are displayed in map relations and manifest as a crenulation cleavage that wraps around the porphyroblasts formed at the peak of metamorphism (Kraus & Williams 1994). Metamorphism during F2 has been dated at 1810 Ma, based on titanite ages from the Anderson–Stall rhylite (Machado & David 1992). F3 produced upright, open folds during retrograde metamorphism at 1800–1790 Ma (Kraus & Williams 1995, Parent et al. 1995). F4 produced east–west-trending folds around gneiss domes in the southern flank of the Kisseynew Domain (Kraus & Williams 1994). Subsequent brittle faults (Bailes & Galley 1992) are associated with minor alteration to pumpellyite (unpubl. data).

**Metamorphism**

Metamorphism in the Snow Lake area has been the subject of several previous studies (Froese & Gasparini 1975, Bailes & McRitchie 1978, Hutcheon 1979, Froese & Moore 1980, Trombat 1986, Aggarwal & Nesbitt 1987, Bryndza & Scott 1987, Bristol & Froese 1989, Zaleski et al. 1991, Kraus & Menard 1997). These studies documented isograd reactions and compositions of minerals, and established the general trend of increasing metamorphic grade to the north. Hutcheon (1979) found that the Fe/(Fe + Mg) of silicate minerals in sulfide-bearing samples is lower than in samples without sulfides. Zaleski et al. (1991) showed that the assemblage kyanite + biotite + chlorite in the Linda deposit appears as the result of Mg- and F-rich biotite and not of the common isogradic reaction St + Chl + Ms + Qtz = Ky + Bt + H2O. Here and elsewhere, mineral symbols follow Kretz (1983). Rare sillimanite was reported from the Anderson Lake deposit in the Snow Lake area (Aggarwal & Nesbitt 1987), which would suggest that metamorphic conditions were near the kyanite–sillimanite phase boundary at some stage of the metamorphic history.

Metamorphism of alteration zones around volcanogenic massive sulfide deposits in the Snow Lake area involved additional stages of compositional alteration during and after the thermal peak of metamorphism (Menard & Gordon 1995). In several locations across the study area, 5- to 20-m-long sections of diamond-drill core now consist of chlorite schist with variable amounts of plagioclase and other minerals. Minerals preserved in the core of porphyroblasts indicate that the rocks had contained biotite and hornblende and may have been diorite. These features may reflect synmetamorphic flow of fluid focused along faults.

**Ore deposits**

The Snow Lake area contains numerous volcanogenic massive sulfide deposits and mesothermal gold deposits. Exploration and mining activities in the area provided access to altered volcanic rocks in the Photo Lake Cu–Zn–Au mine, operated by Hudson Bay Exploration & Development Company, and the New Britannia gold mine (formerly the Nor-Acme mine), operated by TVX Gold, Inc., which is the largest known gold deposit in the Trans-Hudson Orogen. The geochemistry of alteration in the volcanogenic massive sulfide (VMS) deposits was studied at the Chisel Lake deposit by Galley et al. (1993) and at the Cook Lake deposit by Hodges & Manojlovic (1993).

**METHODS**

More than 600 samples of rocks from outcrops, diamond-drill core, and underground exposures in mines were collected from the study area. More than 200 samples from the Flin Flon belt and the Kisseynew Domain in the Snow Lake area, and 10 samples from the Kisseynew gneisses were selected for petrographic analysis to provide geographic distribution and a variety of rock types. From these, 20 samples that contain appropriate mineral assemblages and obvious deformation-related fabrics were selected for electron-microprobe analysis at the University of Calgary and the University of Alberta. The program of analyses included spot analyses, using oxides and natural minerals as standards and secondary standards, back-scattered electron imaging, and X-ray maps of the compositions of mineral grains. Thermobarometric estimates were calculated using the following calibrations: garnet + biotite (Kleeman & Reinhardt 1994), garnet + chlorite (Dickenson & Hewitt 1986) with Berman's (1990) garnet model, garnet + plagioclase + biotite + muscovite (Hodges & Crowl 1985, Powell & Holland 1988, Hohn 1990), and garnet + plagioclase + biotite + quartz (Hohn 1990). The resulting pressures and temperatures were compared with results from the WebINVEQ thermobarometry program (Gordon 1992, Gordon et al. 1994), using thermodynamic data from Berman (1988), as modified in Berman (1991), and activity models for garnet (Berman 1990, Berman & Koziol 1991), amphibole (Mäder et al. 1994), biotite (McMullin et al. 1991), and plagioclase (Fuhrman & Lindsley 1988).

The sequence of pressures and temperatures experienced by a rock during metamorphism reflects the tectonic processes operating at the time, and can be recorded by the history of metamorphic reactions and compositional zoning of the minerals. The theoretical background for computation of a metamorphic P–T path based on the Gibbs method is given by Spear & Selverstone (1983), and a comprehensive review was
given by Spear (1993). Briefly, calculation of a metamorphic P–T path usually requires that the following be known for a given rock: the history of metamorphic reactions, the assemblage of minerals and their compositions at some time, the pressure and temperature at that time, and the correlation between compositional zoning of two minerals. Uncertainties in the starting pressure, temperature, and some mineral compositions usually propagate into relatively small errors in the shape of the P–T path (Kohn 1993). Instead, the critical factor in constructing a P–T path is the correlation of compositional zoning in the minerals. Precision in the calculated P–T path is usually much better than in paths constructed by thermobarometry. The necessary differential thermodynamic equations can be written without using mineral abundances or the bulk-rock composition. Consequently, metasomatism does not affect the calculated P–T path. Calculations based on the Gibbs method were performed using the computer program of Spear et al. (1991) and thermodynamic data from Berman (1988). Thermodynamic data for phase components not listed by Berman (1988) were computed using the method of Kohn et al. (1993), with exchange values from Holland (1989) and data for ZnO from Robie et al. (1979). Nonideal activity models were used for garnet (Berman 1990), plagioclase (Newton et al. 1980), and H2O (Haa r et al. 1979). No miscibility gaps in subsolidus plagioclase were observed.

