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Phillips Cole Thurston

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30 DEC. 1982
THE VOLCANOLOGY AND TRACE ELEMENT GEOCHEMISTRY OF CYCLICAL VOLCANISM IN THE ARCHEAN CONFEDERATION LAKE AREA, NORTHWESTERN ONTARIO

by

Phillips Cole Thurston

Department of Geology

Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Faculty of Graduate Studies

The University of Western Ontario

London, Ontario

March 1980

VOLUME 1

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ABSTRACT

Archean volcanic rocks in the Confederation Lake area northwestern Ontario, are in three mafic to felsic cycles collectively 8500 to 11,240 m thick. Each cycle begins with pillowed basalt and andesite flows and is capped by andesitic and rhyolitic pyroclastic rocks and minor flows. Cycle I is believed to be entirely subaqueous as it is overlain by 90 m of limestone. Cycle II has pillowed basal basalt flows and andesitic to rhyolitic pyroclastic rocks locally overlain by 100 to 150 m of rhyolite tuff with intensely welded fragments. The environment of deposition of this unit appears to have been subaerial. Cycle II is overlain by stromatolitic limestone and pillowed basalt flows at the base of Cycle III. The remainder of Cycle III is dacitic pyroclastic rocks and rhyolitic flows, pyroclastic rocks and coeval hypabyssal intrusions.

Cycle I rhyolites are 2959 Ma old, Cycle II rhyolites are 2794 Ma and Cycle III rhyolites are 2739 Ma old by U-Pb age determination on zircons. These time periods are in accord with observed periodicity and volumes in young volcanic terrains.

In each cycle, tholeiitic basalts are overlain by calc-alkaline andesite to rhyolite. Fe enrichment in
Basalts is accompanied by depletion of Ti, Ca, Al-Cr, Ni, and Sr, and enrichment in P, the rare earth elements, and Nb, Y, and Zr. This is interpreted as open system fractionation of olivine, plagioclase, and minor clinopyroxene. Si enrichment in dacites and rhyolites is attributed to fractional crystallization of plagioclase, quartz, K-feldspar, and biotite. Tholeiitic basalt liquids are believed to be mantle-derived. Intercalated andesites with flat rare earth patterns appear to be products of mixing of tholeiitic basalt and rhyolite liquids and, andesites with fractionated rare earth patterns are probably produced by melting of amphibolite. Felsic magmas are partial melts of tholeiitic basalt, in some instances followed by magma mixing of tholeiites with trondhjemites.

Cycle I is interpreted as a platform upon which Cycle II was deposited in the early stages of caldera development. Cycle III is the central graben of the caldera and is the product of resurgent volcanism, hypabyssal intrusions, and late stage hydrothermal activity which also formed the Cu-Zn-Ag massive sulphide body of South Bay Mine. The tectonic scheme favored on the basis of structural, lithologic, and chemical parameters is a marginal basin behind a volcanic arc.
Acknowledgements

This work would not have been possible without the support of the Ontario Geological Survey which provided a leave of absence for 2 winters, a Ministry of Natural Resources bursary, and field support during the period 1973-1977. M. Raudsepp, B.C. Wilson, W. Waychison, R.M. Falls, and M.C. Jackson mapped parts of the area and numerous junior assistants provided logistical support and several B.Sc. theses which helped with understanding parts of the area. The staff of the South Bay Mine, particularly J. Wan, geologist, and D. Thomson, manager, helped with logistics and accommodation at various times.

The staff and students at the University of Western Ontario provided an excellent environment for learning. Brian Fryer provided help at the University of Western Ontario and at the Memorial University of Newfoundland including some analytical work plus many discussions. Discussion with R. Kerrich, A.D. Edgar, W.R. Church and W.S. Fyfe were of great help. The University of Western Ontario is thanked for travel funds which made possible attendance at the Penrose Conference on subaqueous volcanism and two trips to confer with B. Fryer at Memorial University. Bob Hodder has patiently guided me through the wilderness of Archean volcanology and reviewed the various
drafts of the thesis. B. McKinnon provided help with use of the X-ray fluorescence unit. J. Forth made many of the thin sections. Drafting has been done by B. Moore, and L. Christiansen, and J. Foster. Typing of the final version was done by Miss J. John and Mrs. A. Branicky.

