1985

Paleomagnetism and geochronology of the Bird River Greenstone Belt.

Edwin Allan. Timmins
University of Windsor

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LA THÈSE A ÉTÉ MICROFILMÉE TELLE QUE NOUS L'AVONS RÊCUE
PALÆOMAGNETISK AND GEOCHRONOLOGY
OF THE BIRD RIVER GREENSTONE BELT

by

Edwin Allan Timmins

A Thesis submitted to the Faculty of Graduate Studies through the Department of Geology in partial fulfillment of the requirements for the Degree of Master of Applied Science in Geological Engineering at the University of Windsor

Windsor, Ontario, Canada

1985
ABSTRACT

The Bird River Greenstone Belt of southeastern Manitoba is an isoclinally-folded sequence of supracrustal rocks with an easternly-plunge within the English River structural subprovince of the Superior Province of the Canadian Shield. The sequence contains ultramafic to felsic metavolcanic and associated metasedimentary rocks of Archean age that belong to the Rice Lake Group. These rocks have been intruded by the chromafteferrous ultramafic Bird River Sill, several mafic synvolcanic stocks, the Maskwa Lake quartz diorite batholith and the Lac du Bonnet quartz monzonite batholith.

This study reports: 1) three preterctic metamorphic overprint events indicated by paleomagnetism and 2) four U-Pb zircon ages obtained for four rock units. These results are examined in relation to previously published Rb-Sr ages and field relationships. Two models are proposed for the evolution of the Bird River Greenstone Belt. In both models, the Rice Lake Group reflects the following sequence of events.

Cycle I volcanism terminated with the extrusion of the Peterson Creek felsic volcanics dated by the U-Pb method on zircon at 2741 Ma and by intrusion of the Bird River Sill dated by its U-Pb discordia at 2745 ± 6 (2σ) Ma. The age of Cycle II volcanism is given by a concordant U-Pb age of 2715 Ma obtained from a synvolcanic diorite stock intruded into the basal Bernic Lake mafic volcanics and metasediments. The upper limit of Cycle II is constrained only by a
prefolding paleomagnetic age of 2625 ± 6 (2σ) Ma from the thermal overprint produced by intrusion of the subsequent Lac du Bonnet batholith. The Maskwa Lake quartz diorite batholith gives a U-Pb discordia age of 2779 ± 64 Ma. In the first model, this old age is considered to be the age obtained from a basement rafter in this batholith. A pre-folding paleomagnetic thermal overprint in the Bird River Sill, and a previously published Rb-Sr whole rock isochron of 2590 ± 12 Ma and 2584 ± 12 Ma respectively, that date the age of the intrusion. In the second model, if the 2779 ± 64 Ma age for the batholith is accepted as an emplacement age, then the Maskwa Lake batholith is regarded as basement to the Bird River Greenstone Belt. For both models, the regional metamorphism is dated by a pre-folding paleomagnetic overprint at 2560 ± 7 Ma. The intrusion of the post-tectonic Cat Lake pegmatites, on the basis of previously published Rb-Sr ages, are assigned a 2442 ± 127 Ma to 2279 Ma age range. This places the regional folding at 2560 ± 7 Ma to 2442 Ma. A Paleozoic regional uplift for this area is postulated at about 444 Ma.
ACKNOWLEDGEMENTS

I wish to thank Dr. D.T.A. Symons and Dr. A. Turek for their patience and guidance through this thesis study. Field assistance by Mr. T. Vandall, Dr. W.D. McRitchie, Dr. R.F.J. Scoates, Dr. P. Theyer, and Mr. D. Watson was greatly appreciated. Lab assistance by Mr. B. Taylor, Mr. R. Keller, and thin section work by Mr. A. Knitl was also appreciated. Special thanks are due to Mr. Patrick Smith for doing the mass spectrometry runs for this study and also to Dr. J. Huang for some of the zircon chemistry and Dr. V.R. Van Schmus for use of the laboratory facilities at the University of Kansas. Clerical assistance by Miss. F. Taylor and Miss. A. Bacon was also greatly appreciated. Finally, I would like to thank my mother, Mary, and brother, Jeffery, for their encouragement and tolerance throughout my graduate program. This study has been financed by the Natural Science and Engineering Research Council of Canada, and by the University of Windsor through grants to Dr. D.T.A. Symons and Dr. A. Turek.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>i</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>iv</td>
</tr>
<tr>
<td>NOMENCLATURE</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>viii</td>
</tr>
<tr>
<td>I. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II. REGIONAL GEOLOGY</td>
<td></td>
</tr>
<tr>
<td>A. Stratigraphy</td>
<td>6</td>
</tr>
<tr>
<td>B. Structural Geology</td>
<td>19</td>
</tr>
<tr>
<td>C. Metamorphic Phases</td>
<td>24</td>
</tr>
<tr>
<td>III. PREVIOUS WORK</td>
<td>31</td>
</tr>
<tr>
<td>IV. SAMPLING AND MEASUREMENT</td>
<td></td>
</tr>
<tr>
<td>A. Paleomagnetic</td>
<td>39</td>
</tr>
<tr>
<td>B. Radiometric</td>
<td>44</td>
</tr>
<tr>
<td>V. PALEOMAGNETIC RESULTS</td>
<td></td>
</tr>
<tr>
<td>A. Population Level Screening Analysis</td>
<td>48</td>
</tr>
<tr>
<td>B. Bird River Sill</td>
<td>50</td>
</tr>
<tr>
<td>C. Bernic Lake Formation</td>
<td>66</td>
</tr>
<tr>
<td>VI. RADIOMETRIC RESULTS</td>
<td></td>
</tr>
<tr>
<td>A. Radiometric Theory</td>
<td>72</td>
</tr>
<tr>
<td>B. Analytical Results</td>
<td>80</td>
</tr>
<tr>
<td>VII. DISCUSSION</td>
<td>93</td>
</tr>
<tr>
<td>VIII. CONCLUSIONS AND RECOMMENDITIONS</td>
<td></td>
</tr>
<tr>
<td>A. Conclusions</td>
<td>101</td>
</tr>
<tr>
<td>B. Recommendations</td>
<td>103</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>105</td>
</tr>
<tr>
<td>APPENDICES</td>
<td>115</td>
</tr>
</tbody>
</table>
NOMENCLATURE

meter \text{ m}
kilogram \text{ kg}
kilometer \text{ km}
degree (angular) \text{ o}
degree (temperature) \text{ oC}
percentage \text{ %}
alpha \text{ } \alpha
gamma \text{ } \gamma
sigma \text{ } \sigma
Angular Standard Deviation \text{ ASD}
Intensity \text{ Int}
Magnetic Intensity Units \text{ Am}^{-1}\text{cm}^{-3}
milliTesla \text{ mT}
Natural Remanent Magnetization \text{ NRM}
Viscous Remanent Magnetization \text{ VRM}
Anhysteric Remanent Magnetization \text{ ARM}
FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Structural Subprovinces of the Superior Province and the location of the Study Area</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Location of the Bird River Greenstone Belt, Manitoba</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Stratigraphy of the Bird River Greenstone Belt</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>Stratigraphic Profile of the Bird River Sill</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>Structural Subareas of the Bird River Greenstone Belt</td>
<td>21</td>
</tr>
<tr>
<td>6</td>
<td>Metamorphic Facies of the Bird River Area</td>
<td>25</td>
</tr>
<tr>
<td>7</td>
<td>Metamorphic Subfacies of the Bird River Greenstone Belt</td>
<td>26</td>
</tr>
<tr>
<td>8</td>
<td>Radiometric age groupings for the English River Subprovince</td>
<td>38</td>
</tr>
<tr>
<td>9</td>
<td>Paleomagnetic site locations: Chrome property of the Bird River Sill</td>
<td>40</td>
</tr>
<tr>
<td>10</td>
<td>Paleomagnetic site locations: Bernic Lake Formation, Bird River Greenstone Belt</td>
<td>42</td>
</tr>
<tr>
<td>11</td>
<td>U-Pb sample locations: Bird River Greenstone Belt</td>
<td>47</td>
</tr>
<tr>
<td>12</td>
<td>Stereoplot of Vector Directions for the Bird River Sill before AF demagnetization in the NRM range without tectonic correction</td>
<td>52</td>
</tr>
<tr>
<td>13</td>
<td>Stereoplot of Vector Directions for the Bird River Sill before AF demagnetization in the NRM range with tectonic correction</td>
<td>53</td>
</tr>
<tr>
<td>14</td>
<td>Blocking and coercivity spectrums of magnetite and hematite</td>
<td>55</td>
</tr>
<tr>
<td>15</td>
<td>Mean Intensity on AF step demagnetization for 18 specimens: Bird River Sill</td>
<td>56</td>
</tr>
<tr>
<td>16</td>
<td>Stereoplot of Vector Directions of the Bird River Sill after AF bulk cleaning from 7.5 mT to 60 mT with tectonic correction</td>
<td>57</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>17</td>
<td>Stereoplot of Vector Directions of the Bird River Sill after a 2nd AF bulk cleaning of 30 mT and 40 mT with tectonic correction</td>
<td>60</td>
</tr>
<tr>
<td>18</td>
<td>Stereoplot of Vector Directions of the Chromite Bands of the Bird River Sill after AF demagnetization at 30 mT with tectonic correction</td>
<td>62</td>
</tr>
<tr>
<td>19</td>
<td>Stereoplot of Vector Directions of the Bird River Sill based on all three previous files with tectonic correction</td>
<td>65</td>
</tr>
<tr>
<td>20</td>
<td>Mean thermal intensity on thermal step demagnetization based on 18 specimens: Bird River Sill</td>
<td>67</td>
</tr>
<tr>
<td>21</td>
<td>Stereoplot of Vector Directions of the Bernic Lake Formation after AF demagnetization of 30 mT and 40 mT with tectonic correction</td>
<td>68</td>
</tr>
<tr>
<td>22</td>
<td>Mean AF intensity on AF step demagnetization based on 6 specimens: Bernic Lake Formation</td>
<td>70</td>
</tr>
<tr>
<td>23</td>
<td>Concordia Diagram of 3 proposed theoretical models</td>
<td>77</td>
</tr>
<tr>
<td>24</td>
<td>Unit 10a Great Falls - Maskwa Lake - Quartz Diorite - U-Pb discordia diagram</td>
<td>83</td>
</tr>
<tr>
<td>25</td>
<td>Unit 6a Synvolcanic Event - Diorite Phase U-Pb concordia diagram</td>
<td>85</td>
</tr>
<tr>
<td>26</td>
<td>Unit 4d Peterson Creek - Lapilli Tuff U-Pb discordia diagram</td>
<td>87</td>
</tr>
<tr>
<td>27</td>
<td>Unit 4d Peterson Creek - Lapilli Tuff U-Pb discordia-concordia diagram</td>
<td>88</td>
</tr>
<tr>
<td>28</td>
<td>Unit 3a Bird River Sill - Gabbroic Phase excluding ultramafic point - U-Pb discordia diagram</td>
<td>90</td>
</tr>
<tr>
<td>29</td>
<td>Unit 3a Bird River Sill - Gabbroic Phase including ultramafic point - U-Pb discordia diagram</td>
<td>92</td>
</tr>
<tr>
<td>30</td>
<td>Polar Wander Path for the Archean time frame of 2300 to 2700 Ma</td>
<td>97</td>
</tr>
</tbody>
</table>
# TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Table of Formations in the Bird River Area, Manitoba</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>Correlation of Metamorphism, Deformation, and Structural Analysis in metavolcanic and metasedimentary rocks of the Bird River area</td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>Metamorphic Facies of the Bird River Greenstone Belt, Manitoba</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>Radiometric Age Dates for the English River Subprovince and Surrounding Area: Manitoba</td>
<td>32</td>
</tr>
<tr>
<td>5</td>
<td>Radiometric Age Dates for the English River Subprovince and Surrounding Area: Ontario</td>
<td>36</td>
</tr>
<tr>
<td>6</td>
<td>Paleomagnetic Collection Data</td>
<td>41</td>
</tr>
<tr>
<td>7</td>
<td>U-Pb Sample Locations: Bird River Greenstone Belt</td>
<td>46</td>
</tr>
<tr>
<td>8</td>
<td>Bird River Sill AF Remanence Data (1st cleaning)</td>
<td>58</td>
</tr>
<tr>
<td>9</td>
<td>Bird River Sill AF Remanence Data (2nd cleaning)</td>
<td>61</td>
</tr>
<tr>
<td>10</td>
<td>Bird River Sill Paleomagnetic Pole Locations</td>
<td>64</td>
</tr>
<tr>
<td>11</td>
<td>Bernic Lake Formation AF Remanence Data</td>
<td>71</td>
</tr>
<tr>
<td>12</td>
<td>U-Pb isotope ratios and concentrations for all studied units</td>
<td>81</td>
</tr>
</tbody>
</table>
CHAPTER I
INTRODUCTION

The Archean Superior Province of the Canadian Precambrian Shield contains many definable and important greenstone belts. Most of these belts are composed of mafic to felsic volcanics and associated metasedimentary rocks including chemical sediments (Goodwin and Sklanka, 1969). These belts are important because many economic deposits of gold, iron ore, and base metals are hosted by them.

Geochronologic and paleomagnetic studies are useful in unraveling the complex histories of these Archean greenstone belts. Geochronology provides absolute ages for primary or metamorphic events while paleomagnetism provides a measure of tectonic movements (rotation and translation) of these belts relative to the absolute ages. The combination of both of these techniques permits delineation of any sequence of geological events recorded in such terrains.

The Bird River Greenstone Belt of southeastern Manitoba is part of the English River structural subprovince of the Superior province. The portion of this structural subprovince studied here is bounded on the north by the Uchi structural subprovince, on the east by the Manitoba-Ontario boundary, on the south by the Wabigoon structural subprovince, and on the west by Paleozoic cover (Figure 1). The Bird River Greenstone Belt is surrounded by early gneissic rocks of the English River subprovince (Figure 1) with the Manigatogan.
Figure 1 Structural Subprovinces of the Superior Province and the location of the study area (based on Beakhouse, 1977)
Ear Falls paragneissic belt on the north and the Winnipeg River batholithic belt to the south, all contained within the English River subprovince. This greenstone belt is of economic importance for its cesium-, tantalum-, and lithium-bearing pegmatites, and its strategic sub-ore grade chromite deposits within the Bird River Sill.

The study area is approximately 130 km northeast of Winnipeg (Figure 2) and is accessible from the town of Lac du Bonnet. The area is centered on the western boundary of the Nopiming Provincial Park along Provincial Road 314 between latitudes 95° 09' to 96° 00' W and longitudes 50° 20' to 50° 30' N.