**MINERAL ASSEMBLAGES**

Samples described from Snow Lake come from metamorphosed alteration zones adjacent to the Photo Lake Cu–Zn–Au VMS deposit, 5 km southwest of the town of Snow Lake, and a possible northern extension of the Chisel Lake VMS deposit, 2 km south of the Photo Lake deposit. Metamorphosed altered volcanic rocks around the Snow Lake VMS deposits contain mineral assemblages that include garnet, staurolite, kyanite, quartz, chlorite, biotite, muscovite, and quartz (Hutchcon 1979, Froese & Moore 1980, Zaleski et al. 1991). Metasedimentary rocks at similar metamorphic grade from the town of Snow Lake are staurolite-bearing metaturbidites (Kraus & Williams 1994). We found samples containing the assemblage garnet + chlorite + quartz to be useful for textural analysis because they clearly display the relation between garnet growth and deformational events. Garnet grains in these samples overgrew the chlorite + quartz matrix, successively incorporating quartz grains and preserving the sequence of deformational microfabrics. We also examined samples from a number of different alteration zones that at garnet grade contained the assemblage garnet + biotite + chlorite + plagioclase + quartz + muscovite ± staurolite, in order to obtain detailed correlation of structural events with metamorphic events across the region. These samples were used for analysis of P–T path because they have a relatively low variance and contain minerals that preserve compositional zoning.

A key element of the metamorphic P–T paths described below is the interpretation of the mineral assemblage present at the time of garnet growth. A significant challenge in the interpretation arises where some minerals previously in the garnet-grade assemblage are not preserved in the final assemblage. Chlorite, for example, is commonly consumed during growth, and there may or may not be any chlorite left over at the end of garnet growth. In our opinion, the chlorite was consumed during garnet growth in all samples described here, on the basis of phase petrology correlation from rocks where it is still present, and our experience in other terranes, where the abundance of chlorite decreases with increasing grade and growth of garnet (Menard & Spear 1994).

In our opinion also, some samples described below contained muscovite during garnet growth. Muscovite is common in altered volcanic rocks from Snow Lake, and the mineral assemblages of samples that still contain muscovite are listed in Table 1. These assemblages are similar to those in metapelites; thus it is not surprising that muscovite may have been present during growth of garnet in some rocks. Sample CH93–11–3601, described below, contains no muscovite or plagioclase, and only minor biotite, and likely never contained significant amounts of muscovite. The other samples described, in contrast, do contain biotite and plagioclase. They likely also contained muscovite, by analogy with samples from the area that still do contain muscovite, but the muscovite was consumed during prograde metamorphism.

We contend that some samples described below contained epidote or calcite during garnet growth. An additional Ca-bearing phase such as epidote or calcite is required if there was simultaneous net growth of garnet and plagioclase. Epidote and calcite are commonly consumed in calcic pelites during growth of garnet and plagioclase, and it can be difficult to find traces of them.

| TABLE 1. MINERAL ASSEMBLAGES CONTAINING MUSCOVITE, PHOTO LAKE DEPOSIT |
|------------------|------------------|
| Ky + Bt + Chl +  | Qtz + Ms         |
| Ky +             | Qtz + Ms         |
| St + Grt + Bt +  | Qtz + Ms + Mag   |
| St + Grt + Bt +  | Qtz + Ms + sulfides |
| St + Bt + Chl +  | Qtz + Ms + sulfides |
| St + Bt + Pl +   | Qtz + Ms + sulfides |
| St + Pl +        | Qtz + Ms + sulfides |
| Grt + Bt + Pl +  | Qtz + Ms + Opq   |
| Bt + Pl +        | Qtz + Ms + sulfides |
| Bt + Chl +       | Qtz + Ms + Ilm   |
| Bt + Pl +        | Qtz + Ms         |
| Bt +             | Qtz + Ms + Opq   |
| Chl +            | Qtz + Ms         |

Opq = Ilm, Mag, or sulfides
Fig. 3. Deformational fabrics at Snow Lake. (a) Photomicrograph of sample CH93–11–3601 showing three deformational fabrics: the garnet core overgrew the $S_1$ fabric early during $F_2$, the rim overgrew the $S_2$ fabric, and the $S_2$ fabric in the matrix was crenulated by $F_3$. (b) Compositional zoning of garnet in sample CH93–11–3601 along traverse indicated in (a). Note that Fe/(Fe + Mg) decreases continuously across the textural break (dashed line) marked by the trails of inclusions. The symbols mark locations of 633 analyses.