This thesis is dedicated to my wife Nancy for her unfailing support during the course of the study.
<table>
<thead>
<tr>
<th>TABLE OF CONTENTS</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>v</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF PHOTOGRAPHIC PLATES</td>
<td>xii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xiii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xv</td>
</tr>
<tr>
<td>LIST OF APPENDIX TABLES</td>
<td>xviii</td>
</tr>
<tr>
<td>LIST OF APPENDIX FIGURES</td>
<td>xix</td>
</tr>
<tr>
<td>CHAPTER I - INTRODUCTION</td>
<td></td>
</tr>
<tr>
<td>1.1 Purpose</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Location, Access and Physiography</td>
<td>3</td>
</tr>
<tr>
<td>1.3 Previous Work</td>
<td>3</td>
</tr>
<tr>
<td>1.4 Field and Laboratory Work</td>
<td>5</td>
</tr>
<tr>
<td>CHAPTER II - REGIONAL GEOLOGY</td>
<td>7</td>
</tr>
<tr>
<td>2.1 General Statement</td>
<td>7</td>
</tr>
<tr>
<td>2.2 Structural Geology</td>
<td>21</td>
</tr>
<tr>
<td>CHAPTER III - GEOLOGY OF THE CONFEDERATION LAKE AREA</td>
<td>24</td>
</tr>
<tr>
<td>3.1 Cycle I Formation A</td>
<td>24</td>
</tr>
<tr>
<td>3.1.1 Field Occurrence and Petrography</td>
<td>33</td>
</tr>
<tr>
<td>3.2 Cycle I Formation B</td>
<td>33</td>
</tr>
<tr>
<td>3.2.1 Field Occurrence and Petrography</td>
<td>33</td>
</tr>
<tr>
<td>3.3 Cycle I Formation C</td>
<td>42</td>
</tr>
<tr>
<td>3.3.1 Field Occurrence and Petrography</td>
<td>42</td>
</tr>
<tr>
<td>3.4 Cycle I Formation D</td>
<td>43</td>
</tr>
<tr>
<td>3.4.1 Field Occurrence and Petrography</td>
<td>43</td>
</tr>
<tr>
<td>3.5 Geochronology</td>
<td>44</td>
</tr>
<tr>
<td>3.6 Cycle II Formation E</td>
<td>45</td>
</tr>
<tr>
<td>3.6.1 Field Occurrence and Petrography</td>
<td>45</td>
</tr>
<tr>
<td>3.7 Cycle II Formation F</td>
<td>52</td>
</tr>
<tr>
<td>3.7.1 Field Occurrence and Petrography</td>
<td>52</td>
</tr>
<tr>
<td>3.8 Cycle II Formation G</td>
<td>55</td>
</tr>
<tr>
<td>3.8.1 Field Occurrence and Petrography</td>
<td>55</td>
</tr>
<tr>
<td>3.9 Cycle II Formation H</td>
<td>66</td>
</tr>
<tr>
<td>3.9.1 Field Occurrence and Petrography</td>
<td>66</td>
</tr>
<tr>
<td>3.10 Cycle II Formation J</td>
<td>84</td>
</tr>
<tr>
<td>3.10.1 Field Occurrence and Petrography</td>
<td>84</td>
</tr>
</tbody>
</table>
### Chapter IV - Physical Volcanology

- **4.1** Cyclical Volcanism .......................... 114
  - **4.1.1** General Statement .......................... 114
  - **4.1.2** Cyclicality in the Confederation Lake Area .................................................. 118
- **4.2** Facies Variation and Paleovolcanic Reconstruction ...................... 119
  - **4.2.1** General Statement .......................... 122
  - **4.3** Reconstruction of Facies ..................... 122
  - **4.3.1** Cycle I Confederation Lake Area .......... 122
    - **4.3.1.2** Eruption Type and Environment of Deposition ........................................... 128
    - **4.3.1.3** Large-Scale Reconstruction ............ 129
    - **4.3.2** Cycle II Confederation Lake Area ....... 130
      - **4.3.2.1** Reconstruction of Facies ............... 130
      - **4.3.2.2** Eruption Type and Environment of Deposition ........................................... 136
    - **4.3.2.3** Large-Scale Reconstruction ............ 139
    - **4.3.3** Cycle III Confederation Lake Area ...... 140
      - **4.3.3.1** Reconstruction of Facies ............... 140
      - **4.3.3.2** Eruption Type and Environment of Deposition ........................................... 144
  - **4.4** Time Constraints on Volcanism ........................................... 146
    - **4.4.1** Confederation Lakes Area ................. 148