This thesis is divided into eight chapters, Chapter I is the Introduction. In Chapter II, several aspects of regional geology are discussed while Chapter III outlines previous work conducted in the area. Chapter IV discusses sampling and measurement procedures and Chapters V and VI present the paleomagnetic and radiometric results, respectively. Chapter VII entitled 'Discussion' correlates all presented information with Chapter VIII listing conclusions and recommendations.

The purposes of this thesis study are:

1. to establish the geochronology of the Bird River Greenstone Belt;
2. to determine the tectonic and paleomagnetic history of the Bird River Sill and the Bernic Lake Formation;
Figure 2 Location of the Bird River Greenstone Belt, Manitoba (Hannatyne and Trueman, 1982)
3. to establish if the intrusion of the Bird River Sill represents the initial stage of Kenoran metamorphism and deformation of the Rice Lake Group and of the Bird River Greenstone Belt;

4. to determine if the culmination of the Kenoran orogeny is associated with post-tectonic granitic and pegmatitic intrusions;

5. to test the hypothesis of the existence of more than one orogenic event as postulated by Krogh et al. (1974) in the study area;

6. to outline a detailed evolutionary history for the belt based on geochronology, paleomagnetism, structural relationships and stratigraphy;

7. to provide the chronostratigraphy for the area.
CHAPTER II
REGIONAL GEOLOGY

A. Stratigraphy

The Bird River Greenstone Belt is comprised predominantly of layered rocks of the Rice Lake Group. Intrusive rocks within the belt have been subdivided on the basis of field relationships, composition and internal structure into synvolcanic, syn-tectonic and late-tectonic events (Trueman, 1980). Six formations subdivide the Rice Lake Group which in order of age from oldest to youngest are termed: the Eaglenest Formation, the Lamprey Falls Formation, the Peterson Creek Formation, the Bernic Lake Formation, the Flanders Lake Formation and the Booster Lake Formation (Table 1). Units within the Bird River Greenstone Belt have been described in detail by Cerny et al. (1981), Trueman (1980), McRitchie and Weber (1971) and Davies (1952, 1955, 1956, 1957).

1. Clastic Rocks
   a. The Eaglenest Formation

The Eaglenest Formation is considered to be the oldest unit in the greenstone belt on the basis of stratigraphy. The southern contact has been intruded by rocks of the Winnipeg River Batholithic Belt (Beakhouse, 1977) and its northern edge lies on the fault contact of the Lamprey Falls metabasalt (Fig. 3).

The Eaglenest Formation is comprised of metamorphosed volcanic and pebbly wackes and volcanic sandstones. Less abundant are biotite schists and amphibolites of uncertain origin that outcrop between bands of tonalitic and dioritic intrusive
Table 1  Table of Units for the Bird River Area, Manitoba (based on Trueman 1980)

<table>
<thead>
<tr>
<th>FORMATION</th>
<th>UNIT</th>
<th>META VOLCANIC AND METASEDIMENTARY ROCKS</th>
<th>UNIT</th>
<th>INTRUSIVE ROCKS</th>
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<tbody>
<tr>
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<td>Pegmatite, granite</td>
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<td></td>
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<td>17</td>
<td>quartz monzonite</td>
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<td></td>
<td></td>
<td>Maskwa, Marijane</td>
<td>10</td>
<td>Lake batholiths</td>
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<tr>
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<td>clastic derivatives</td>
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<td>Metamorphosed:</td>
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<tr>
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<td></td>
<td>metarhyolite</td>
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<td>gabbro</td>
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</tr>
<tr>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>UNCONFORMITY</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peterson Creek</td>
<td>4</td>
<td>metarhyolite</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>clastic equivalents</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lamprey Falls</td>
<td>2</td>
<td>metabasalt</td>
<td>3</td>
<td>Bird River Sill</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>metagabbro</td>
</tr>
<tr>
<td>Eaglenest Lake</td>
<td>1</td>
<td>metamorphosed volcanic wacke</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
Figure 20  Mean thermal intensity on thermal step demagnetization based on 18 specimens:
Bird River Sill
Figure 3 Geological Sketch Map of the Bird River Greenstone Belt. All units are Archean in age (based on Trueman, 1980)
materials near the southern contact (Trueman, 1980; Cerny et al., 1981). This unit also contains banded iron formations which occur near the northern fault boundary (Trueman, 1980).

The dominant subunit is a volcanic wacke which outcrops on the northern shore of Eaglenest Lake. It is dark grey to buff weathering, fine to coarse grained, and moderately to strongly schistose (Cerny et al., 1981). The wacke is poorly bedded and lacks sorting with its clasts showing strong deformation and flattening parallel to the schistosity. Obviously, these rocks are derived from a volcanic source, but are of uncertain relative age. While the formation may represent its true position in the stratigraphic succession, it may also represent a faulted segment (allochthon) of the Bernic Lake Formation (Trueman, 1980). This formation exhibits a strong lithologic similarity with clastic rocks of the Bernic Lake Formation (Trueman, 1980).

b. Lamprey Falls Formation

Mafic metavolcanics and related hybabyssal intrusive rocks are predominant in the formation with a maximum thickness of approximately 3 km and a lateral thinning to the east and west. Rock types include metamorphosed pillow basalts, tuffs, hyaloclastite, aquagene breccias, megacrystic basalts, porphyritic and amygdaloidal metabasalts and iron formation (Cerny et al., 1981). These units outcrop extensively along the Winnipeg River and north of Bird River with both locations being marked by faults and intrusive contacts (Cerny et al., 1981).
Metamorphosed pillow basalts are the dominant rock type of the formation and range from a dark grey-black to green in color. The pillows are characterized by a fine to medium grain size, massive to weakly schistose texture, and display a well-selveded pillow structure (Cerny et al. 1981).

c. Peterson Creek Formation

The Peterson Creek Formation consists essentially of metarhyolites of flow and clastic origin. Some of these rocks were subaerially erupted, transported, reworked, and redeposited subaqueously as felsic sandstones. All of these rocks are in fault contact with and along both flanks of the synclinorium formed by the Lamprey Falls Formation and in turn are overlain and interfolded with mixed rocks of the Bernic Lake Formation (Trueman, 1980).

Specific rock types of the formation include flow-banded metarhyolites (quartz porphyry), rhyolite breccia, rhyolite tuffs and epiclastic sandstone derivatives (Cerny et al. 1981).

The metarhyolite flows are buff to greenish weathering, porphyritic, aphanitic to fine grained, flow-banded, and weakly schistose with quartz being the dominant phenocryst (Cerny et al. 1981). The flows are moderately thick ranging from 6 to 20 m, and are intercalated with clastic equivalents (Trueman, 1980). These clastic equivalents are typically brownish to buff-green in color and carry up to 60% lapilli-sized clasts. They are thinly bedded (<6 m), unsorted and moderately schistose with traces of internal bedding (Cerny et al. 1981).
The clastic felsic metavolcanic rocks are subdivided into tuffs, lapillistone and pyroclastic breccia. Pyroclastic breccia and lapillistone predominate in the western and central map area and grade eastwards into lapillistone, tuffaceous units and ultimately into their derived epiclastic counterparts (Trueman, 1980).

d. Ω Bernic Lake Formation

Rock types of the Bernic Lake Formation include metamorphosed basalt, andesite, dacite, rhyolite, iron formation, polymictic and oligomictic conglomerates, volcanic wackes and sandstones (Cerny et al. 1981). The metabasalt and iron formation provide the only lateral continuity in the unit. The polymictic and oligomictic metaconglomerates are the dominant rocks and are clastically interlayered with each other and with the other rock types (Trueman, 1980). The metabasalt is the most abundant of the flow rocks and forms two prominent units: one in the Bernic Lake area and one just south of the Bird River.

The polymictic metaconglomerates are typically dark grey to black in color. They are fine to coarse grained with clasts ranging from pebble to boulder size (Cerny et al. 1981). Bedding is evident and results from either variation in clast content and size and/or variation in matrix composition. A strong lineation corresponding with the downdip of the schistosity is outlined by the elongation of clasts.

The oligomictic metaconglomerate is dominant in the southern exposure of the Bernic Lake Formation. These rocks
are typically greyish weathering, fine to coarse grained with a grey to black strongly schistose matrix. Clasts are pebble to boulder size and are intermediate to felsic in composition (Trueman, 1980).

The metabasalts are the dominant flow rocks and are typically pillowed flows. They weather greyish to black and are marked by a moderate to strongly developed schistosity.

The Bernic Lake Formation is infolded with the Peterson Creek Formation and it forms a separate structural entity in the core of the synclinorium of the Lamprey Falls Formation. The bimodal nature of these two conglomerate rock types suggest a high energy subaqueous deposition through debris flows. Detritus of both conglomerate types suggests that it originated from rocks underlying the Bernic Lake Formation. Materials include fragments from the Bird River Sill and rhyolite fragments from the Peterson Creek Formation. However, the exhuming of the Bird River Sill implies profound or deep erosion of the greenstone terrain and for this reason an unconformity has been postulated to be at the base of the Bernic Lake Formation (Trueman, 1980).

e. Flanders Lake Formation

The Flanders Lake Formation includes polymictic metaconglomerates and related meta-arenites which outcrop extensively along Flanders, Ryerson, Starr, and Raynar Lakes.

The meta-arenite is the dominant rock type of the formation. It is typically greyish weathering, moderately well bedded and sorted. It displays a schistose foliation that develops
into a gneissosity close to intrusive contacts (Trueman, 1980; Cerny et al., 1981). Primary structures are rare.

The metaconglomerates are distinctive and are characterized by abundant stretched pebble and cobble-sized clasts differing composition (Posehn, 1976). Primary bedding structures are locally preserved in the metaconglomerates (Posehn, 1976) which suggest that deposition was by turbidity and debris flow mechanisms with subsequent reworking in a fluvial regime (Posehn, 1976; Trueman, 1980).

f. Booster Lake Formation

The dominant rock types of the Booster Lake formation are greywacke and mudstone turbidites with minor iron formation and conglomerate units. The latter units are well exposed and contain clasts up to 2 m in diameter (Cerny et al., 1981). The turbidites are typically buff weathering, well bedded, fine-to coarse-grained and moderately schistose (Trueman, 1980). Primary structures are abundant in the turbidites and include the graded bedding phase of the classical Bouma sequence (Trueman, 1980).

2. Intrusive Rocks
   a. Synvolcanic Intrusive Rocks
      1. Bird River Sill

The Bird River Sill is intruded along the contact between the Lamprey Falls Formation and the Bernic Lake Formation (Trueman, 1980). This sill is a layered ultramafic to gabbroic body formed by gravitational settling and accumulation of layers of olivine, chromite and plagioclase (Trueman,
1971, 1980). The sill can be subdivided into five principal units: a feeder dike, a layered ultramafic cumulate, a picrite layer, a gabbroic cumulate, and a granophyre. The layered ultramafic, cumulate rocks include dunite and peridotite, both of which contain varying amounts of chromite. This unit is approximately 200 m thick with serpentinized peridotite being the predominant rock type. Two major and several minor chromite layers occur within this subunit. These layers range from approximately 0.5 m thick for the minor ones to approximately 2 m thick for the two major ones. These layers can be traced along the entire length of the sill and they constitute a unique stratigraphic horizon. The chromite, generally mantled by chlorite, exhibits a magnetite-enriched rim (Gait, 1964) formed through deuteric alteration (Trueman, 1980). Primary structures are abundant in the layered ultramafic cumulate and include features such as bifurcation and disruption of chromite layers, graded bedding and flame structures (Trueman, 1971, 1980).

The main picrite layer is identified by the disappearance of original olivine and the first appearance of cumulus plagioclase (Trueman, 1971, 1980). The main picrite forms the uppermost layer of the ultramafic portion of the sill and measures approximately 10 m in thickness on the Chrome Property (Trueman, 1980). Minor zones of picrite occur in the layered ultramafic section and the marginal group section of the sill (Fig. 4).
Figure 4  Stratigraphic Profile of the Bird River Sill  
(based on Bannatyne and Trueman, 1982)
The layered gabbroic unit is approximately 380 m thick and forms the thickest portion of the sill on the Chrome Property. Its rock types include anorthositic gabbro, laminated and glomeroporphyritic gabbro and anorthosite (Trueman, 1980).

The granophyre unit is sandwiched between the downward accumulation of the overlying anorthosite and the upward accumulation of the gabbros (Bannatyne and Trueman, 1982). This unit varies from 6 to 9 m in thickness and has been interpreted to be the last crystallization product of the sill magma.

ii. Intrusive Stocks of the Bernic Lake and Lamprey Falls Formations

These stocks show both mutually intrusive relationships and differentiation from gabbro to diorite, quartz and feldspar porphyry and granodiorite (Trueman, 1980).

The metagabbro forms the earliest intrusive phase of these composite rocks (Trueman, 1980). It is typically grey to black weathering, medium-to coarse-grained (Trueman, 1980), but becomes fine-grained and schistose near contacts (Cerny et al., 1981). The metagabbro shows a faint banding of plagioclase-enriched layers which gives rise to phase layering (Jackson, 1967) parallel to the intrusive boundaries.

The metadiorite is grey-weathering, medium to coarse-grained, equigranular and moderately schistose. It occurs as intrusive stocks near Bernic Lake and as thin sills north and east of Osis Lake (Cerny et al., 1981).
b. Syntectonic Intrusive Rocks

The Maskwa Lake and the Marijane Lake Batholiths are assigned to a syntectonic association because their emplacement correlates with the second regional metamorphic event (M2). S2 schistosities are parallel to the intrusive boundaries of the batholiths.

The Maskwa Lake Batholith exhibits two intrusive phases. There is a coarse-grained, equigranular to porphyritic, massive to locally gneissic, dark grey to buff-colored diorite and an equigranular, medium-to coarse-grained, massive, pink to buff-colored granite.

The Marijane Lake Batholith is a weakly foliated, equigranular, medium-to coarse-grained, buff-colored granite (Trueman, 1980). The Marijane Lake and the Maskwa Lake Batholiths are considered to be coeval with the Marijane Lake Batholith extending east of the study area. Carlson (1958) mapped an extensive area of dioritic rocks within this same body (Trueman, 1980).

Ermanovics et al. (1979) and Cerny et al. (1981) interpreted these quartz diorites to be partial melts of amphibolite in the lower crust or upper mantle at a depth of less than 60 km rather than to originate from the fractional crystallization of gabbroic progenitors. Cerny et al. (1981) further defines the source as one of a deep-seated juvenile origin by partial melting of an intermediate to mafic source rather than by igneous differentiation.
c. **Late-Tectonic Intrusive Rocks**

Late tectonic intrusive rocks include the Lac du Bonnet quartz monzonite batholith, related dikes and sills, stocks and dikes of pegmatitic granite and pegmatites (Trueman, 1980). The Lac du Bonnet quartz monzonite outcrops for the most part south of the Bird River Greenstone Belt. It is a composite intrusion of batholithic size (>2,500 km$^2$)(Fig. 3) containing areas of quartz diorite enclosed by two phases of granite (Cerny et al., 1981) with one phase being biotite-rich and the other being devoid of biotite.