TABLE 2. MINERAL COMPOSITIONS USED FOR REPRESENTATIVE P–T RESULTS

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mineral</th>
<th>$#$</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>TiO$_2$</th>
<th>MgO</th>
<th>FeO</th>
<th>MnO</th>
<th>CaO</th>
<th>Na$_2$O</th>
<th>K$_2$O</th>
<th>ZnO</th>
<th>Wt% Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>DUB54–1401</td>
<td>Grt A rim</td>
<td>3</td>
<td>37.7</td>
<td>21.1</td>
<td>na</td>
<td>3.90</td>
<td>30.4</td>
<td>5.81</td>
<td>2.60</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>101.5</td>
</tr>
<tr>
<td>DUB54–1401</td>
<td>Grt A core</td>
<td>3</td>
<td>37.6</td>
<td>20.8</td>
<td>na</td>
<td>2.68</td>
<td>26.2</td>
<td>9.73</td>
<td>3.73</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>100.7</td>
</tr>
<tr>
<td>DUB54–1401</td>
<td>Grt B core</td>
<td>3</td>
<td>37.5</td>
<td>19.6</td>
<td>na</td>
<td>1.65</td>
<td>21.1</td>
<td>15.40</td>
<td>4.71</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>100.0</td>
</tr>
<tr>
<td>DUB54–1401</td>
<td>Bt</td>
<td>3</td>
<td>37.0</td>
<td>18.9</td>
<td>na</td>
<td>13.80</td>
<td>16.6</td>
<td>&lt;0.20</td>
<td>0.50</td>
<td>&lt;0.20</td>
<td>9.17</td>
<td>na</td>
<td>96.0</td>
</tr>
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<td>DUB54–1401</td>
<td>Chl retro</td>
<td>3</td>
<td>25.6</td>
<td>23.9</td>
<td>&lt;0.20</td>
<td>20.50</td>
<td>19.9</td>
<td>0.24</td>
<td>&lt;0.20</td>
<td>&lt;0.20</td>
<td>&lt;0.20</td>
<td>na</td>
<td>90.1</td>
</tr>
<tr>
<td>DUB85–1137</td>
<td>Chl</td>
<td>8</td>
<td>25.0</td>
<td>24.1</td>
<td>0.06</td>
<td>16.10</td>
<td>24.2</td>
<td>0.06</td>
<td>&lt;0.20</td>
<td>&lt;0.20</td>
<td>&lt;0.20</td>
<td>na</td>
<td>89.5</td>
</tr>
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<td>DUB85–1137</td>
<td>Grt rim</td>
<td>3</td>
<td>37.8</td>
<td>22.2</td>
<td>na</td>
<td>2.89</td>
<td>34.7</td>
<td>1.30</td>
<td>2.48</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>101.4</td>
</tr>
<tr>
<td>DUB85–1137</td>
<td>Grt core</td>
<td>3</td>
<td>37.7</td>
<td>22.1</td>
<td>na</td>
<td>1.44</td>
<td>29.1</td>
<td>7.30</td>
<td>4.01</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>101.7</td>
</tr>
<tr>
<td>ZYL124–552</td>
<td>Gt mmt</td>
<td>3</td>
<td>37.7</td>
<td>21.3</td>
<td>na</td>
<td>3.65</td>
<td>33.2</td>
<td>3.58</td>
<td>2.24</td>
<td>na</td>
<td>na</td>
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<td>101.7</td>
</tr>
<tr>
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<td>Gt near mmt</td>
<td>3</td>
<td>38.6</td>
<td>21.6</td>
<td>na</td>
<td>7.64</td>
<td>29.8</td>
<td>1.07</td>
<td>2.41</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>101.1</td>
</tr>
<tr>
<td>ZYL124–552</td>
<td>Gt plateau</td>
<td>3</td>
<td>38.6</td>
<td>22.0</td>
<td>na</td>
<td>7.25</td>
<td>30.0</td>
<td>1.23</td>
<td>2.79</td>
<td>na</td>
<td>na</td>
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<tr>
<td>ZYL124–552</td>
<td>Gtd</td>
<td>4</td>
<td>42.9</td>
<td>17.4</td>
<td>0.23</td>
<td>13.00</td>
<td>23.2</td>
<td>0.40</td>
<td>0.51</td>
<td>1.63</td>
<td>&lt;0.20</td>
<td>na</td>
<td>99.3</td>
</tr>
<tr>
<td>ZYL124–552</td>
<td>St in Grt</td>
<td>1</td>
<td>26.9</td>
<td>54.9</td>
<td>0.59</td>
<td>3.54</td>
<td>12.7</td>
<td>0.12</td>
<td>&lt;0.20</td>
<td>&lt;0.20</td>
<td>1.29</td>
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<td>100.1</td>
</tr>
<tr>
<td>ZYL124–552</td>
<td>Bt</td>
<td>9</td>
<td>37.6</td>
<td>18.1</td>
<td>1.30</td>
<td>14.00</td>
<td>15.9</td>
<td>&lt;0.20</td>
<td>&lt;0.20</td>
<td>0.60</td>
<td>8.31</td>
<td>na</td>
<td>95.8</td>
</tr>
</tbody>
</table>

#: number of analytical data-sets averaged; retro: retrograde phase, in Grt: included in garnet; na: not analyzed.
in the rock (unpubl. data). Their early presence in a rock can be interpreted from phase petrology (simultaneous growth of garnet and plagioclase), rare inclusions in porphyroblasts, correlation from other similar rocks that still contain epidote or calcite, and the development of garnet with elevated and fairly constant proportion of the grossular component, $X_{Ga}$ (Menard & Spear 1993). Thus, we contend that some samples had an assemblage during garnet growth that is characteristic of metasedimentary calcic pelitic schists. Menard & Spear (1993) described the phase petrology of calcic pelitic schists from Vermont. One of their samples, TM825A from the Elizabeth Cu deposit, is a coarse garnet schist that is strikingly similar to samples DUB54–1401 and DUB85–1137 (described below). These three rocks contain large (1–4 cm) porphyroblasts of garnet, with trails of inclusions that preserve an early schistosity and contain plagioclase zoned with $X_{Aa}$ increasing toward the rim. Sample TM825A is also very similar to associated samples of calcic pelitic schist in Vermont in terms of the suite of minerals included in porphyroblasts, the textures of inclusion trails in porphyroblasts, the compositions of minerals, the patterns of compositional zoning of minerals, the calculated pressure and temperature, and the calculated P–T path (Menard & Spear 1993). The main differences are that sample TM825A contains larger crystals of garnet, less muscovite, and more plagioclase, which made the coarse garnet schist a mappable unit. Slack (1997a, b) re-interpreted the coarse garnet schists in Vermont as altered mid-ocean-ridge basalts on the basis of trace-element geochemistry. Thus, the altered volcanic rocks and the metasedimentary calcic pelitic schists in Vermont have similar mineral assemblages and similar metamorphic histories. A similar origin as altered volcanic rocks is obvious for the coarse garnet schists from Snow Lake, suggesting that the coarseness of the garnet from Snow Lake and from Vermont may be related to minor peculiarities in the bulk-rock composition of metamorphosed altered volcanic rocks.