### Chapter V - Chemical Composition of the Rocks

- **5.1** General Statement ................................ 152
- **5.2** Metasomatism .................................... 159
- **5.3** Cycle I Mafic Volcanic Rocks .................. 165
  - **5.3.1** Major and trace element abundances ...... 165
  - **5.3.2** Abundances of Rare Earth Elements ...... 174
- **5.4** Cycle I Metavolcanic Rocks of Intermediate Composition ...................... 177
  - **5.4.1** Major and Trace Element Abundances ...... 177
5.4.2 Abundances of Rare Earth Elements...178
5.5 Cycle I Metavolcanic Rocks of Pelsic Composition.........................178
5.5.1 Major and Trace Element Abundances...178
5.5.2 Abundances of Rare Earth Elements...183
5.6 Cycle II Metavolcanic Rocks of Mafic Composition..........................183
5.6.1 Major and Trace Element Abundances...184
5.6.2 Abundances of Rare Earth Elements...185
5.7 Cycle II Metavolcanic Rocks of Intermediate Composition.................185
5.7.1 Major and Trace Element Abundances...185
5.7.2 Abundances of Rare Earth Elements...188
5.8 Cycle II Metavolcanic Rocks of Pelsic Composition..........................189
5.8.1 Major and Trace Element Abundances...189
5.8.2 Abundances of Rare Earth Elements...192
5.9 Cycle III Metavolcanic Rocks of Mafic Composition..........................197
5.9.1 Major and Trace Element Abundances...197
5.9.2 Abundance of Rare Earth Elements...199
5.10 Cycle III Varioilitic Flows.................200
5.11 Cycle III Metavolcanic Rocks of Pelsic Composition.........................203
5.11.1 Major and Trace Element Abundances...203
5.11.2 Abundances of Rare Earth Elements...204
5.12 Granodiorites.......................204
5.13 Cyclical Volcanism..........................209
5.13.1 General Statement.......................209
5.13.2 Cycle I......................212
5.13.3 Cycle II..........................217
5.13.3 Cycle III..........................218

CHAPTER VI - PETROGENESIS........................................221
6.1 General Statement.......................221
6.2 Basalt Genesis..........................221
6.2.1 Basaltic Primary Magmas.................221
6.2.2 Conditions of Melting..................222
6.2.3 Liquid Immiscibility..................223
6.3 Andesite Genesis.......................227
6.3.1 General Statement.......................227
6.3.2 Archean Andesites.....................228
6.3.3 Petrogenesis of Andesites...............229
6.3.3.1 Fractional Crystallization from a Basaltic parent magma........229
6.3.3.2 Mixing Hypothesis.....................231
6.3.3.3 Andesitic Primary Magmas..........233
6.3.4 Origin of Archean Andesites............234
6.4 Genesis of Pelsic volcanic rocks........235
6.4.1 Origin by partial melting of Eclogitic Rocks......................... 235
6.4.2 Origin by fractional crystallization of basalt....................... 237
6.4.3 Origin by partial melting of amphibolite.......................... 238
6.4.4 Origin by partial melting of grey- wackes.......................... 239
6.4.5 Trace Element signature of various fractionating phases............ 241
6.5 Origin of volcanic rocks in the Confederation Lake Area.............. 241
6.5.1 Basalts........................................ 241
6.5.1.1 Cycle I Basalts.................................. 241
6.5.1.2 Cycle II Basalts-Formation E.......................... 246
6.5.1.3 Cycle II Basalts-Formation F.......................... 249
6.5.1.4 Cycle III Basalts.................................. 249
6.5.2 Andesites......................................... 250
6.5.2.1 Cycle I........................................ 250
6.5.2.2 Cycle II........................................ 251
6.5.2.3 Cycle III........................................ 252
6.5.3 Felsic Volcanic Rocks................................ 252
6.5.3.1 Cycle I........................................ 252
6.5.3.2 Cycle II-Formation F............................. 253
6.5.3.3 Cycle II East limb of regional synclinorium..................... 253
6.5.3.4 Cycle II West limb of regional synclinorium...................... 254
6.5.3.5 Rocks of Intermediate Composition.......................... 254
6.5.3.6 Cycle III Felsic Meta-Volcanic Rocks.......................... 255
6.6 The Role of Fractional Crystallization in cyclical volcanism........ 256
6.7 Role of Magma Mixing-Confederation Lake area.......................... 258
6.7.1 Genesis of Andesites.................................. 259
6.8 The Role of Liquid Immiscibility................................. 260
6.8.1 Preamble........................................... 260
6.8.2 Application to the Confederation Lake Area......................... 262