The quartz monzonite is massive to weakly foliated, coarse-grained, biotite-bearing and buff to reddish in color (Trueman, 1980). Its northern intrusive boundary isolates the southern contact of the Bird River Greenstone Belt, while its southern contact marks the northern extent of the Winnipeg River Batholithic belt.

The pegmatites are typically coarse-grained assemblages of quartz feldspars, micas, and appear to occupy previously formed bedding, D2 schistosity and D3 faulting structures. These pegmatites exhibit spatial preference for areas of pegmatitic granites with which they can be genetically related (Cerny et al. 1981; Trueman, 1980).

Ermanovics et al. (1979) and Cerny et al. (1981) proposed the same source for these granites as for the quartz diorites. Cerny et al. (1981) proposed a fusion pressure of 5-8 kilobars (20-32 km depth) which places the source within the uppermost mafic crust. It extends from 21 to 30 km below the present
surface in the immediate vicinity of the Lac du Bonnet pluton
(Hall and Hajnal (1973), Hall (1974), Beakhouse (1977)).

B. Structural Geology

The Archean Bird River Greenstone Belt forms the central
part of the western extremity of a broad linear crustal
feature termed the English River gneissic belt (Trueeman, 1980;
Wilson, 1971) (Fig. 1). The English River subprovince is
distinguished from the northern Uchi (Red Lake) and the southern
Wabigoon structural subprovinces by a lithologic change from
volcanic to sedimentary rocks and by an increase in metamorphic
grade (McGlynn, 1968; Beakhouse, 1977; Ermanovics and Froase,
1978). Thurston and Breaks (1978) subdivided the English
River subprovince into a northern supracrustal domain and a
southern plutonic domain. Beakhouse (1977) designated the
northern metasedimentary belt as the Manigatagon-Ear Falls
gneissic belt and the southern plutonic belt as the Winnipeg
River Batholithic belt. The northern boundary of the English
River Subprovince is gradational in stratigraphic terms with
the northern Uchi Subprovince but is marked by the Sydney Lake
Fault System (Thurston and Breaks, 1978). The Bird River
Greenstone Belt marks the boundary between the northern
Manigatagon-Ear Falls belt and the southern Winnipeg River
plutonic belt.

The Bird River Greenstone Belt is a broad easterly plunging
anticlinorium-synclinorium bounded on its northern contact by
the Maskwa Lake Batholith and on its southern contact by the
Lac du Bonnet Batholith. The belt is subdivided into six formations based on detailed field mapping and several synvolcanic, syntectonic, and late-tectonic intrusive events. These Archean metasedimentary and metavolcanic units display four deformational and metamorphic events (Trueman, 1980). Trueman (1980) subdivided this belt into five fault-bounded structural subareas (Fig. 5) based on different structural styles and lithologies as follows:

<table>
<thead>
<tr>
<th>Subarea</th>
<th>Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Booster Lake</td>
</tr>
<tr>
<td>4</td>
<td>Bernic Lake</td>
</tr>
<tr>
<td>3</td>
<td>Peterson Creek</td>
</tr>
<tr>
<td>2 (a,b)</td>
<td>Bernic Lake</td>
</tr>
<tr>
<td>1</td>
<td>Flanders Lake</td>
</tr>
<tr>
<td></td>
<td>Lamprey Falls</td>
</tr>
<tr>
<td></td>
<td>Eaglenest Lake</td>
</tr>
</tbody>
</table>

Subarea 5 (D1, D2)

This area corresponds to the major fault segment of the Booster Lake Formation. This area forms an east-west trending, south facing, steeply dipping monoclinal sequence. The s1 schistosity is present and is assumed to be younger in age than the M1 metamorphism and the D1 deformational event (Trueman, 1980). The penetrative tectonic s2 foliation is quite evident and parallel to bedding (s0). Structural analysis indicates that the folding is conical with the cone axes plunging moderately steeply in a north-northwest direction (Cerny et al. 1981).
Figure 5 Structural Subareas of the Bird River Greenstone from Trueman (1980). See text for explanation.
Subarea 4 (D1, D2)

This subarea deals with the major fault-bounded segment of the Bernic Lake Formation. Bedding (s0) is poorly defined overall but where bedding is locally preserved, the oldest schistosity (s1) is parallel to it. The bedding is oblique to a younger schistosity (s2) and converges to parallel the boundaries of the intrusives (Trueman, 1980). This second schistosity is pervasive as an east-west strike, showing steeply dipping north and south of vertical alignment of micaceous minerals.

Subarea 3 (D1, D2)

This subarea contains the Peterson Creek, Flanders Lake, and a northern portion of the Bernic Lake Formations.

Bedding (s0) is evident and includes primary structures diagnostic of the facing direction. Two schistosities; the oldest (s1) is well developed and parallel to s0 layering while the younger schistosity (s2) has an orientation that is parallel to the axial planes of the fold structures of subarea 3 which deforms s0 and s1 (Trueman, 1980). This deformation event is designated as D2. These folds display ideal Type III interference patterns. The f2 fold axes are southwest-plunging with the axial planes being northeast-plunging and dipping to the southwest (Trueman, 1980). These fold axes share a general correlation with mineral elongation, clast elongation and minor fold axis linear data (Cerny et al., 1981).
Subarea 2 (D1, D2)

The Lamprey Falls Formation is contained within this subarea and is subdivided into two segments, A and B. Both A and B display s0 layering or bedding in particular lava flows, gravity stratification in the Bird River Sill and silica bedding in the iron formations. Segment A is the south facing sequence of rocks north of Bird River while B is a north facing sequence along the Winnipeg River (Cerny et al., 1981). The bedding (s0) strikes east-west, dips slightly south of vertical and outlines a major synclinal fold structure. A single penetrative schistosity is evident but is weakly developed. The s2 foliation strikes east and dips south of vertical in segment A and north of vertical in segment B, proving the existence of a major synclinal fold structure.

Subarea 1 (D1, D2)

Bedding (s0) is evident as are two schistosities; s1 is the older and parallel to bedding while the younger s2 schistosity is discrete and only recognizable in the hinge areas of minor f2 folds. The minor folds are of the Type III (Ramsay, 1964) and display interference patterns formed through passive (f2) refolding on s2 surfaces of earlier f1 folds (Trueman, 1980). The f1 folds can be described as steep (75°), westerly plunging, isoclinal synforms (Cerny et al., 1981; Trueman, 1980).
Faulting (D3, D4)

All subareas are fault-juxtaposed by F3 events and are truncated by F4 events.

D3 deformation marks the east-west trending F3 faults that occur close to or at formation boundaries (Fig. 5). D4 deformation marks a northwest trending group of faults that truncate F3 faults and lithologic boundaries. The pattern of distribution of the F4 faults is apical-perianticlinal (Trueman, 1980) and they cross into the Maskwa Lake Batholith. Similar northwest trending faults (F4) affect the Lac du Bonnet Batholith, thus they too must be younger than the batholith (Cerny et al., 1981).

C. Metamorphic Phases

Butrenchuk (1970) proposed a metamorphic scheme for the Bird River Greenstone Belt and identified several metamorphic facies. The higher grades of metamorphism occur in the eastern and southern portions of the belt. The metamorphic grades decrease to the west and north where original sedimentary structures are preserved. The five facies proposed by Butrenchuk (1970) (Fig. 6) listed by increasing grade, are:

1. albite-epidote hornfels,
2. hornblende hornfels,
3. greenschist facies,
4. almandine amphibolite with epidote; and,
5. almandine amphibolite without epidote.

Trueman (1980) subdivided the belt into six subfacies based on the metamorphic mineral assemblages of Winkler (1967) (Fig. 7). They are in increasing grade:
Figure 6 Metamorphic Facies of the Bird River Area (based on Butrenchuk, 1970)
Figure 7 Metamorphic Subfacies of the Bird River Greenstone Belt (taken from Trueman, 1980)
1. quartz-albite-muscovite-biotite-chlorite
2. quartz-andalusite-plagioclase-chlorite
3. andalusite-cordierite-muscovite
4. sillimanite-cordierite-muscovite-almandine
5. sillimanite-cordierite-orthoclase-almandine
6. orthopyroxene-hornblende

Trueman (1980) isolated metamorphic textures in all the schists of the area. They have alignment with two deformational events, D1 and D2, producing mineral assemblages M1 and M2. Secondly, two post-tectonic hydrothermal replacement events that occurred during F3 and F4 faulting which produced M3 and M4 mineral assemblages (Table 2) that replaced some of the M2 minerals.

1. M1, M2 Mineral Assemblages

M1 and M2 assemblages represent prograde metamorphic events with the M1 event being poorly preserved and only present in the hinge areas of f2 folds of pelitic rocks. It is a result of the first (D1) deformational event producing an east-west regional folding of the belt and the development of the s1 schistosity. A1.1 through to A2.3 subfacies of Winkler (1967) outline the different metamorphic mineral assemblages used by Trueman (1980) (Fig. 7).

The M2 events are quite evident. They display increased temperature and pressure regimes from low grade assemblages in the western and northern part of the map area to high grade assemblages in the eastern and southern part of the map area (Trueman, 1980). It is a result of the second (D2) deformational episode and is accompanied by the development of an s2 schistosity. The intrusion of the Maskwa Lake and Marijane
TABLE 2: Correlation of metamorphism, deformation, and structural events in metavolcanic and metasedimentary rocks of the Bird River area (based on Trueman, 1980).

<table>
<thead>
<tr>
<th>METAMORPHIC EVENT</th>
<th>DEFORMATION EVENT</th>
<th>SURFACE DEVELOPED</th>
<th>STRUCTURE DEVELOPED</th>
<th>NOTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_4$</td>
<td>$D_4$</td>
<td>$F_4$</td>
<td>NW and apical periclineal faulting; retrogression</td>
<td></td>
</tr>
<tr>
<td>$M_3$</td>
<td>$D_3$</td>
<td>$F_3$</td>
<td>E-W episodic faulting; retrogression.</td>
<td></td>
</tr>
<tr>
<td>$H_2$</td>
<td>$D_2$</td>
<td>$S_2$</td>
<td>$F_2$</td>
<td>Emplacement of Maskwa and Marijane to batholiths E-W regional folding of passive mechanism.</td>
</tr>
<tr>
<td>$H_1$</td>
<td>$D_1$</td>
<td>$S_1$</td>
<td>$F_1$</td>
<td>E-W regional folding of flexural mechanism.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$S_0$</td>
<td></td>
<td>$S_0 =$ primary bedding</td>
</tr>
</tbody>
</table>

*f* - folding

*F* - Faulting
Lake Batholith is thought to have produced the f2 folding and the s2 schistosity. Also, east-west regional folding of a passive nature resulted from the intrusion of these two batholiths.

2. **M3, M4 Mineral Assemblages**

These two assemblages are a result of east-west episodic faulting (F3) and northwest apical-perianticlinal faulting (F4). Both assemblages are retrograde and most fault contacts display protoclastic to cataclastic textures (Trueman, 1980). M3 mineral assemblages include chlorite, albite, epidote, and actinolite while M4 mineral assemblages also include serpentine-talc-carbonate alteration in faults transecting the ultramafic Bird River Sill (Juhas, 1973); Coats and Suchan (1979); Trueman (1980); Cerny et al. (1981).

Overall, two major folding events and two major faulting events are recognized across the entire belt based on structural and petrographic analysis. The lower grade assemblages on the western and northern map area and the higher grade assemblages in the eastern and southern map area suggest that the belt has undergone differential uplift (Dwidebi, 1966). Correlating depth with metamorphism, the southern and eastern areas were metamorphosed at a greater depth than the northern and western areas of the Bird River Greenstone Belt. Table 3 summarizes the degree of metamorphism found in each of the sampling locations.
Table 3. Metamorphic Phases of the Bird River Greenstone Belt.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Facies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bernic Lake</td>
<td>greenschist, (Al.2)*</td>
</tr>
<tr>
<td>Bird River Sill</td>
<td>greenschist, (Al.1)</td>
</tr>
<tr>
<td>Radiometric</td>
<td>n/a</td>
</tr>
<tr>
<td>Maskwa Lake Batholith</td>
<td></td>
</tr>
<tr>
<td>Synvolcanic (Unit 6)</td>
<td>almandine with epidote, (A2.1)</td>
</tr>
<tr>
<td>Peterson Creek</td>
<td>greenschist, (Al.2)</td>
</tr>
<tr>
<td>Bird River Sill (gabbro phase)</td>
<td>greenschist, (Al.1)</td>
</tr>
</tbody>
</table>

*Terms in brackets refer to Trueman (1980); others refer to Butrenchuk (1970)
Chapter III
PREVIOUS WORK


Various geological studies of this structural subprovince have been conducted in both Ontario and Manitoba. Most current work on the Bird River Sill has been done by Trueman (1980), Bannatyne and Trueman (1982), Scoates (1983), Theyer (1983) and Watson (1984).

Relevant radiometric studies in Manitoba have been done on the Rice Lake Group ((Turek and Peterman (1968, 1971), Penner and Clark (1971), Penner (1970)), on the Bird River Greenstone Belt ((Penner (1970), Penner and Clark (1971), Farquharson (1975)) and on the Winnipeg River Batholithic Belt ((Nier et al. (1941), Cummings et al. (1956), Eckelman and Gast (1957), Gast et al. (1958), Laughlin (1969) and Farquharson and Clark (1971)). A summary of the above radiometric ages is given in Table 4.