A description of our samples and data follows.
Fig. 5. Simple garnet in sample DUB54–1401. (a) Photomicrograph showing \( S_1 \) fabric in the garnet core, and \( S_2 \) and \( S_3 \) fabrics in the matrix. The dark mica is biotite, the pale phyllosilicate is chlorite, and quartz and plagioclase appear white. (b) Compositional traverse across garnet in (a) (178 data points).

**Microstructures at Snow Lake**

We recognize three distinct deformational fabrics in samples of altered metavolcanic rocks from Snow Lake. \( S_1 \) and \( S_2 \) schistosities developed during prograde metamorphism at chlorite grade and near the thermal peak, respectively. They were both well developed, but \( S_3 \) commonly obscures \( S_1 \). Consequently, \( S_1 \) is best preserved as trails of inclusions within porphyroblasts. \( S_3 \) crenulation of \( S_2 \) developed during retrograde metamorphism at chlorite grade.

All three fabrics are exhibited in sample CH93–11–3601 (Fig. 3a), from near Chisel Lake (UTM 14U 6077800mN, 428900mE). The sample contains the assemblage garnet + chlorite + quartz + ilmenite, with minor biotite, sulfides, apatite, monazite, and zircon. It has less than 0.02% (by weight) \( K_2O \) and \( Na_2O \), and consequently contains no plagioclase or muscovite, and only minor biotite. Chlorite, quartz, and ilmenite in the matrix display an \( S_2 \) schistosity that was subsequently crenulated by \( F_3 \) (Fig. 3).

In this sample, \( S_1 \) and \( S_2 \) are displayed as internal foliations in garnet porphyroblasts, which typically have a pink core with abundant inclusions (quartz, ilmenite, chlorite, apatite, monazite, and trace sulfides) and a purple rim with few inclusions (Fig. 3). Abundant inclusions of quartz in the core display a weak, slightly bent \( S_1 \) fabric. Some round aggregates of quartz grains 1–2 mm across in the garnet core may be relict, recrystallized volcanic phenocrysts (Fig. 3a). The garnet rim contains inclusions of ilmenite aligned continuously with the matrix \( S_2 \) fabric, but at a high angle to trails of inclusions in the core. Garnet growth occurred during \( F_2 \), as indicated by bending of \( S_1 \) trails in the garnet core, and continued until after \( S_2 \) was fully developed, as indicated by the rim that overgrew \( S_2 \). Furthermore, garnet growth predated \( F_3 \), as indicated by the \( F_3 \) crenulation cleavage, which is found only in the matrix and not inside the garnet.

\( \text{Fe/(Fe+Mg)} \) zoning of the garnet decreases continuously from core to rim (Fig. 3b), which may indicate increasing temperature during garnet growth in this assemblage, by analogy with pelitic assemblages (Spear et al. 1990). The continuity of compositions from core to rim suggests that growth of garnet occurred throughout development of the \( S_3 \) fabric.
P–T PATH AT SNOW LAKE: SAMPLE DUB54–1401

**Description**

Sample DUB54–1401 from the Photo Lake deposit (UTM 14U 6080000mN, 429300mE) is an altered volcanic rock, for which a metamorphic P–T path was computed. The sample contains the assemblage garnet + biotite + plagioclase + quartz + ilmenite + pyrrhotite + chalcopyrite + sphalerite + S₂ chlorite, with minor staurolite, zincian spinel, apatite, and trace retrograde pyrite. Most of the sulfide is concentrated in a single layer in the sample, and appears not to have participated in net-transfer reactions with the silicate minerals. Biotite and chlorite are oriented in S₂, which is a crenulation fabric of S₁. Minor variation of biotite compositions (Al ranges from 1.63 to 1.73 atoms per formula unit, apfu, for example) may reflect partial modification during F₃ (Table 2). Compositions of chlorite are fairly uniform in the sample, with Fe/(Fe + Mg) ranging from 0.345 to 0.358.

Plagioclase grains in this sample are zoned, with a core of composition An₈₈ separated by a sharp break from a rim in which Xₐₙ increases outward from An₄₈ to An₈₈ (Fig. 4). The core of plagioclase grains contains abundant inclusions of quartz, whereas the rim contains
few inclusions. Fine laminations in the compositional zoning of some plagioclase grains replaced the S	extsubscript{2} foliation, which indicates that they postdate the S	extsubscript{1} foliation (not shown). Compositions of the rim of plagioclase grains in the matrix are similar to those of plagioclase included in the garnet. Some plagioclase grains were partially replaced by a second generation of biotite and chlorite, which likely are F	extsubscript{3} minerals.

In some grains of garnet, the core (X	extsubscript{Alm} = 0.58) contains abundant inclusions of quartz that display a faint shape fabric, whereas the rim (X	extsubscript{Alm} = 0.65) contains few inclusions (Fig. 5). The core of these grains overgrew the S	extsubscript{1} fabric, and the rim overgrew the S	extsubscript{2} fabric, as in sample CH93–11–3601 (above). Plagioclase grains with compositions of An	extsubscript{85-80} partially replaced the rim, and hence postdate the growth of the garnet.

The complete history of garnet compositions, however, is more complicated. A second type of grain of garnet (Fig. 6) has a rim with few inclusions and the same compositions as the previously described grain, a zone near the rim of thin inclusions of quartz that displays the S	extsubscript{1} fabric, an inner zone of coarse inclusions of quartz with some compositions matching the post-S	extsubscript{1} core of the first, and patches in the core with few inclusions and higher X	extsubscript{Sp} than the above-described garnet. These zones of high X	extsubscript{Sp} in the core likely are older than the garnet in Figure 5. X	extsubscript{Gr} in the core exhibits a sharp break in composition along an irregular zone that could have been a fracture healed by later growth of garnet. The other components, in contrast, are smoothly zoned in this region, possibly the result of minor, late modification by diffusion superimposed on a step-function zoning patterns similar to X	extsubscript{Gr}.

**Reaction history**

Matrix plagioclase (Fig. 4) and the first garnet grain (Fig. 5a) both display similar textures of trails of inclusions and hence likely grew at the same time. Thus, the decrease of X	extsubscript{An} from An	extsubscript{88} to An	extsubscript{48} occurred during development of the S	extsubscript{2} fabric, and correlates with the core–rim break in the first garnet. The correlation of the increase X	extsubscript{An} in the plagioclase rim to the garnet is less certain, as the plagioclase may have grown after garnet growth ceased. The simplest interpretation is that X	extsubscript{An} decreased during growth of the garnet, and increased during subsequent consumption of garnet. Garnet may have grown by a reaction like: Chl + Ms + Qtz = Grt + Bt + Pl + H	extsubscript{2}O. During F	extsubscript{3}, minor chlorite grew at the expense of plagioclase and biotite.

**Thermobarometry**

Using the garnet composition with the lowest X	extsubscript{Sp} near the rim of the grains and matrix biotite or chlorite compositions gives temperatures of approximately 560°C and 530°C, respectively. Using the garnet, biotite, An	extsubscript{48} plagioclase, with a fictitious pure muscovite gives maximum pressures of 3.5–5.0 kbar (assuming 550°C). The range of pressures results from differences in the calibrations used. Using the same minerals without muscovite gives pressures of 4.1 to 4.2 kbar (assuming 550°C). Use of WebINVEQ with garnet + biotite + plagioclase + muscovite gives similar results, 570°C and 4.8 kbar.

**P–T path**

Figure 7 shows the P–T path constructed for the time of garnet growth in this sample in the assemblage garnet + biotite + chlorite + plagioclase + quartz + muscovite + H	extsubscript{2}O (Table 3). The problem has a phase-rule variance of four, and a two-point path was calculated using X	extsubscript{Alm}, X	extsubscript{Sp}, X	extsubscript{Gr}, and X	extsubscript{An} as monitor variables. The P–T path for the time of garnet growth was computed backward in time from rim to core, but paths are...
Fig. 7. Metamorphic P–T paths for \( F_2 \) deformation determined in this study (solid arrows). Black arrows calculated for samples from the Photo Lake mine in Snow Lake; shaded arrow is estimated for samples from Wolverton Lake in the Kisseynew Domain (see Fig. 15). Both locations experienced increasing pressure during \( F_2 \) deformation at approximately the same time and P–T conditions, but subsequent heating was much greater in the Kisseynew Domain than at Snow Lake (dashed portion of grey arrow). The shaded box outlines the range of thermobarometric estimates of the peak conditions of metamorphism for the Kisseynew samples.

consistently reported in the forward direction. During growth of garnet, which textures show overlapped \( F_2 \), pressure increased by 1.1 kbar and temperature by 12°C. Uncertainty in this path may be as much as 10–25% of the changes in pressure and temperature, as a result of counting statistics in the analytical data, real compositional variability, and uncertainties in the thermodynamic data and mixing models. However, that does not affect the shape of the path or the tectonic implications. The critical factor for uncertainty in the path is the correlation of mineral compositions.

P–T PATH AT SNOW LAKE: SAMPLE DUB85–1137

Description

Sample DUB85–1137 (Fig. 8) is also from the Photo Lake deposit (UTM 14U 6080000mN, 429300mE). It contains the assemblage garnet + chlorite + plagioclase + quartz + magnetite, with minor pyrite, ilmenite and calcite. Garnet porphyroblasts contain inclusions of quartz that display a shape fabric in the garnet core and middle region (Fig. 9). The size of the quartz inclusions decreases from the core (20 x 60 \( \mu \)m and 20 x 100 \( \mu \)m) to the middle region (5 x 20 \( \mu \)m and 2 x 5 \( \mu \)m), although some larger grains relict from the time of growth of the garnet core also are included in the middle region. Quartz grains included in the core and middle region were resorbed by continued growth of garnet, as shown by facets on the garnet crystal impinging into the inclusions, obscuring the original ellipsoidal shapes of the inclusions. The garnet rim, by contrast, contains coarser (15 x 30 \( \mu \)m), unoriented inclusions of quartz. Thus the garnet core overgrew a \( S_1 \) fabric with thin grains of quartz, the garnet middle region overgrew a later fabric with thinner grains of quartz, and the rim overgrew the \( S_2 \) fabric with relatively coarse grains of quartz. In other samples, a similar coarsening of quartz grains is associated with the development of the \( S_2 \) schistosity. Apparently, \( S_1 \) was subparallel to \( S_2 \) at this location, or was rotated into parallelism. The absence of sharp textural breaks suggests that the garnet grew during a single metamorphic event that spanned \( F_2 \) deformation.
Garnet also contains inclusions of chalcopyrite, pyrite, and minor sphalerite in the core and middle region, and inclusions of magnetite in the rim (Fig. 9), indicating a change of assemblage from core to rim. The sulfide inclusions are resorbed and partially replaced by garnet, further indicating consumption of sulfides during growth of garnet. In addition, garnet contains inclusions of ilmenite, the core contains inclusions of calcite, and the middle region contains abundant inclusions of chlorite and minor An$_{36}$ plagioclase.

Garnet is compositionally zoned in domains (Fig. 9). Around inclusions of sulfide, values of $X_{\text{Alm}}$ and $X_{\text{Sp}}$ are similar to those at the rim. In contrast, $X_{\text{Grt}}$ is uniformly higher in the core than in the rim. These features suggest that $X_{\text{Alm}}$ and $X_{\text{Sp}}$ around sulfide inclusions were modified by diffusion after garnet growth. In a similar manner, compositions of the middle region of the garnet around the abundant inclusions of chlorite may have been modified by localized re-equilibration by diffusion.