U-Pb and Rb-Sr age determinations in Ontario relevant to the study area focussed on the Beren River, Uchi-Confederation,
Table 4. Radiometric Age Dates for the English River Subprovince and Surrounding Area, Manitoba

1. **English River Subprovince**
   
   A. **Bird River Greenstone Belt**
   
   Penner and Clark (1971)  
   Rb-Sr: $2442 \pm 127$ Lac du Bonnet quartz monzonite  
   $2584 \pm 132$ Maskwa Lake Batholith  
   $2593 \pm 34$ Volcanics-Bird River  
   $2320$ Pegmatite-Tanco Mine  
   
   Farquharson (1975)  
   Rb-Sr: $2623 \pm 89$ Lac du Bonnet quartz monzonite

   B. **Winnipeg River Batholithic Belt**
   
   Nier et al. (1941)  
   U-Pb: $2475 \text{ (207/206)}$ - Uraninite Huron Claim  
   
   Cummings et al. (1955)  
   U-Pb: $2580 \pm 100 \text{ (207/206)}$ - Huron Claim - Uraninite  
   $2535 \pm 160 \text{ (207/206)}$ - Huron Claim - Uraninite Salt  
   
   Stevens and Stillibeer (1956)  
   K-Ar: $2150 \pm 180$ Muscovite-Huron Claim  
   $2030 \pm 170$ Albite-Huron Claim  
   
   Aldrich et al. (1956b)  
   Rb-Sr: $2623 \pm 69$ Lepidolite Silver-leaf Claim  
   
   Eckelmann and Gast (1957)  
   Rb-Sr: $2623 \pm 88$ Lepidolite Silver-leaf Claim  
   $2613 \pm 64$ Lepidolite Silver-leaf Claim  
   $2290 \pm 137$ Microcline Silver-leaf Claim  
   
   Gast et al. (1958)  
   Rb-Sr: $2613 \pm 64$ Lepidolite Silver-leaf Claim  
   $2290 \pm 137$ Microcline Silver-leaf Claim
Laughlin (1969)

Rb-Sr: 2450 ± 70 Lepidolite
2880 ± 90 Albite
2340 ± 70 Albite
5160 ± 150 Spodumene Chemalloy Pegmatite
2630 ± 80 Quartz

Farquharson and Clark (1971)

Rb-Sr: 2608 ± 49 Pink granodiorite
2548 ± 313 Rennie Batholith
2554 ± 111 Whiteshell porphyritic
2504 ± 12 Caddy Lake - quartz monzonite
2569 ± 60 Microgranite and pegmatite
2504 Huron Claim

2. North of the English River Subprovince, Manitoba

Turek and Peterman (1968) Rb-Sr: 2496 ± 78 Northern Granite
2662 ± 181 Gold-bearing veins
2437 ± 88 Metasedimentary rocks - Rice Lake group

Turek and Peterman (1971) Rb-Sr: 2501 ± 68 Quartz diorite
2677 ± 54 Black Lake - quartz monzonite
2295 ± 98 Mylonites

2424 ± 74 Bagley Lake Pluton
2680 ± 125 Hayes River Group

Turek et al. (1984) U-Pb: 2886 ± 7 Bella Lake tonalite
2801 ± 4 Bunny Lake tonalite

Carson (1983)
2765 ± 11 Dog Island and Linklater Is. and porphyry
2730 Late Plutonic Rocks
2699 ± 1 Horseshoe Island porphyry

(1) Above ages have been corrected for changes in decay constants. The decay constant used is \( \frac{\ln(2)}{T_{1/2}} \approx 1.42 \times 10^{-11} \text{ yr}^{-1} \) as per Steiger and Jäger (1977). For K-Ar and U-Pb systems no changes have been made as their effect is negligible.
English River and the Kenora (Wabigoon) structural subprovinces and are given in Table 5.

Reports most pertinent to the Bird River Greenstone Belt are by Penner and Clark (1971) and Farquharson (1975) which isolate a metamorphic range for the Kenoran Orogeny. Figure 8 describes the metamorphic and primary ages for the English River Subprovince in Ontario and Manitoba.
Table 5. Radiometric Age Dates for the English River Subprovince and Surrounding Area, Ontario (1)

1. English River Subprovince

<table>
<thead>
<tr>
<th>Reference</th>
<th>Method</th>
<th>Age</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hart and Davis (1969)</td>
<td>Rb-Sr:</td>
<td>2572 ± 76</td>
<td>Couthchiching Whole Rock</td>
</tr>
<tr>
<td></td>
<td>U-Pb:</td>
<td></td>
<td>2414 ± 96 Laurentian Intrusives</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2688 ± 48 Couthchiching Whole Rock</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2607 ± 105 Laurentian Intrusives</td>
</tr>
<tr>
<td>Krogh et al. (1974)</td>
<td>U-Pb:</td>
<td>2662 ± 52</td>
<td>Granitic sill</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2560 ± 40 Pegmatitic granitic dike</td>
</tr>
<tr>
<td>Krogh et al. (1975)</td>
<td>U-Pb:</td>
<td>3008 ± 12</td>
<td>tonalitic</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(3043 ± 35) gneiss</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2681 ± 26 Pegmatitic lense</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2660 ± 20 Post-orogenic granite</td>
</tr>
<tr>
<td>Hinton and Long (1979)</td>
<td>U-Pb:</td>
<td>3300 ± 100</td>
<td>(207/206) Tonalite gneiss</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2930 ± 50 Metamorphic event</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2780 ± 90 Trondhjemite granodiorite gneiss</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2580 ± 230 Granodiorite sill</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2580 ± 45 Granitic Dike</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2630 ± 70 Melich tonalite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2725 ± 55 Biotite-tonalite gneiss</td>
</tr>
<tr>
<td>Clark et al. (1981)</td>
<td>Rb-Sr:</td>
<td>2950 ± 150</td>
<td>Tonalitic gneiss</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lake of the Woods</td>
</tr>
</tbody>
</table>
2. **Wabigoon Subprovince**

Davis *et al.* (1980)  

U-Pb: \[2756.1 \pm 12.8\]  
Rhyolite flow  
\[2742.5 \pm 6.9\]  
Atikwa Batholith  
\[2748.5 \pm 3.0\]  
Atikwa Batholith  
\[2745.2 \pm 2.8\]  
porphyritic dacite  
\[2752\]  
Sabaskong Batholith  
\[2732.1 \pm 2.3\]  
Phinney-Dash Lake Stock  
\[2739.6 \pm 15.9\]  
South Sturgeon Lake Volcanics  
\[2789\]  
Meggisi Batholith  
\[2739.7 \pm 10.6\]  
ultramafic sill-Kakagi Lake  
\[2704\]  
tuff-Kabaguksi Lake  
\[2776\]  
Wabigoon Volcanics

3. **Uchi-Confederation Subprovince**

Nunes and Thurston (1980)  

U-Pb: \[2958.6 \pm 1.7\]  
Cycle I tuff  
\[2738 \pm 5\]  
Cycle III rhyolite  
\[2794\]  
Cycle II rhyolite  
\[2729.6 \pm 1.3\]  
quartz monzonite

4. **Berens River Subprovince**

Nunes and Wood (1980)  

U-Pb: \[2730 \pm 6\]  
Ryan Point quartz diorite  
\[2768 \pm 17\]  
Macedowell Lake quartz diorite  
\[3013 \pm 168\]  
monolithic tuff breccia  
\[2975\]  
granitoid clast

(1) See footnotes.
Figure 8  Previously Published Radiometric Age Groupings for the English River Subprovince excluding U-Pb ages reported in this study.
CHAPTER IV

SAMPLING AND MEASUREMENT

A. Paleomagnetic

1. Sampling

   a. Bird River Sill Collection

   Eighteen sites (BS83 numbers) were sampled from outcrops in the Bird River Sill on the Chrome Property (Fig. 9). Sampling was done along a stratigraphic profile across the exposed section of the sill. The sites started at the base of the sill and moved up sequence at approximately 50 m intervals. Each site represents an approximate 5 m stratigraphic cross-section with one core being drilled and oriented every meter. Sites 18, 19, and 20 span the two major chromite bands and several minor ones with cores being drilled every 0.15 m (~6 inches) (Table 6). Figure 9 gives the location of the sites within the sill area. This paleomagnetic sampling profile of the sill runs the same as the platinum profile sampled by Dr. P. Theyer of the Manitoba Department of Energy and Mines, Mineral Resources Division (Theyer, 1983).

   b. Bird River Collection

   Paleomagnetic sampling was done in June 1983, from outcrops mainly along road cuts. Six sites (BR83 numbers) were sampled in the Bird River area (Fig. 10) particularly the Bernic Lake Formation along Provincial Road 314 just west of the Bird River Airport. Sites for paleomagnetic coring were chosen on the basis of exposed outcrop, convenience of drilling, availability of water and degree of weathering.
Figure 9  Paleomagnetic Site Locations: Chrome Property of the Bird River Sill (base map from Theyer, 1983)
Table 6. Paleomagnetic Collection Data

<table>
<thead>
<tr>
<th>Site</th>
<th>Long. (W°)</th>
<th>Lat. (N°)</th>
<th>Number of core</th>
<th>Formation</th>
<th>Attitude Str.</th>
<th>Dip</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50.40</td>
<td>95.75</td>
<td>5</td>
<td>Bernic Lake</td>
<td>080</td>
<td>78</td>
</tr>
<tr>
<td>2</td>
<td>50.40</td>
<td>95.75</td>
<td>5</td>
<td>Bernic Lake</td>
<td>072</td>
<td>69</td>
</tr>
<tr>
<td>3</td>
<td>50.40</td>
<td>95.75</td>
<td>4</td>
<td>Bernic Lake</td>
<td>113</td>
<td>72</td>
</tr>
<tr>
<td>23</td>
<td>50.40</td>
<td>95.75</td>
<td>5</td>
<td>Bernic Lake</td>
<td>082</td>
<td>72</td>
</tr>
<tr>
<td>24</td>
<td>50.40</td>
<td>95.75</td>
<td>5</td>
<td>Bernic Lake</td>
<td>079</td>
<td>72</td>
</tr>
<tr>
<td>25</td>
<td>50.40</td>
<td>95.75</td>
<td>5</td>
<td>Bernic Lake</td>
<td>080</td>
<td>78</td>
</tr>
</tbody>
</table>

Bird River Sill Collection (BS83)

<table>
<thead>
<tr>
<th>Site</th>
<th>Long. (W°)</th>
<th>Lat. (N°)</th>
<th>Number of core</th>
<th>Formation</th>
<th>Attitude Str.</th>
<th>Dip</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-6</td>
<td>50.45</td>
<td>95.56</td>
<td>5</td>
<td>Bird River Sill</td>
<td>260</td>
<td>85</td>
</tr>
<tr>
<td>7</td>
<td>50.45</td>
<td>95.56</td>
<td>4</td>
<td>Bird River Sill</td>
<td>260</td>
<td>85</td>
</tr>
<tr>
<td>8-11</td>
<td>50.45</td>
<td>95.56</td>
<td>5</td>
<td>Bird River Sill</td>
<td>260</td>
<td>85</td>
</tr>
<tr>
<td>12,13</td>
<td>50.45</td>
<td>95.55</td>
<td>5</td>
<td>Bird River Sill</td>
<td>260</td>
<td>85</td>
</tr>
<tr>
<td>15,17</td>
<td>50.46</td>
<td>95.55</td>
<td>10</td>
<td>Chromite Band (Maj)</td>
<td>260</td>
<td>85</td>
</tr>
<tr>
<td>18</td>
<td>50.46</td>
<td>95.55</td>
<td>7</td>
<td>Chromite Bank (Min)</td>
<td>260</td>
<td>85</td>
</tr>
<tr>
<td>19</td>
<td>50.46</td>
<td>95.55</td>
<td>8</td>
<td>Chromite Band (Min)</td>
<td>260</td>
<td>85</td>
</tr>
</tbody>
</table>

Note: sites 14, 16 not drilled - unit too hard.
sites 18, 19, 20 - chromite bands.
site 20 - second half of profile at site 18 location.
(Maj) - Major, (Min) - Minor
Figure 10 Paleomagnetic Site Locations: Bernic Lake Formation, Bird River Greenstone Belt (map based on Cerny et al. 1981)
2. **Orientation Procedure**

Five to six cores were drilled at each site except for sites 18, 19, and 20 of the Bird River Sill Collection. They were oriented in situ using a Canada Astro Sun Compass MK II (error 2° arc) and a Brunton compass (error 2° arc). The sun compass reading was used to check the Brunton compass readings. If the sun compass could not be used, then the magnetic readings were checked for local magnetic distortion by using topographic sitings. Except for sites 18, 19, and 20 of the BS83 collection, each site yielded on the average, 10 to 14, 25 cm long by 24 cm diameter right-cylindrical specimens. The number of specimens recovered depended on the original core length and homogeneity.

3. **Magnetic Measurement Procedure**

The remanent magnetization of the specimens from the eighteen sites of the Bird River Sill and the six sites from the Bernic Lake formation were measured using a Schonstedt SSM-1A magnetometer. The natural remanent magnetization (NRM) of two specimens per core from all sites was measured. The core displaying the best combination of highest vector intensity (INT), the lowest specimen angular standard deviation (ASD) and the most coherent declination and inclination from that site was chosen for further step demagnetization. One specimen from this core was alternating field (AF) demagnetized in 16 steps (0, 2.5, 5.0, 7.5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, and 100 mT) using a Schonstedt GSD-1 demagnetizer. The second specimen from the same core was thermally demagnetized in 10 steps (450, 475, 500, 520, 540, 570, 600, 620, 640, and
670°C) using a non-inductive shielded furnace. All step
demagnetization and measurements were conducted in a triple
shielded magnetic room in which the Earth’s magnetic field
(EMF) is reduced from 60,000 γ to approximately 60 γ (Huschilt,
1983).

The AF step remanence or pilot specimen data was
processed whereby a sudden and coherent change in the vector
direction, ASD and INT over more than three AF steps signified
an important vector component. Each specimen may or may not
signify such a change based on the magnetic carriers and the
stability of these carriers (i.e. magnetite, hematite). The
remaining specimens for each site were AF demagnetized at a
specific AF blocking coercivity value between 2.5 and 100 mT
based on the behavior of the pilot specimen.

The second thermal step remanence or pilot specimen data
was processed to determine if the dominant magnetic carrier
for that specimen was magnetite, hematite or a combination of
both by isolating the blocking temperatures of the magnetic
carriers. Secondly, once the magnetic carrier source has been
isolated, a thermal pilot analysis enables primary magnetizations
to be distinguished from secondary magnetizations by the use
of a fold test (Graham, 1949).

B. Radiometric

1. Sampling

Four large samples were collected for U-Pb zircon radiometric age dating from the Bird River Sill, Peterson Creek
Formation, composite stocks, and the Maskwa Lake Batholith
in the Bird River area. All samples were collected from large outcrops or road cuts with Figure 11 and Table 7 giving locations of the U-Pb samples. These samples weighed from 30 to 150 kg each, were fresh and unaltered and free of weathering surfaces.