The cores of plagioclase grains overgrew a thin quartz shape fabric ($4 \times 20 \mu\text{m}$, with some $20 \times 100 \mu\text{m}$), whereas their rims contain few inclusions of quartz grains (Fig. 10). Plagioclase grains are compositionally zoned from An$_{44}$ in the core to...
An\textsubscript{50} just beyond the thin quartz inclusions to An\textsubscript{43} at their rim. Trails of inclusions in the core of plagioclase grains vary in orientation from grain to grain, reflecting rotation of grains with respect to each other during F\textsubscript{3} crenulation.

Chlorite occurs as coarse, undeformed (recrystallized) grains aligned in the S\textsubscript{1}–S\textsubscript{2} fabric and in the S\textsubscript{3} crenulation fabric (Fig. 9). Coarse grains of quartz are interpreted as being formed during S\textsubscript{3}.

**Reaction history**

The petrography suggests that garnet and plagioclase grew by a reaction like:

\[
\text{Chl + Cal + Qtz = Grt + Pl + fluid}
\]

Calcite is preserved as relict inclusions in garnet. Furthermore, the petrography suggests that sulfides were removed from the sample during F\textsubscript{2} and associated growth of garnet by a reaction like:

\[
\text{Cpy + Py + Sp + O}_2 = \text{Mag} + \text{Cu}^{2+} + \text{Zn}^{2+} + \text{S}^{2-}
\]

Correlation of plagioclase compositions with garnet compositions is shown in Figure 9e. The rims of plagioclase and garnet are correlated on the basis of the sparseness of inclusions compared to their cores. The core and the An\textsubscript{50} ring in plagioclase contain the same size of quartz inclusions as does the middle region of
Fig. 9.e. Compositional traverse across garnet shown in Figure 8 and 9a, b, c, and d. Garnet compositions were modified around sulfide inclusions in the garnet core (322 data points). Also shown are An contents of correlated plagioclase

the garnet, indicating that these zones correlate. Inclusions of An\textsubscript{36} plagioclase in the middle region and outer portion of the garnet core support this correlation, and suggest that the garnet core grew with lower \textit{X}_{\text{An}} (possibly An\textsubscript{36-30}) plagioclase. The sequence of quartz textures during metamorphism is preserved in garnet grains in this and other samples, and suggests that correlation on the basis of these textures is reliable even though quartz was a reactant during garnet growth.

**Thermobarometry**

Thermometry using matrix chlorite with the lowest Fe/(Fe + Mg) garnet near the rim gives a temperature of ca. 540°C (assuming 5 kbar). In the absence of good barometers applicable to the assemblage in this sample, metamorphic pressures for the garnet rim were assigned as 5.0 kbar, consistent with data from other samples (above and unpubl. data), from Zaleski \textit{et al.} (1991), and from Kraus & Menard (1997).

**P-T path**

A P-T path (Fig. 7) was computed for the time of garnet growth in this sample in the assemblage garnet + chlorite + plagioclase + clinzoisite + quartz + H\textsubscript{2}O (Table 3). Clinzoisite is used as an approximation for calcite observed as inclusions in the garnet in order to reduce the variance of the problem to 4. Calculations in other assemblages indicate that this approximation produces only minor changes in the phase petrology computed (unpubl. data). Furthermore, clinzoisite may have been in the assemblage, even though relics were not found. The correlations of plagioclase with garnet discussed above were used in computing the path for the time spanning the development of the \textit{S\textsubscript{2}} foliation. This path shows a temperature increase of 30–40°C, followed by heating of 25°C and a pressure increase of 1.3 kbar.

**METAMORPHISM IN THE SOUTHERN KISSEYNEW DOMAIN**

Samples from the south flank of the Kisseynew Domain (Fig. 1) were collected from an alteration zone around a VMS deposit at the south end of Wolverton Lake, 8 km northeast of Snow Lake. Additional samples collected from the Wim VMS deposit on the west side of the Herblet Lake gneiss dome (Fedikow & Ziprick 1991) 16 km northeast of Snow Lake display a similar metamorphic history, but are not described here. Gneisses from the central Kisseynew Domain contain the assemblages sillimanite + garnet + biotite or garnet + cordierite, indicating that the peak pressure was less than 6 kbar (Bailles & McRitchie 1978, Spear 1993).

**MICROSTRUCTURES IN THE SOUTHERN KISSEYNEW DOMAIN**

Sample ZYL134–513, from the south end of Wolverton Lake (UTM 14U 6090800mN, 440200mE), contains the assemblage sillimanite + staurolite + garnet + biotite + quartz, with minor ilmenite, monazite, pyrite, and chalcopyrite. The core of garnet grains contains inclusions of fine-grained quartz that display an \textit{S\textsubscript{2}} shape fabric (Fig. 11). The rim of the garnet grains, in contrast, contains few inclusions of medium-grained quartz. The same textures occur in samples from Snow Lake (see above), suggesting comparable and possibly correlative growth of garnet and development of an \textit{S\textsubscript{2}} fabric in both places. The assemblage at the time of garnet growth (garnet + biotite + chlorite + quartz + ilmenite) suggests temperatures of 500–550°C, on the basis of our experience with similar rocks from other locations. Thermobarometric calculations for the time of \textit{F\textsubscript{2}} development were not made for this sample because of the lack of plagioclase.
Sample ZYL134–552 is from the same drill hole as sample ZYL134–513 (above). It is a gneiss that contains the assemblage garnet + biotite + plagioclase + gedrite + quartz + retrograde chlorite (Fig. 12). The gedrite contains inclusions of quartz, ilmenite, plagioclase, and biotite. Porphyroblasts of gedrite are generally oriented in the gneissic foliation, and hence grew later than garnet (see below). Minor retrograde chlorite partially replaced garnet and biotite.

Inclusions in the garnet core are relatively small and euhedral (Fig. 12), inclusions in a middle region are coarser, and inclusions in the garnet rim are sparse. Other samples from the same drill hole indicate that this textural change from the middle region to the rim marks the development of a deformational fabric older than the gneissosity. By correlation with the previous sample, we interpret the garnet-grade foliation as S₂.

Compositional zoning of garnet is shown in Figure 13. The garnet exhibits a general trend of decreasing $X_{Sp}$ from core to rim, and slightly increasing $X_{Ca}$ up to a plateau near the rim. Fe/(Fe + Mg) increases sharply in the outermost 1 mm of the garnet, in a pattern following the resorbed edges of the garnet, indicating that it is a relatively late, retrograde modification (later than possible re-equilibration by diffusion at peak conditions).

Porphyroblasts of garnet contain inclusions of staurolite, plagioclase, biotite, chlorite, quartz, and ilmenite. Compositions of plagioclase inclusions in garnet are strikingly zoned with respect to position in the grains of garnet (Fig. 14). Some plagioclase grains in the center of the garnet core have compositions of An₀₅, whereas others are zoned from An₀₅ to An₉₇, indicating increase of $X_{An}$ prior to growth of garnet. In the middle region, compositions of the rim of plagioclase inclusions decrease to An₄₄ with increasing distance from the core of the garnet. Near its rim, one plagioclase inclusion is zoned from An₄₄ to An₅₈, indicating a late increase of $X_{An}$ during garnet growth.

Fig. 10. Back-scattered electron image of plagioclase in sample DUB85–1137. The size and shape of the quartz inclusions suggest that the core and rim correlate with the middle region and rim of the garnet, respectively.
Staurolite occurs only as inclusions in garnet and plagioclase. Staurolite grains included in the garnet core are euhedral, whereas those in the middle region of the garnet were partially resorbed, indicating partial consumption of staurolite during growth of garnet. Furthermore, staurolite compositions vary with position in the garnet, from 0.18 atoms Zn per 48 atoms of oxygen in the garnet core to 0.39 atoms Zn in the garnet rim. Relict grains of staurolite included in plagioclase, by comparison, contain up to 0.47 apfu Zn, reflecting continued consumption of staurolite. Although the compositions appear stoichiometric (Table 2), the sum of the octahedrally coordinated cations is near 5, which suggests that the grains may be a rare occurrence of anhydrous staurolite (cf., Hawthorne et al. 1993, Holdaway et al. 1995). The Fe/(Fe + Mg) of staurolite inclusions varies with the composition of the surrounding garnet, allowing the interpretation that Fe and Mg of the staurolite were modified during diffusion of cations in the garnet. The same high-temperature event may have dehydrated staurolite grains preserved as isolated relics in the garnet, whereas staurolite grains in the matrix reacted with quartz and were removed.

In the matrix, plagioclase grains are compositionally zoned from An\textsubscript{99} to An\textsubscript{53} where they progressively replaced relict staurolite. Thus, replacement of staurolite by plagioclase correlates with plagioclase inclusions in the middle region of the garnet. Other plagioclase grains are zoned from An\textsubscript{53} to An\textsubscript{66}, which suggests that they grew at the same time as those in the garnet rim.

**Reaction history**

Prior to growth of garnet, the sample was fine grained and contained the assemblage chlorite + biotite + muscovite + plagioclase (An\textsubscript{99}) + calcite + quartz + ilmenite. The presence of muscovite is suggested by subsequent growth of biotite and correlation with muscovite-bearing samples from VMS deposits at lower metamorphic grade. Growth of plagioclase with increasing X\textsubscript{An} prior to garnet growth suggests that a Ca-bearing phase such as calcite was present early.
Subsequent consumption of plagioclase and growth of the garnet core and middle region occurred by a reaction such as: chlorite + plagioclase + muscovite + staurolite + quartz = garnet + biotite + fluid. When the rim plateau grew, staurolite was effectively gone from the assemblage, and $X_{\text{As}}$ started to increase. Subsequently, temperature increased, the gneissosity was developed, gedrite, some biotite, and some plagioclase grew, and quartz recrystallized and coarsened.

**Thermobarometry**

Thermometry based on compositions of the garnet rim and biotite in contact with garnet yields temperatures near 530°C, which are much lower than the peak temperature (see below). This finding supports the interpretation above that the garnet rim was modified during cooling. The effects of retrograde modification of composition appear to be limited to the edge of the

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Fig. 12. Photomicrograph of sample ZYL134–552 showing garnet that grew during $F_2$, inclusions of plagioclase and staurolite in the garnet, and gedrite aligned in gneissic fabric. The location of Figure 14 is outlined.
grains of garnet, but core compositions may have been modified as well at the thermal peak. Garnet compositions with the lowest Fe/(Fe + Mg) 0.8 mm from the rim provide the best available estimate of the compositions at the thermal peak of metamorphism (Spear 1993). Thermometry based on biotite and the near-rim compositions of the garnet gives peak temperatures of 685–700°C (assuming 6 kbar) (Fig. 7). Thermometry based on garnet + amphibole gives similar results (Graham & Powell 1984). Barometry based on the same garnet and biotite, matrix plagioclase and a fictive pure muscovite gives peak conditions of 6.3–6.8 kbar (assuming 700°C), and gives 6.8–7.7 kbar without muscovite. The WebINVEQ approach, using the assemblage garnet + biotite + plagioclase + gedrite, gives dissimilar results, 820°C and 4.5 kbar. In spite of the barometric calculations on this sample, the peak pressure must have been less than 6 kbar, because garnet + cordierite assemblages occur nearby and to the north in the central Kisseynew belt (Bailes & McRitchie 1978). Kraus & Menard (1997) calculated similar peak conditions of 670 °C and 6 kbar for a sample from a similar structural position 3 km to the west. Gordon et al. (1994) calculated dissimilar conditions of 580°C and 4.3 kbar for a sample from 45 km northeast of sample ZYL134–552 (and hence not in a similar structural position) and did not claim that these conditions were representative of the peak of metamorphism. Consequently, we prefer 650–700°C and 5–6 kbar as the best estimate of the peak conditions, and explain the discrepancy with our calculations as the result of garnet compositions that were incompletely re-equilibrated at peak conditions or partially reset after the peak of metamorphism. Thus, the peak temperatures are significantly higher than peak temperatures at Snow Lake, although the peak pressures are similar.