2. **Zircon Separation Procedure**

Zircon separation methods of Miao (1984), Uza (1983) and Smith (1981) were used to concentrate zircons. Elaborate precautions were taken to avoid sample contamination, e.g. thorough vacuuming and washing of all facilities after each rock sample was processed. Smith (1981) outlined the zircon separation procedure used in detail. It should be noted that the sequence of steps taken may change according to mafic content of the sample and the amount of heavy minerals present after the Wilfley Table separation step.
Table 7. Uranium-Lead Sample Locations in the Bird River Area

<table>
<thead>
<tr>
<th>Sample</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Maskwa Lake Batholith</td>
<td>95° 45'</td>
<td>50° 23'</td>
<td>Sample - 4 km north of the Hwy. 315 and Hwy. 314 intersection along Hwy. 314. Quartz monzonite sampled</td>
</tr>
<tr>
<td>6 Synvolcanic</td>
<td>95° 27'</td>
<td>50° 26'</td>
<td>Sample - Bernic Lake Road, north of Tanco Mine. Sampled - metadiorite</td>
</tr>
<tr>
<td>4 Peterson Creek</td>
<td>95° 25'</td>
<td>50° 27'</td>
<td>Sample - Transmission Road, Lapilli Tuff and Lapillistone sampled</td>
</tr>
</tbody>
</table>
CHAPTER V
PALEOMAGNETIC RESULTS

A. Population Level Screening Analysis


The data for each demagnetizing group was plotted on an equal-area stereonet projection using both upper and lower hemispheres. The within-specimen angular standard deviation (ASD) of the remanence vector was also computed from the four (6-spin) redundant measurements of each Cartesian component of the remanence vector. The ASD gives a measure of the within-specimen remanence homogeneity and it was used as a screening criterion for selecting only homogeneously (reliably) magnetized specimens for interpretation (Stupavsky and Symons, 1982). ASD screening was done whereby any vector, whose ASD was below a set value (usually 30°) was plotted. If it was above that set value, it was not plotted for there is an estimated 5% probability that the specimen retains no coherent magnetization (Harrison, 1980; Stupavsky and Symons, 1982).

The vector populations on the stereoplots were contoured after reversing up or reversed vectors to the equivalent down directions on one stereoplots using a smoothing circle of area \( A \) equal to 1% of the area of the stereonet. A vector population anomaly is statistically significant at the 95%
confidence level when defined by a closed contour of at least $E + 2\sigma$ or $0.01N + 0.20N^{\frac{1}{2}}$, where $N$ is the number of specimens plotted, $E$ is the number of randomly directed vectors and $\sigma$ is defined as $\sigma = 0.10N^{\frac{1}{2}}$ where $A = 0.01$ (Stupavsky and Symons, 1982). It should be noted however, that an anomaly may be statistically but not paleomagnetically significant. An additional requirement for paleomagnetic significance is that the calculated anomaly must represent several sites with more than 5% of the population (Stupavsky and Symons, 1982).

Population A, B and C of the Bird River Sill and populations D and E of the Bernic Lake Formation fall within the above constraint. The above analysis was conducted using an Apple II+ microcomputer connected directly to the spinner magnetometer and using programs written by Dr. I. Stupavsky and Dr. D. T. A. Symons, both of the University of Windsor.

The calculated anomaly forming a contoured population was further analyzed to determine the mean paleopole direction for that population. All specimen directions that occurred within a specified contoured anomaly were grouped by site and sites by formation. All specimens from a known site were first averaged with the "up" directions being reversed to down directions or their antipole positions. This was done to insure that all inclinations for all known sites were positive. Averaging was done on each site to determine $N$, $k$, $R$, mean declination (mean dec), mean inclination (mean incl), and $A(95)$, where $N$ = the number of vectors averaged, $k$ = precision parameter for a Fisherian Distribution (Fisher, 1953), $R$ = length
of the resulting vector, mean dec = mean declination for the set of vectors averaged, mean incl = mean inclination for the set of vectors averaged, and \( A(95) \) = is the angular radius of the cone of confidence about the calculated mean (Tarling, 1983). The second averaging step was done on all calculated site means with the paleopole position for that specific population being resolved. The resulting pole position was given with constraints of co-latitude, \( \delta m \) and \( \delta p \) where:

- \( \delta m \) = is the radius of the ellipse of 95% confidence along the direction of the magnetic median from the site to the vertical pole; and

- \( \delta p \) = is the same radius at the pole perpendicular to the median (Tarling, 1983).

The resulting paleopole position displayed in longitude and latitude coordinates were plotted on the Apparent Polar Wander path. Both parallel and anti-parallel poles were plotted to correct for earlier stereonet direction reversals.

B. Bird River Sill

Specimens from each site were bulk demagnetized at a set alternating field based on the pilot specimen's behavior for that site. Some sites were bulk demagnetized at a second higher alternating field. Analysis of the resulting vector data was grouped in five data files based on demagnetizing fields:

1. NRM file (BS83 NRM),
2. 1st bulk cleaning file (BS83 AFBULK),
3. 2nd bulk cleaning file (BS83 AF (2ND)).
4. Chromite Bands-AF cleaning (BS83 CRABULK), and,
5. Thermal Analysis

1. NRM File

All 174 uncorrected NRM magnetic vectors were plotted, smoothed, and contoured producing a triangular anomaly (Population A) containing three internal peaks. Two peaks were defined by a 5.5% density contour (>99.9% confidence) while the third peak was defined by a 7.1% density contour (>99.99% confidence) (Fig. 12). The uncorrected NRM data has an average within-specimen (mean ASD) of 9.6° (s.d. 6.8°) and within-site mean ≈95 of 17.8° (s.d. 11.3°) remanence homogeneity.

Upon structural correction for strike, dip, and regional plunge, population A (Fig. 13) displayed an elongated triangular shape and density contour groupings. It should be noted that due to the limited structural data available pertaining to the sill, a true fold test (Graham, 1949) could not be utilized to its full potential.

The abnormally high NRM intensity (average 6.5799 E⁻² Am⁻¹ cm⁻³) for the sill specimens is due to the ultramafic mineralogy of the sill and the presence of deteurec magnetite rims associated with the chromite grains in the chromite bands (Gait, 1964). Population A of the uncorrected NRM data gives a mean direction of 326°, 78° (declination, inclination), suggesting that this grouping reflects the Viscous Remanent Magnetization (VRM) component of the present EMF. This VRM component has been acquired by the low coercivity components
Figure 12  Stereoplot of Vector Directions for the Bird River Sill before AF demagnetization in the NRM range without tectonic correction.
Figure 13  Stereoplot of Vector Directions for the Bird River Sill before AF demagnetization in the NRM range with tectonic correction
(i.e. coarse-grained magnetite) (Fig. 14) over the last 15,000 years. These low coercivity components are removed by later AF bulk demagnetization in the higher AF coercivity spectrum.

2. 1st Bulk Cleaning File

During the 1st bulk cleaning of all 18 sites of the Bird River Sill, the resulting remanence directions moved to a stable end point. The average remanence intensity on AF demagnetization dropped rapidly to 50% of the original NRM intensity at approximately 7.5 mT. By 20 mT, 17% of the original NRM intensity remained while at 50 mT, only about 1.5% of the NRM intensity remained (Fig. 15). This indicated that the dominant magnetic carrier is held in low AF coercivity domains, presumably of the coarse-grained magnetite.

The corrected B and C components (355°, -19°); (331°, -19°) (Fig. 16) have a limited coercivity range (7.5 mT - 60 mT) with most release forces being - 50 mT. The dominant B component was defined by a 9.8% density contour (>>> 99.99% confidence) while component C was defined by a 4.5% density contour. The resulting B and C component directions were calculated using an ASD screening of 30° and they resided in a coercivity spectrum with 5 sites of less than 25 mT and 7 sites of greater than 25 mT but less than 60 mT (Table 8).

3. 2nd AF Bulk Cleaning

Based on pilot specimen behavior, several sites were bulk demagnetized at a 2nd higher alternating field. The resulting data produced an elongated anomaly (population B) and two subsequent semi-circular ones (populations C and D). (Fig. 17).
Figure 14 Blocking and Coercivity Spectrums of Magnetite and Hematite (from Tarling 1989)
<table>
<thead>
<tr>
<th>File</th>
<th>AF Field (mT)</th>
<th>Intensity (Am$^{-1}$cm$^{-3}$)</th>
<th>J/Jo</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR83AF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot</td>
<td>NRM</td>
<td>1.61 E-2</td>
<td>1.00</td>
</tr>
<tr>
<td>2.5</td>
<td>9.54 E-3</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>5.0</td>
<td>6.00 E-3</td>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>7.5</td>
<td>2.25 E-3</td>
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<td>10.0</td>
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<td>15.0</td>
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<td>20.0</td>
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<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>25.0</td>
<td>2.50 E-4</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>30.0</td>
<td>2.17 E-4</td>
<td>0.015</td>
<td>0.015</td>
</tr>
<tr>
<td>40.0</td>
<td>1.60 E-4</td>
<td>0.013</td>
<td>0.013</td>
</tr>
<tr>
<td>50.0</td>
<td>1.60 E-4</td>
<td>0.010</td>
<td>0.010</td>
</tr>
<tr>
<td>60.0</td>
<td>1.46 E-4</td>
<td>0.006</td>
<td>0.006</td>
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<td>70.0</td>
<td>1.68 E-4</td>
<td>0.009</td>
<td>0.009</td>
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<td>80.0</td>
<td>1.93 E-4</td>
<td>0.010</td>
<td>0.010</td>
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<td>1.79 E-4</td>
<td>0.012</td>
<td>0.012</td>
</tr>
<tr>
<td>100.0</td>
<td>1.59 E-4</td>
<td>0.011</td>
<td>0.011</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 15: Mean Intensity on AF step demagnetization for 18 specimens: Bird River Sill
Figure 16  Stereoplot of Vector Directions of the Bird River Sill after AF bulk cleaning from 7.5 mT to 60 mT with tectonic correction
Table 8. Bird River Sill AF Remanence Data (1st Cleaning)

<table>
<thead>
<tr>
<th>Site</th>
<th># of Specimen</th>
<th>N/R</th>
<th>Treatment (mT)</th>
<th>Dec.</th>
<th>Incl.</th>
<th>R</th>
<th>$\lambda_{95}$</th>
<th>ASD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pop. B</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>R</td>
<td>25</td>
<td>-8.78</td>
<td>-24.06</td>
<td>5.98</td>
<td>4.38</td>
<td>9.32</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>R</td>
<td>20</td>
<td>-10.50</td>
<td>-29.02</td>
<td>3.92</td>
<td>15.51</td>
<td>8.04</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
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*Note: N= normal direction or downward direction
R= reverse direction or upward direction
Population B (35°, 29°) was defined by an 8.6% density contour (99.95% confidence). The main magnetic carriers reside in a coercivity spectrum of 50 to 90 mT (Table 9) and were contained in 5 of the 7 sites demagnetized representing 14% of the original population.

Population C (149°, 17°) was defined by an 8.6% density contour and resided in a 50 to 90 mT coercivity spectrum (Table 9). This reversed population was isolated in 3 of the 7 sites demagnetized and represents 16% of the original population.

Population D (274°, 14°) is an anomalous population that acquired its magnetic signal by ARM. This is a result of all release forces being surpassed and the resulting magnetic carriers paralleling the existing anomalous field. It was isolated in only one site and represents only 12% of the original population. This population has statistical significance but has no regional paleomagnetic significance.

4. Chromite Bands

All present structural information pertains to the chromite bands. Sites 18, 19, and 20 are stratigraphic profiles of 2 bands; one major and one minor. Analysis of these 3 sites isolated a very coherent semi-elongated anomaly having one central peak (Fig. 18). The corrected 24% density contour (>>99.99%) at 357°, -15° outlines a very well defined population B. The coercivity field of 30 mT for all 3 sites portrays a low coercivity component presumably a coarse-grained magnetite as being the dominant carrier. The deuteric
Figure 17  Stereoplot of Vector Directions of the Bird River Sill after a 2nd AF bulk cleaning of 30 mT and 40 mT with tectonic correction.
Table 9. Bird River Sill AF Remanence Data (2nd Cleaning)

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* Note: see note on Table 8 for explanation
Figure 18
Stereoplot of Vector Directions of the Chromite Bands of the Bird River Sill after AF demagnetization at 30 mT with tectonic correction
magnetite rims around the chromite grains (Cait, 1964) reflect the coarse-grained nature of both chromite and magnetite.

Table 10 summarizes the conclusions reached for the four AF files studied:

1. The dominant B and C components reside in a low coercivity component presumably a coarse-grained magnetite.

2. Component B and C are the only significant magnetic components present within the sill.

3. The improved clustering on structural correction implies that population B and C are prefolding overprints.

4. The low ASD and χ95 values for each collection strongly suggest that components B and C are real and component D is a result of Anhysteretic Remanent Magnetization (ARM) due to the low AF coercivity and high susceptibility of the ultramafic rock specimens.

Figure 19 shows all three files (BS83AFBULK, BS83AF(2ND), and BS83CRAFBULK) plotted, smoothed, and contoured producing a semi-elongated anomaly peaking at 356°, -20° being contained within an 7.8% density contour (> 99.99% confidence).
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Table 10  Bird River Sill Paleomagnetic Pole Locations
Figure 19  Stereoplot of Vector Directions of the Bird River Sill based on all three previous files with tectonic correction
5. Thermal Analysis

Eighteen thermal pilot specimens were thermally step demagnetized through ten steps from 450° to 670°C. This was done to determine if any other magnetic components were present other than populations B and C. After the 450°C demagnetization step, 13% of the original NRM intensity remained while at 570°C (maximum blocking temperature of magnetite). 9.5% of the original NRM intensity remained (Fig. 20). If hematite was present and contained an original prefolding component, it is not feasible that it would be detected as less than 1% of the original NRM intensity remained after 670°C (blocking temperature of hematite) (Fig. 14). Conclusively, the low coercivity nature of the dominant magnetic carriers makes thermal analysis impractical due to the low magnetic intensity. Therefore, thermal results are inconclusive due to low intensities that border on the edge of instrumental error.

C. Bernic Lake Formation

One specimen from each of the six sites from the Bernic Lake Formation was step demagnetized using 15 AF steps. Examination of the AF step data led to the decision to AF clean the remaining specimens at 30 and 40 mT.

All 66 corrected magnetic vectors were plotted, smoothed and contoured producing two significant anomalies. Populations C and E are defined by 4.9% density contours (>99.5% confidence) with C directed at 326°, 13° and E at 012°, 14° (Fig. 21).
<table>
<thead>
<tr>
<th>File</th>
<th>Thermal Step (°C)</th>
<th>Intensity (Am(^{-2})cm(^{-3}))</th>
<th>J/Jo</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS83Tstep</td>
<td>NRM</td>
<td>7.02 (\times) 10(^{-2})</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td>9.04 (\times) 10(^{-2})</td>
<td>0.13</td>
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<tr>
<td></td>
<td>475</td>
<td>1.07 (\times) 10(^{-2})</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>500</td>
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<td>0.23</td>
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<tr>
<td></td>
<td>520</td>
<td>9.98 (\times) 10(^{-2})</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>540</td>
<td>8.77 (\times) 10(^{-2})</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>570</td>
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<td>0.10</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>2.46 (\times) 10(^{-2})</td>
<td>0.03</td>
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<tr>
<td></td>
<td>620</td>
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<td>0.03</td>
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<td>670</td>
<td>6.34 (\times) 10(^{-2})</td>
<td>0.009</td>
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Figure 20: Mean thermal intensity on thermal step demagnetization based on 18 specimens: Bird River Sill
Figure 21  Stereoplot of Vector Directions of the Bernic Lake Formation after AF demagnetization of 30 mT and 40 mT with tectonic correction
Population C had a below average within-specimen (mean ASD 39.3°, s.d. 21.0°) and within-site (mean A95, 23.5, s.d. 13.3) remanence homogeneity based on 12 magnetic vectors without ASD screening. Population E similarly had a below average within specimen (mean ASD 35.2°, s.d. 19.8°) and within site (mean A95, 15.3, s.d. 9.92) remanence homogeneity based on 12 magnetic vectors. The average remanence intensity (Fig. 22) on AF demagnetization dropped rapidly to 39% of the original NRM intensity at 2.5 mT. By 7.5 mT, the J/Jo ratio had dropped to 0.14. Bulk demagnetizing fields of 30 and 40 mT produced J/Jo ratios of 0.10 and 0.13. Both populations C and E are low coercivity pre-folding components ranging from low to high coercivity magnetite (Fig. 14). Based on the increasing ASD for population C as more release forces are being surpassed, its magnetic signal is carried by low coercivity magnetite while population E with a decreasing ASD statistically suggests that its carrier is a higher coercivity magnetite than population C. Table 11 outlines the resulting population C and E vectors, ASD, and A95.

Population C has 6 specimens at 30 mT and 4 at 40 mT while population E has 3 at 30 mT and 5 at 40 mT. Population E reflects a thermal metamorphic overprint while Population C reflects on initial burial overprint.
Table:

<table>
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<tr>
<th>File</th>
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<td>5.0</td>
<td>3.78 E(^{-2})</td>
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<td>10.0</td>
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<td>1.88 E(^{-2})</td>
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<td>20.0</td>
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<td>4.71 E(^{-4})</td>
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<td>80.0</td>
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<td>100.0</td>
<td>2.62 E(^{-4})</td>
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Figure 22: Mean AF intensity on AF step demagnetization based on 6 specimens: Bernic Lake Formation
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<th>Number of Specimens</th>
<th>Treatment (mT)</th>
<th>Dec.</th>
<th>Incl.</th>
<th>R</th>
<th>A</th>
<th>K</th>
<th>ASD</th>
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<td>7.80</td>
<td>1025.03</td>
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<td>136.06</td>
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<td>16</td>
<td>1.988</td>
<td>27.21</td>
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<tr>
<td>AVG.</td>
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<td>10 spec.</td>
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<tr>
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<td>---</td>
<td>---</td>
<td>21.61</td>
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<tr>
<td>AVG.</td>
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<td>8 spec.</td>
<td>--</td>
<td>12</td>
<td>14</td>
<td>3.986</td>
<td>6.37</td>
<td>208.72</td>
<td>36.83</td>
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Chapter VI
RADIOACTIVE RESULTS

A. Radiometric Theory


1. U-Pb Method

The following section gives the relevant theoretical background of U-Pb age determinations. Most of this section is based on Faure (1977), Smith (1981) and Carson (1983). In addition, supplemental information is given in Appendix 1.

Single mineral species such as zircon are used for isotopic measurements of the U/Pb decay series. Three characteristics of zircon make it an ideal mineral for U/Pb geochronology. First, it contains measurable amounts of U; secondly, primeval Pb is almost entirely excluded from the zircon lattice due to its low charge and large atomic radius; and
thirdly, zircon is very retentive of U-Th-Pb and their intermediate daughter isotopes (Faure, 1977).

Pb has four naturally occurring isotopes $^{208}\text{Pb}$, $^{207}\text{Pb}$, $^{206}\text{Pb}$ and $^{204}\text{Pb}$. Lead 208, 207, and 206 are common, radiogenic and the stable end-members of $^{232}\text{Th}$, $^{235}\text{U}$, $^{238}\text{U}$ decay series respectively. The fourth isotope $^{204}\text{Pb}$ is non-radiogenic, extremely stable and for these reasons is used as a stable reference isotope. $^{206}\text{Pb}$ is measured in order to determine the contribution of thorium to the total amount of Pb that was measured by isotope dilution. The general age equation is: $\lambda t = \ln(1+D/P)$ where $D$ is the number of daughter isotopes, $P$ is the number of parent isotopes, and is expressed in units of the number of disintegrations per atom per year. This is the law of radioactivity. Alternatively, the above equation can be written as: $D = P(e^{\lambda t} - 1)$. These equations are derived and explained in Appendix 1.

The ratios $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ are substituted into the general age equation as the mass spectrometer will only measure mass ratios directly. Substitution results in:

$$\frac{^{206}\text{Pb}}{^{204}\text{Pb}} = \left(\frac{^{206}\text{Pb}}{^{204}\text{Pb}}\right)_0 + \frac{^{238}\text{U}}{^{204}\text{Pb}} (e^{\lambda_{1t}} - 1)$$  \hspace{1cm} (1)

$$\frac{^{207}\text{Pb}}{^{204}\text{Pb}} = \left(\frac{^{207}\text{Pb}}{^{204}\text{Pb}}\right)_0 + \frac{^{235}\text{U}}{^{204}\text{Pb}} (e^{\lambda_{2t}} - 1)$$  \hspace{1cm} (2)
noting:

(1) The ratios $^{207}_{\text{Pb}}/^{204}_{\text{Pb}}$, $^{206}_{\text{Pb}}/^{204}_{\text{Pb}}$, $^{238}_{\text{U}}/^{204}_{\text{Pb}}$ and $^{235}_{\text{U}}/^{204}_{\text{Pb}}$ are present-day ratios and can be used as $^{204}_{\text{Pb}}$ has remained unchanged since the time of crystallization.

(2) $(^{206}_{\text{Pb}}/^{204}_{\text{Pb}})_0$ and $(^{207}_{\text{Pb}}/^{204}_{\text{Pb}})_0$ are the initial isotope ratios of lead that were present in the sample at the time of crystallization.

(3) $\lambda_1$ and $\lambda_2$ are decay constants for $^{238}_{\text{U}}$ and $^{235}_{\text{U}}$ respectively.

Rearranging equations 1 and 2 for $t$, reliable, agreeable ages for rock crystallization can be obtained provided the U-Pb system is closed, which is not always the case.

$$t_{^{206}_{\text{Pb}}} = \frac{1}{\lambda_1} \ln \left( \frac{^{206}_{\text{Pb}}}{^{204}_{\text{Pb}}} \right) + 1$$ (3)

$$t_{^{207}_{\text{Pb}}} = \frac{1}{\lambda_2} \ln \left( \frac{^{207}_{\text{Pb}}}{^{204}_{\text{Pb}}} \right) + 1$$ (4)

These ages tend to be too young and are said to be discordant.

Present day Pb ratios can be changed to radiogenic Pb ratios by subtracting the original Pb ratios from the present day ratios. Stacey and Kramer's (1975) proposed model of
terrestrial lead evolution outlines the original lead ratios.

\[
\frac{^{207}\text{Pb}}{^{204}\text{Pb}}_{\text{present}} = \frac{^{207}\text{Pb}}{^{204}\text{Pb}}_{\text{radiogenic}} + \frac{^{207}\text{Pb}}{^{204}\text{Pb}}_{\text{original}} \quad (5)
\]

\[
\frac{^{206}\text{Pb}}{^{204}\text{Pb}}_{\text{present}} = \frac{^{206}\text{Pb}}{^{204}\text{Pb}}_{\text{radiogenic}} + \frac{^{206}\text{Pb}}{^{204}\text{Pb}}_{\text{original}} \quad (6)
\]

Substituting radiogenic lead into equations 1 and 2 yields:

\[
\frac{^{206}\text{Pb}}{^{204}\text{Pb}}_{\text{radiogenic}} = \left( \frac{^{238}\text{U}}{^{204}\text{Pb}} \right) e^{\lambda_1 t} - 1 \quad (7)
\]

\[
\frac{^{207}\text{Pb}}{^{204}\text{Pb}}_{\text{radiogenic}} = \left( \frac{^{235}\text{U}}{^{204}\text{Pb}} \right) e^{\lambda_2 t} - 1 \quad (8)
\]

The third method for age determination can be done on the basis of a \(^{207}\text{Pb}/^{206}\text{Pb}\) ratio. Division of equation 7 into equation 8 results in:

\[
\frac{^{207}\text{Pb}}{^{206}\text{Pb}}_{\text{radiogenic}} = \frac{\frac{^{235}\text{U}}{^{238}\text{U}}}{\frac{e^{\lambda_2 t} - 1}{e^{\lambda_1 t} - 1}} \quad (9)
\]

Where the \(^{235}\text{U}/^{238}\text{U}\) ratio is constant and equal 1/137.88. Equation 9 is transcendental and must be solved for \(t\) by iteration.
3. Concordia Diagrams

Concordia diagrams are a graphic and mathematical approach to resolving the discordancy problems of varying U/Pb decay rates. This diagram has the atomic ratio $\frac{^{206}\text{Pb}}{^{238}\text{U}}$ plotted on the ordinate and the atomic ratio $\frac{^{207}\text{Pb}}{^{235}\text{U}}$ plotted on the abscissa (Fig. 23). This concordant curve is a function of equations 7 and 8 with the locus of all concordant U/Pb systems being termed the 'concordia' (Wetherill, 1956).

Each point represents a specific age with concordant ages ($t = \frac{^{206}}{^{238}} = t = \frac{^{207}}{^{235}} = t = \frac{^{207}}{^{206}}$) plotting on the concordia curve. Zircons do not behave as completely closed systems with Pb loss or U gain, resulting in the plotting of a linear chord of the concordia curve. This chord is called the 'discordia' and the linear relationship is due to the fact that lead isotopes are chemically equivalent. This results in different zircon separates losing different amounts of lead. Mixing results with different zircon separates being displaced toward the origin by varying distances during a lead loss episode (Fig. 23). The upper age intercept of the discordia with the concordia will give an age of crystallization for the rock. The lower intercept may have several interpretations based on the lead loss model used.

The amount of lead loss is a function of zircon size as small zircons have larger surface area per unit volume. As lead is lost, it tends to be replaced by iron which makes the mineral more magnetic and more discordant. Sorting and
Figure 23. Concordia Diagram of 3 proposed theoretical models (based on Tilton, 1960)
sizing of zircons is based on the magnetic and size characteristics of those zircons present resulting in the definition of a discordant line or cord.

4. Lead Loss Models

Three lead loss models have been developed to try and explain discrepancies in the graphical and mathematical results of the U/Pb decay systems.

a. Episodic Lead Loss Model

This model proposed by Wetherill (1956) defines lead loss as occurring in a period of time that is much shorter than the total time since crystallization. Some episodic event such as metamorphism or chemical weathering results in rock losing lead. The final concordia diagrams will have a discordia with an upper intercept for the true age and a lower intercept dating with age of episodic lead loss.

This process has the effect of rotating the discordia line about the upper intercept age (concordant point) (Fig. 23).

b. Continuous Diffusion Model

Tilton (1960) suggested a continuous diffusion model that treats lead loss as a continuous rather than an episodic process. This model suggests that continuous diffusion of lead from the crystal lattice at a rate governed by the diffusion coefficient, the effective radius of the mineral and the concentration gradient (Tilton, 1960). The more concordant points on the discordia will still have a linear
relationship using this model but the lower intercept of the discordia will have no geological significance (Fig. 23).

c. Dilatancy Model

Based on the theory that radiometric minerals are subjected to radiation damage by alpha particle decay, Goldich and Mudrey (1972) proposed that this damage forms micro-capillary channels that permit water to enter the crystal. This water is released upon uplift and erosion releasing the pressure on the mineral crystal. The resulting dilatancy allows water to escape along with any dissolved radiogenic lead. The lower concordia intercept gives an age of uplift and erosion for the sampled area (Fig. 23).

5. Lab Procedures

All subsequent mass spectrometry analysis was conducted by Mr. Patrick Smith at the University of Kansas. Previous rock sample preparations were done at the University of Windsor. All dissolution procedures were conducted at the University of Kansas Mass Spectrometry Lab. by Mr. Patrick Smith and Dr. J. Huang.
B. **Analytical Results**

Eight rock samples were collected from the Bird River Greenstone Belt. Five were subsequently found feasible for age determination.

1. **Great Falls Quartz Diorite - Unit 10a - Maskwa Lake Batholith**

Sample 10 was collected 4.1 km from the intersection of highway 315 and highway 314 along highway 315. All hand samples within the 50 kg sample were coarse grained, equigranular and light to medium grey in color. Mafic minerals, hornblende, biotite and epidote are randomly oriented, with felsic minerals being quartz, bytownite and anorthoclase. Magnetite, sphene, and zircon were found as trace minerals associated with biotite and bytownite edges and fissures.

Two groups of zircons were found with the finer sized groups (less than 200 mesh) being pink to pinkish purple in color, semi-cubic to semi-elongated and gem-like with well defined crystal faces. The coarser sized groups (greater than 200 mesh) were opaque brown, elongated crystals with magnetite and hematite inclusions and pitted surfaces. This rock sample contained an ample supply of zircons with fracturing associated with the coarser sized groups (Appendix 2). The U content of the zircons tested ranged from 384 to 556 ppm with the Pb content varying from 187 to 256 ppm (Table 12).

Three zircon samples (10a, 10b, 10c) defined a discordia line with an upper intercept concordia intercept age of 2779 ±
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<th>Sample No.</th>
<th>Description</th>
<th>Tyler Mesh</th>
<th>( ^{206}\text{Pb} / ^{207}\text{Pb} )</th>
<th>( ^{206}\text{Pb} / ^{238}\text{U} )</th>
<th>( ^{207}\text{Pb} / ^{206}\text{Pb} )</th>
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<td>UM 3</td>
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*Blank and mass fractionation corrected.*
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<td>13.675</td>
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<td>2707</td>
<td>2737</td>
<td>2745 ± 6 &amp; 459 ± 263</td>
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<td>9.949</td>
<td>2141</td>
<td>2430</td>
<td>2682</td>
<td></td>
</tr>
</tbody>
</table>
64 Ma and a lower concordia intercept age of 615 ± 325 (Model 2, Ludwig, 1982) (Figure 24). Conclusively, the low plus and/or minus error and the uniform nature of the zircon crystals (less than 200 mesh) strongly suggest one primary igneous population of zircons and one primary age.