The conditions of metamorphism at the end of garnet growth are poorly known, but likely were similar to those at Snow Lake, on the basis of similar relationships of mineral growth to deformational events in similar assemblages in similar rocks. This similarity is most evident between sample ZYL134–513 (above) and the samples from Snow Lake (above). Although the Fe/(Fe + Mg) value of the garnet core is markedly higher in sample ZYL134–552 than in the Snow Lake samples, the rim compositions are similar (Table 2). The differences in composition of garnet core may simply reflect the different peak temperatures of the samples and partial re-equilibration in sample ZYL134–552, and the similarity of rim compositions may reflect similar retrograde temperatures.

On the basis of these similarities, we estimate that the temperatures at the end of garnet growth were likewise similar in both places, i.e., between 530 and 570°C. Compositions from sample ZYL134–552 for the garnet near-rim, An$_{50}$ plagioclase included in the garnet rim, matrix biotite, with an ideal muscovite yield poorly constrained maximum pressures of 5.1–6.3 kbar (assuming 550°C) and 4.7–5.3 kbar without muscovite, as estimates of conditions at the end of garnet growth.

**$P$–$T$ path**

Therefore, the pressure at the end of garnet growth for this sample may have been similar (within 1 kbar) to that at Snow Lake. Furthermore, pressure at the end of garnet growth for sample ZYL134–552 may have been similar to the peak pressure. Although there is no evidence for the shape of the path between these two points, the simplest scenario is that heating up to the peak temperatures was nearly isobaric (Fig. 7). Although compositional zoning of the garnet should not be used in calculating a $P$–$T$ path because of the possibility of modification by diffusion, a $P$–$T$ path for the time of garnet growth can be estimated. The following observations place constraints on the $P$–$T$ trajectory during garnet growth: garnet grew, staurolite was consumed, with increase in the Zn content (0.18 to 0.39 Zn atoms per 48 atoms of oxygen, or 0.04 to 0.08 $X_{Zn}$), and plagioclase was consumed, with decrease in $X_{An}$ ($An_{40}$ to $An_{50}$). The assemblage garnet +

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**Fig. 13. Compositional zoning of garnet in sample ZYL134–552 along traverse shown in Figure 12 (400 data points).**
staurolite + biotite + chlorite + plagioclase + quartz + muscovite + H₂O was modeled in a 10-component system (Table 3). The addition of mass-balance constraints (using mineral modes in the calculations) reduces the variance to 2, allowing isopleths to be contoured in P–T space. The composition of chlorite was estimated (Dickenson & Hewitt 1986) with the garnet activity model of Berman (1990), because prograde chlorite was not preserved. Figure 15 shows calculated isopleths of garnet composition and abundance, plagioclase composition (related to plagioclase abundance), and the Zn content of staurolite (inversely related to staurolite abundance). The path that best satisfies the available constraints is a nearly isothermal increase in pressure of 1–2 kbar. Uncertainty in the amount of muscovite does not propagate into a change of the model isopleths. Doubling the amount of chlorite in the model results in an insignificant change in the shape of the isopleths.

SUMMARY OF METAMORPHIC HISTORY

In our collection of samples, metamorphism during the F₁ isoclinal folding event is recorded by a chlorite + quartz or muscovite + quartz schistosity, depending on rock composition. These mineral assemblages suggest that temperatures during F₁ reached 300–400°C (Spear & Cheney 1989). Conditions of metamorphism during F₂ were broadly similar in the samples from Snow Lake and from the Kisseynew gneisses 8 and 16 km to the northeast. Pressure increased during F₂ by 1–2 kbar up to a maximum of ca. 5 kbar during minor heating of 10–40°C. The shape of this P–T path is similar to paths characteristic of terranes with nappe- or thrust-style deformation (Spear & Selverstone 1983, Spear 1993). A “nappe- or thrust-style” interpretation for F₂ folds at Snow Lake is consistent with interpretations of Lithoprobe seismic data for the south flank of the Kisseynew Domain (Fig. 2). We conclude that F₂ deformation produced 3–6 km of crustal thickening above samples at the level of the present erosion-surface at Snow Lake, and that the thickening was of similar magnitude across the study area.

The rim of the garnet in some Photo Lake samples (see above) and staurolite porphyroblasts in other samples (unpubl. data) overgrew S₂ and record a minor late heating event of ca. 10°C that postdates F₂. In contrast, our samples from the Kisseynew Domain display post-S₂–F₂ heating of 100–150°C. Some heating is expected following overthrusting or emplacement of nappes, simply by relaxation of the perturbed geotherms (England & Thompson 1984, Spear 1993), which explains the minor heating at Photo Lake. The much greater post-F₂ heating in the Kisseynew gneisses, however, requires that there be some additional cause for the heating. Several models are possible to explain the production of a thermal anomaly in the Kisseynew Domain immediately after F₂ shearing, including overthrusting, crustal thinning, emplacement of plutons, or crustal delamination. These models are discussed in the companion paper by Kraus & Menard (1997).

In the Snow Lake area, F₃ is displayed as minor chloritization associated with development of a crenulation cleavage and a locally important fluid-flow event (Menard & Gordon 1995).

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Fig. 15. Model isopleths of compositions of garnet ($X_{\text{alm}}$, $X_{\text{sps}}$, $X_{\text{grs}}$), plagioclase ($X_{\text{an}}$), and Zn in staurolite ($X_{\text{ZnSt}}$), and garnet abundance ($M_{\text{grt}}$) calculated for sample ZYL134–552. Petrological constraints (see text) suggest an increase of pressure at the time of garnet growth, as shown. The large dot indicates conditions at the end of garnet growth, and the shaded box indicates conditions at the peak of metamorphism. Thus, post-$F_2$ heating up to the thermal peak (dashed arrow) is interpreted to have been isobaric.
METAMORPHIC P-T PATHS, SNOW LAKE, MANITOBA


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