2. Synvolcanic Event - Unit 6a - Gabbroic - Diorite Intrusion

This unit was collected along the Bernic Lake Road, 0.3 km north of the Tanco mine gate. It is a fine grained moderately schistose diorite. Thin section analysis (Appendix 3) outlined two distinct grain sizes; large phenocrysts and a fine grained matrix. Phenocrysts were minor and dominantly zoned plagioclase (anorthoclase) with quartz inclusions and magnetite outlining crystal edges. Phenocrysts were elongated with zoning perpendicular to crystal length. The fine grained matrix was dominantly round crystals of quartz exhibiting euhedral extinction, elongated biotite crystals and magnetite inclusions in quartz and plagioclase crystals. Magnetite outlined crystal fissures, edges and voids. Petrographic analyses outlined the dioritic and schistose nature of this rock.

The zircon population for this rock sample is dominantly colorless but cloudy (100 - 200 mesh) containing minor magnetite inclusions. A honey-combed surface texture is present on most crystals with larger crystals portraying fracturing perpendicular and parallel to crystal length. Finer fractions are pink to pinkish purple in color and clear with most crystals exhibiting a semi-cubic to semi-elongated non-
Figure 24  Unit 10a Great Falls - Maskwa Lake - Quartz Diorite - U-Pb discordia diagram
symmetrical shape (Appendix 2). Zircons with magnetite or other mineral inclusions were excluded from testing with zircon concentrations being defined as good to moderate.

One zircon analysis (613) outlined a concordia age of 2715 based on a $^{207}\text{Pb}/^{206}\text{Pb}$ ratio (Fig. 25). The U concentration was low at 141 ppm corresponding to a low Pb concentration of 85.9 ppm (Table 12).

3. **Peterson Creek Formation - Unit 4e, 4d - Lapillistone - Lapilli in Tuff**

Sampling was done along the transmission road south of the Bird River and highway 315. Unit 4C and 4D were sampled along and between the easterly-plunging steeply dipping synform synclinal and anticlinal traces of the Peterson Creek Formation. Units sampled included a lapillistone and a lapilli tuff with the lapilli tuff being stratigraphically younger. The lapilli tuff is typically brown to buff in color, carrying up to 60 percent lapilli size clasts with clasts exhibiting moderate flattening. Thin section work outlined elongated, fractured and fragmented quartz-rich lapilli with fracturing semi-parallel to the schistosity. The fine grained matrix is dominantly biotite and quartz with minor amounts of microcline and albite. The lapilli and biotite show a preferred orientation as displayed by the schistose nature of the tuff (Appendix 3).

The zircons for this unit (Sample 4a, 4b, 4c, 4d, 4a-abraded) range from clear pink to opaque brown and fractured. Sample 4a is clear pink, 4b is clear pink with
Figure 25  Unit 6a Synvolcanic Event - Diorite Phase
U-Pb concordia diagram
cracks, 4c is opaque brown with some clear patches, 4d is opaque white with a low refractive index and 4a-abraded is a subsample of 4a. The coarser sized crystals (greater than 70 mesh) are light brown, opaque, and cloudy with crystal faces showing a honey-combed texture. Magnetite inclusions are associated with pink, well-formed crystals while brown opaque crystals contain magnetite on the outer surfaces and crystal ends. The finer sized crystal fraction (100 - 200 mesh) were semi-clear, light pink to colorless and moderately to poorly formed. Magnetite inclusions seem to be associated with clearer crystals. All crystals of both groups have a tendency to be cubic or semi-elongated. No needle-shaped crystals were present (Appendix 2). Zircon concentration is extremely high for all sieved groupings. The U concentration ranged from 92.6 ppm to 1654 ppm (Table 12).

The zircon fractions analyzed (4a, 4b, 4c, 4d, 4a-abraded) displayed a discordant line with an upper concordia intercept age of 2741 Ma and a lower concordia intercept age of 261 Ma based on samples 4a, and 4a-abraded (Fig. 26). Samples 4a, 4b, 4c, 4d and 4a-abraded give a discordia upper intercept age of 2744 +34 -19 with a lower concordia intercept age of 745 +531 -535 Ma. Samples 4a, 4b, and 4a-abraded outlined an upper discordia intercept age of 2741 +49 -20 Ma with a lower concordia intercept age of 605 +805 -814 Ma.

Conclusively, an upper concordia intercept age of 2741 Ma and a lower concordia intercept age of 261 Ma is proposed based on the lines of best fit (Fig. 26, Fig. 27).
Figure 77  Unit 4d  Peterson Creek - Lapilli Tuff  
U-Pb discordia-concordia diagram
4. Bird River Sill - Chrome Property - Gabroic Phase

This unit was sampled from the Bird River Sill approximately 240 meters stratigraphically above the sill base on the Chrome Property. Sampling focussed on the coarse gabbroic phase of the sill stratigraphically above the chromite bands. The gabbroic samples were very coarse grained, equigranular, massive and have been described as an anorthositic gabbro (Trueman, 1980). Thin section analysis confirmed this description (Appendix 3).

The zircons for this unit have well-defined crystal faces, with the coarser sized fraction (200-325 mesh) being brownish pink to reddish in color and containing some clear crystals. The finer sized fraction (less than 325 mesh) had a tendency to be pink and clear with well-defined symmetrical crystals. The extremely coarse fractions (greater than 100 mesh) were opaque, brown, fractioned with a honey-combed or pitted surface texture and displayed limited zoning (Appendix 2). Zircon crystal concentrations for this rock were very low, with the U-concentration ranging from 173 ppm to 256 ppm (Table 12).

The three zircon analyses (3a, 3b, 3c) outlined a discordia line with an upper concordia intercept age of $2745 \pm 6$ Ma and a lower concordia intercept age of $459 \pm 263$ Ma based on Model 1 of Ludwig (1982) (Fig. 28). This age is proposed to be primary and the age of intrusion and cooling for this sub-ore-grade sill.
Figure 28  Unit 3a  Bird River Sill - Gabbroic Phase  
excluding ultramafic point - U-Pb  
discordia diagram

Sample - Intercept

3G - 2745 ± 6,
459 ± 263
5. Bird River Sill - Gabbroic Phase - Chrome Property

This sample was collected from the chromite band contact of the Bird River Sill. This sample is stratigraphically between the chromite bands and the previous sample.

Thin section observations outline the metamorphosed nature of the gabbro sample. Intergranular clinopyroxene and oligoclase with zones of alteration containing sericite and chlorite are quite evident throughout the thin section.

The zircons for this unit are few, with the smaller sized fractions (less than 100 mesh) being light brown to pinkish brown, honey combed and cloudy. All zircons display minimal fracturing, are poorly shaped, cubic to semi-elongated with a few clear pink fragments and crystals (Appendix 2). The U concentration was 478 ppm for the single tested point (Table 12).

The one zircon analysis outlined a discordant point with an upper concordia intercept age of 2711 Ma based on a lower concordia intercept age of zero. If we use the lower concordia intercept age of 459 as proposed for the sill, the upper concordia intercept age is 2729 Ma. (Fig. 29).
Figure 29  Unit 3a Bird River Sill - Gabroic Phase including ultramafic point - U-Pb discordia diagram
DISCUSSION

On the bases of present geochronologic and paleomagnetic ages, the following sequence of events is proposed for the evolution of the Rice Lake Group contained within the Bird River Greenstone Belt.

<table>
<thead>
<tr>
<th>Event</th>
<th>Time Frame (Ma)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Deposition of the Eaglenest Formation</td>
<td></td>
</tr>
<tr>
<td>2) Extrusion of the Lamprey Falls Formation</td>
<td></td>
</tr>
<tr>
<td>3) Extrusion and Deposition of the Peterson Creek Formation</td>
<td>2741@</td>
</tr>
<tr>
<td>4) Intrusion of the Bird River Sill (Gabbroic Phase)</td>
<td>2745 ± 6@</td>
</tr>
<tr>
<td>Unconformity - end of Cycle I</td>
<td></td>
</tr>
<tr>
<td>5) Deposition and Extrusion of the Bernic Lake Formation</td>
<td></td>
</tr>
<tr>
<td>6) Intrusion of the composite Diorite Stocks, the core of the synclino</td>
<td>2715@</td>
</tr>
<tr>
<td>Unconformity - end of Cycle II</td>
<td></td>
</tr>
<tr>
<td>7) Deposition of the Flanders Lake Formation</td>
<td></td>
</tr>
<tr>
<td>8) Deposition of the Booster Lake Formation</td>
<td></td>
</tr>
<tr>
<td>9) Intrusion of the Lac du Bonnet Batholith</td>
<td>(2625 ± 6)+</td>
</tr>
<tr>
<td>(2623 ± 89)*</td>
<td></td>
</tr>
</tbody>
</table>

*Note: Type of age determination is:

@ - U-Pb zircon (this study)
& - Rb-Sr whole rock isochron
  (Penner + Clark (1971); Farquharson (1975))
+ - Paleomagnetic (this study)
Extrusion of the Eaglenest Lake Formation occurred before 2745 ± 6 Ma based on the lithologic contacts of the Eaglenest Lake Formation, the Lamprey Falls Formation and the Bird River Sill. The lithologic similarity of the Eaglenest Lake and the Bernic Lake Formations, if they are correlative (Trueman, 1980) may alter this interpretation.

The Lamprey Falls pillow basalts were extruded before 2745 ± 6 Ma. Intrusion of the Bird River Sill along the upper contact of this formation defines this minimum age for extrusion.

The general succession of extrusive events from the tholeiitic Lamprey Falls Formation to the calc-alkaline Peterson Creek Formation dated at 2741 Ma defines the first cycle of volcanism. The rhyolite to lapilli-tuff lithology of the latter formation suggests that it represents a very brief episode of volcanism.

Intrusion of the Bird River Sill along the contact between the Lamprey Falls and Bernic Lake Formations was the culmination of the first volcanic cycle of the belt. The U-Pb zircon age of 2745 ± 6 Ma for the sill is not different from the 2741 Ma age found for the Peterson Creek Formation and it is possible that the Bird River Sill may be the subsurface equivalent of the Peterson Creek Formation.

Extrusion of the basaltic to dacitic flow rocks of the Bernic Lake Formation (Unit 5a - 5d) initiated the second cycle of volcanism within the belt. This would be between
Figure 30  Polar Wander Path for the Archean Time Frame of 2300 to 2700 Ma (based on Irving, 1979)
2745 ± 6 Ma and 2715 Ma, which is the age of the sill and the synvolcanic diorite stocks respectively. Clasts from the Bird River Sill chromite bands and the Peterson Creek lapillistone are found in the Bernic Lake polymictic conglomerate which infers that the Bernic Lake Formation postdates the sill. A maximum age of 2745 ± 6 Ma is given by the Bird River Sill while the minimum age of 2715 Ma is that obtained for the subsequent intrusion of the synvolcanic composite diorite stocks (Unit 6) into the Bernic Lake mafic volcanics and metasediments. The author suggests that the Bernic Lake flow rocks and the synvolcanic gabbro to quartz diorite stocks may be from a common magma source and of the same age because of the similarity in rock composition.

The intrusion of these composite diorite stocks with their concordant U-Pb age of 2715 Ma represents the culmination of the second cycle of volcanism and associated plutonism.

Deposition of the Flanders and Booster Lake Formations occurred after 2715 Ma and before 2625 ± 6 Ma. The Flanders Lake Formation is stratigraphically older and limited in areal extent within the belt so that it likely represents a short depositional time period. This formation has been mapped and is continuous into the Manigotagan Gneissic Belt to the north (Trueman et al. 1976). The younger and more laterally extensive occurrence of the Booster Lake Formation
isochron ages of 2584 ± 132 Ma for the Maskwa Lake batholith, and 2593 ± 34 Ma for the Bird River Volcanics (modified from Penner & Clark, 1971). The initial $^{87}$Sr/$^{86}$Sr ratio of 0.7014 ± 0.0021 for the Maskwa Lake batholith suggests a primary magmatic source.

In the second model, if the 2779 ± 64 Ma age for this batholith is considered an emplacement age, then the batholith becomes basement to the supracrustal rocks of the Bird River Greenstone Belt. The 2590 ± 12 Ma paleomagnetic age may be a result of unmapped block rotation about the regional fold axis within the Bird River Sill. The Rb-Sr ages of 2584 ± 132 Ma and 2594 ± 34 may signify a metamorphic overprint correlatable with the Lac du Bonnet Rb-Sr whole rock isochron age at 2623 ± 89 Ma as all three ages are statistically the same. Initial $^{87}$Sr/$^{86}$Sr ratios of 0.7014 ± 0.0021, 0.7015 ± 0.0015 and 0.6998 ± 0.0032 for the Maskwa Lake batholith, the Bird River Volcanics and the Lac du Bonnet Batholith respectively, may also signify a metamorphic overprint event with open system behaviour.

Regional metamorphism and/or uplift of the belt occurred after 2560 ± 7 Ma, a prefolding thermal overprint is identified in both the Bird River Sill and the Bernic Lake Formation by paleomagnetism. This indicates that the major isoclinal folding occurred after 2560 ± 7 Ma and before the intrusion of the posttectonic Cat Lake pegmatite fields at 2442 ± 127 Ma to 2270 Ma (modified from Penner and Clark, 1971).
The exact age for these pegmatites would be difficult to obtain because no zircons were found during this study and of the open Rb-Sr system behaviour commonly found in pegmatite minerals. Field evidence suggests that these cross-cutting posttectonic pegmatite fields are the final pulse of igneous fluids from the Lac du Bonnet batholith because the batholith contains an interior core of similar pegmatitic granite (Cerny et al. 1981).

The lower intercept ages given by the concordia for the radiometrically dated samples may have a geologic meaning. Based on the episodic lead loss theory, these ages may signify regional uplift and/or the F4 faulting events of Trueman (1980). These lower intercept ages of 459 ± 263, 615 ± 325, and 262 Ma give an average age of about 444 Ma. Uplift during the Paleozoic time period from 570 to 225 Ma is evident in the straight vertical up-and-down movement of the Tyndall Limestone (Davies et al. 1962) found to the west of the study area in Manitoba. The F4 transcurrent and rotational faulting may have resulted from stress releases that occurred during regional uplift.

Igneous activity in the supracrustal rocks of the Bird River Greenstone Belt is marked by two cycles of volcanism with each containing at least 1 phase of plutonism.
<table>
<thead>
<tr>
<th>Volcanism</th>
<th>Plutonism</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cycle I</strong></td>
<td><strong>Cycle II</strong></td>
</tr>
<tr>
<td>Lamprey Falls (basic)</td>
<td>Bird River Sill (ultramafic)</td>
</tr>
<tr>
<td>Peterson Creek (felsic)</td>
<td></td>
</tr>
<tr>
<td>Formation</td>
<td>Formation</td>
</tr>
<tr>
<td>Bernic Lake Flow Rocks (basic)</td>
<td>Composite Stocks (mafic - intermediate)</td>
</tr>
<tr>
<td>(felsic)</td>
<td></td>
</tr>
</tbody>
</table>

Preseltectonic intrusions are the Maskwa Lake Batholith (Model 1 and 2), the Bird River Sill (Model 1 and 2), and several composite Diorite stocks (Model 1 and 2). Syntectonic and posttectonic intrusions are the Lac du Bonnet Batholith (Model 1 and 2), the Maskwa Lake Batholith (Model 1) and the Cat Lake pegmatite fields (Model 1 and 2). Overall, Cycle I and II of the Rice Lake Group may represent successive phases of the same period of igneous activity. On the other hand, the two cycles may have originated from two different magma sources. This would be compatible with the observed variability of the rocks, lherzolite to rhyolite, that make up the two cycles.
CHAPTER VIII
CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

(1) The time interval for the formation of the Rice Lake Group is approximately 154 Ma from the basement (2779 Ma) to the extrusion of the Lac du Bonnet Batholith (2625 Ma). This assumes the 2779 Ma age is a basement age.

(2) The time frame for the thermal events of the Kenoran Orogeny is postulated to be about 65 Ma from intrusion of the Lac du Bonnet Batholith (2625 Ma) to the regional metamorphism set at 2560 Ma.

(3) The major folding of the belt occurred after 2560 Ma but before 2442 to 2220 Ma based on regional metamorphism and post-tectonic Cat Lake pegmatite fields.

(4) A general tectonic history for the belt consisted of:

a. deposition of all supracrustal rocks including the development of the unconformable and conformable boundaries before 2625 Ma.

b. intrusion of the Lac du Bonnet batholith at 2625 Ma.

c. intrusion of the Maskwa Lake batholith at 2590 Ma.

d. regional metamorphism and uplift of the belt at 2560 Ma.

e. major isoclinal folding and the development of F3 dip slip faulting between 2560 Ma to 2442 Ma.
f. subsequent P$_{h}$ transcurrent faulting, and block rotation about the belt's fold axis during Paleozoic uplift at about 444 Ma.

(5) The intrusion of the Bird River Sill is not related to the Kenoran Orogeny and predates the regional metamorphism by about 185 Ma.

(6) Based on previously published Rb-Sr ages and field evidence, the Cat Lake pegmatite fields represent the final stage of the Kenoran Orogeny across the Bird River Greenstone Belt.

(7) The hypothesis that more than one orogenic event (Krog et al. 1974) occurred across the belt cannot be proven conclusively. However, the time of 65 Ma for the pre-folding thermal events of the Kenoran Orogeny postulated here may in fact include several smaller events. Syn-tectonic folding of the belt between 2560 Ma to 2442 Ma may constitute a secondary orogenic event. Similarly, the intrusion of the Cat Lake Pegmatite fields between 2442 Ma and 2220 Ma may also represent another smaller orogenic event terminating within the Kenoran Orogeny.

(8) The effect of this study on the regional mapping of the area is:

a. on the basis of the first model the Lac du Bonnet Batholith (2625 Ma) predates the intrusion of the Maskwa Lake Batholith (2590 Ma).

b. while the second model makes the Maskwa Lake Batholith basement (2779 Ma) to the supracrustal rocks.

Both above implications to the chronostratigraphy do not contradict any proven field relations.
(9) The relatively thick upper crust and attenuated lower crust (Hall, 1974) outlines a peculiar crustal configuration that is apparently associated with a deep sedimentary trough. This trough became the focus of a strongly heated zone which resulted in folding and metamorphism (Wilson, 1971). The Bird River Greenstone Belt is proposed to be such a trough, with the deepest portion being associated with the areal location of the composite diorite stocks and the Cat Lake pegmatite fields.

(10) The overall general trend of the English River subprovince based on the evaluation of published ages of Turek, (1971); Penner, (1970); Farquharson, (1975); and others suggests that the subprovince becomes younger to the south.

B. Recommendations

(1) More radiometric work (U/Pb geochronology) be conducted on the following units within the Bird River Greenstone Belt:

Unit 2a - pillow basalt
Unit 5a - 5d - basalt to rhyolite
Unit 10a - Maskwa Lake Quartz Diorite (intercore of batholith)
Unit 10b - Marijane Lake Batholith
Unit 17 - Lac du Bonnet quartz monzonite
Unit 18a - pegmatites

(2) Structural mapping in the area should concentrate on:

a. block rotations within the Bird River Sill on the Chrome Property and the western portion of the Greenstone Belt,
b. contact relationships between the Bird River Greenstone Belt and the Lac du Bonnet and Maskwa Lake batholiths to be further investigated.

(3) Paleomagnetic work be continued to outline both posttectonic and pretectonic events and/or overprints:

Unit 1  - volcanic and pebble wackes
Unit 2a - pillow basalt
Unit 6a - gabbro
Unit 7b - polymictic conglomerate
Unit 8b - conglomerate
Unit 10a - Maskwa Lake quartz diorite
          (batholith core and outer rim)
Unit 17 - Lac du Bonnet Batholith
          (interior core and outer rim)
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Appendix I

Radiometric Decay Equation
RADIOACTIVE DECAY RELATIONS

Decay rate $\propto$ number of radioactive atoms

$A$ (disintegrations/hr.) $\propto N$ (number of atoms)

$A = \lambda N$

where: $\lambda$ is a decay constant and is characteristic of decaying atoms.

$A = -\frac{dN}{dt} = -\lambda N$

by integration:

$$\int_{N_0}^{N} \frac{dN}{N} = -\lambda \int_{t_0}^{t} dt$$

$N_0 =$ number of atoms at $t_0 = 0$

$N =$ number of atoms at any given time $t$

$$N = N_0 e^{-\lambda t}$$

$$\frac{N}{N_0} = e^{-\lambda t}$$

$P = N =$ number of parent atoms present at time $= t$

$P_0 = N_0 =$ number of parent atoms present originally at time $= t_0$

$$\frac{P}{P_0} = e^{-\lambda t}$$

$$\frac{P_0}{P} = e^{\lambda t}$$
but \( P_0 = P + D^* \)

where \( D^* = \text{number of daughter atoms} \)

\[
\frac{P_0}{P} = 1 + \frac{D^*}{P}
\]

\[
e^{\lambda t} = 1 + \frac{D^*}{P}
\]

OR \( t = \ln \left[ \frac{1 + \frac{D^*}{P}}{\lambda} \right] \)

This law applies to all parent-daughter decay systems.
Appendix 2

Zircon Description
Unit - Maskwa Lake Quartz Diorite (Unit 10a)

Sampled - Approximately 4 km north of the junction of Highway 314 and 315 along Highway 314.

Quantity - The 50 kg sample contains an ample supply (about 20 grams) of zircon crystals.

Description - (a) Size Range - most of the zircons found sieved out in the 100 to 325 mesh size range. A normal distribution was observed about the 200 mesh size.

(b) Color - the coarser fractions (100 mesh) are opaque brown with the finer fractions (200 mesh) being pink to pinkish purple in color and clear.

(c) Fractures - fracturing is isolated in the larger sized fractions (200 mesh) with minimal fracturing below 200 mesh.

(d) Crystal Shape and Form - smaller sized fraction have well defined crystal faces and form with coarser fractions being elongated but not needle like.

(e) Special Notes - 1) larger crystals contain hematite and magnetite inclusions, usually at the ends of the crystal.

2) larger crystals show a pitted or honeycombed surface texture.
3) finer fractions
(> 200 mesh) display a
gem-like appearance
and shape.
Unit - Synvolcanic Event - Diorite (Unit 6a)

Sampled - Along the Tanco Mine road, 0.3 km from mine gate.

Quantity - The 50 kg sample produced a moderate supply of zircons crystals (about 35 grams).

Description - (a) **Size Range** - the majority of zircon crystals were in the 100 to 325 range. A skewed normal distribution centered on the 100 - 200 range was observed.

(b) **Color** - coarser fractions (> 200 mesh) were pink to pinkish purple in color with the finer fraction being cloudy and colorless.

(c) **Fractures** - crystals larger than 100 mesh should minimal fracturing. Finer fractions show no fracturing.

(d) **Crystal Shape and Form** - majority of crystals have well defined crystal faces but are not symmetrical.

(e) **Special Notes** - 1) some crystals contain minor magnetite inclusions.

2) no zoning or color variation in any crystals.

3) zircons with minor magnetite inclusions were excluded from testing.
Unit - Peterson Creek Formation - Lapilli Tuff (Unit 4a)  
Sampled - Based on the map of Trueman (1980), sampling was  
south along the Transmission Road.  
Quantity - This 50 kg sample produced an ample supply of  
zircons (about 150 grams).  
Description - (a) Size Range - the majority of zircons were  
contained within the 70 to 200 mesh size range. A skewed normal distribution was  
observed about the 100 mesh size.  
(b) Color - the coarser fractions (> 200  
mesh) were opaque and light brown. The  
finer fraction (< 200 mesh) were  
colorless to light pink in color and  
semi-clear.  
(c) Fractures - all sizes showed some form of  
fRACTuring or traces of.  
(d) Crystal Shape and Form - all crystals  
exhibited well defined crystal faces but  
were moderately to poorly symmetrical.  
(e) Special Notes - 1) all crystals showed a  
honeycomb surface  
texture.  
2) most brown and opaque  
crystals contain magnetite  
inclusions.  
3) on finer fractions,  
magnetite inclusions are  
associated with clear, pink  
crystals.
4) finer fractions show a tendency toward cubic or semi-elongated crystal forms with no needle shapes present.
Unit - Bird River Sill - gabbro (Unit 3a).

Sampled - Collected from the Bird River Sill, anorthositic gabbro, phase of sill on the Chrome Property.

Quantity - A limited number of zircons were found from a 50 kg sample (approximately 100 - 200 grains from all sieve sizes).

Description - (a) Size Range - most of the zircons found ranged in size from 100 mesh to less than 325 mesh with the majority in the 200 - 325 sieve size range.

(b) Color - most zircons less than 325 mesh were pink and clear while others greater than 325 mesh were brownish pink to red in color. A few zircons ~100 mesh were opaque and brown in color.

(c) Fractures - fracturing was associated with sieved fractions 200 mesh. Sieved fractions (> 100 mesh) showed a pitted or honeycombed outer surface texture.

(d) Crystal shape and form - all fractions (< 200) mesh show well defined crystal faces and symmetrically shaped crystals.

(e) Special Notes - some crystals in the 200 mesh range showed zoning with one crystal end being brown in color and the other pink in color.
Unit - Bird River Sill - Ultramafic Contact (Unit 3a)

Sampled - Sample was collected from the Chrome property, about 5 m above the chromite bonds within the gabbroic phase of the sill.

Quantity - minimal zircons were found for testing.

Description - (a) Size Range - As a result of the quantity quantity, no sieving was conducted.

(b) Color - the vast majority of larger zircons were cloudy, light brown to pinkish brown with finer sizes exhibiting a pink, clear color.

(c) Fractures - minimal fracturing, associated with larger sized crystals.

(d) Crystal Shape and Form - most crystals are poorly formed, cubic to semi-cubic in shape with no elongated or needle shaped crystals found.

(e) Special Notes - 1) all crystals exhibit a honey combed surface texture.

2) no zoning is evident on any studied crystals.

3) larger fractions contained minimal magnetite inclusions.
Appendix 3

Petrographic Description
THIN SECTION DESCRIPTION

1. Great Falls - Maskwa Lake Quartz Diorite
   The major constituents of this coarse-grained equigranular quartz diorite are biotite, hornblende, bytownite and quartz. The mafic scheme of this rock is randomly oriented hornblende biotite spene and epidote. The hornblende minerals are highly fragmented, contain inclusions of biotite and are associated with spene. The biotite minerals are green to brown fragmented, contain inclusions of quartz bytownite and minor tracés of labradorite, sphene and epidote. The mineral, bytownite, exhibits albite and minor Carlsbad twinning within the large highly fragmented crystals. Quartz exhibits euheral extinction and is void infill. This sample was collected along Hwy. 314, 4.1 km north of the Hwy. 314 and Hwy. 315 intersection on the western side of the road (Latitude 95°, 28', 40"; Longitude 50°, 30', 50").

2. Synvolcanic Event - Unit 6a - Diorite
   This fine-grained schistose diorite shows a preferred orientation of the biotite, epidote, and plagioclase minerals. Two distinct grain sizes are evident: phenocrysts of anorthoclase surrounded by a fine-grained matrix. The anorthoclase phenocrysts contain quartz inclusions, magnetite on crystal edges with zoning perpendicular to crystal length. The matrix consists of biotite, anorthoclase and magnetite. The biotite minerals are fine-grained, pleochroic brown to colorless, rectangular in shape. The quartz crystals are
rounded, display euhedral extinction and form void infills. The magnetite forms inclusions in the quartz and anorthoclase crystals. It outlines the crystal form while the anorthoclase and quartz crystals are not associated with biotite. This rock was sampled along the Bernic Lake Road (Tanco Mine Road), 0.3 km north of the Tanco Mine gate along the northern side of the road (Latitude 95°, 29', 58"; Longitude 50°, 25', 20").

3. Peterson Creek Formation - Lapillistone - Lapilli Tuff

This extrusive rock shows a preferred orientation being outlined by a flattening of the lapilli. This rock displays two grain sizes: the lapillistones and a fine-grained quartz-rich matrix. The lapilli are dominantly quartz, highly fragmented with fracturing semi-parallel to schistosity. The fine-grained matrix is dominantly quartz and biotite with minor traces of microcline. The quartz crystals form two distinct grain sizes with euhedral extinction. The grains of biotite are very fine-grained, elongated, semi-cubic, and semi-pleochroic. The microcline traces contain inclusions of quartz and minor crystals of albite. The preferred orientation of the lapilli and biotite outline the schistose nature of the unit. Unit was sampled south of the Bird River and north of the Schellenberg Creek (Latitude 95°, 25', 05"; Longitude 50°, 26', 57").
4. **Bird River Sill - Gabbroic Phase**

   This unit is coarse-grained, equigranular containing clinopyroxene, plagioclase, chlorite, sericite, k-feldspar, and sphene. The clinopyroxenes exhibit an intergranular texture and euhedral extinction. Zones of alteration show oligoclase and clinopyroxene altering to sericite and inclusions of chlorite. The crystal contacts show a fibrous intergrowth with oligoclase crystals being well-formed and partly fragmented and fractured. Traces of K-feldspar and sphene were also observed. This rock unit was collected approximately 5 m above the chromite bands from the chrome property of the sill (Latitude 95°, 33', 19"; Longitude 50°, 27', 50").
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