CHAPTER VII - TECTONIC RECONSTRUCTION............................. 267
7.1 General Statement......................................... 267
7.1.1 Fixist Concepts....................................... 267
7.1.2 Plate Tectonic Concepts.................................. 269
7.1.2.1 Chemical Studies.................................... 271
7.2 Tectonic Reconstruction of the Confederation Lake area.............. 274
7.2.1 General Statement....................................... 274
7.2.2 Chemical Aspects........................................ 274
**LIST OF PHOTOGRAPHIC PLATES**

<table>
<thead>
<tr>
<th>Plate</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate I</td>
<td>28</td>
</tr>
<tr>
<td>Plate II</td>
<td>38</td>
</tr>
<tr>
<td>Plate III</td>
<td>48</td>
</tr>
<tr>
<td>Plate IV</td>
<td>58</td>
</tr>
<tr>
<td>Plate V</td>
<td>71</td>
</tr>
<tr>
<td>Plate VI</td>
<td>86</td>
</tr>
<tr>
<td>Plate VII</td>
<td>95</td>
</tr>
</tbody>
</table>
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Stratigraphy of the Confederation Lake area</td>
<td>14</td>
</tr>
<tr>
<td>2-2</td>
<td>Metamorphic and deformation events in the Confederation Lake area</td>
<td>18</td>
</tr>
<tr>
<td>3-1</td>
<td>Metamorphic assemblages in mafic metavolcanic rocks</td>
<td>25</td>
</tr>
<tr>
<td>3-2</td>
<td>Metamorphic assemblages in ultramafic rocks</td>
<td>31</td>
</tr>
<tr>
<td>3-3</td>
<td>Metamorphic assemblages in sedimentary rocks</td>
<td>41</td>
</tr>
<tr>
<td>3-4</td>
<td>Field characteristics and petrography of subaqueous ignimbrites Formations G</td>
<td>65</td>
</tr>
<tr>
<td>3-5</td>
<td>Characteristics of subaerial vs subaqueous ignimbrites</td>
<td>67</td>
</tr>
<tr>
<td>3-6</td>
<td>Metamorphic assemblages in felsic volcanic rocks</td>
<td>69</td>
</tr>
<tr>
<td>3-7</td>
<td>Detailed stratigraphy of the Woman Lake Tuff</td>
<td>73</td>
</tr>
<tr>
<td>3-8</td>
<td>Summary of modal data Woman Lake tuff</td>
<td>76</td>
</tr>
<tr>
<td>3-9</td>
<td>Textural and Mineralogical changes caused by welding in the Woman Lake Tuff</td>
<td>82</td>
</tr>
<tr>
<td>3-10</td>
<td>Metamorphic assemblages in intermediate metavolcanic rocks</td>
<td>93</td>
</tr>
<tr>
<td>4-1</td>
<td>Scale of volcanic cyclicity in the Archean</td>
<td>116</td>
</tr>
<tr>
<td>4-2</td>
<td>Stages in the Smith and Bailey caldera cycle (after Smith and Bailey, 1968)</td>
<td>124</td>
</tr>
<tr>
<td>4-3</td>
<td>Summary of stratigraphy and paleoenvironment of Cycle I volcanic rocks</td>
<td>125</td>
</tr>
<tr>
<td>4-4</td>
<td>Summary of stratigraphy and paleoenvironment of Cycle II volcanic rocks</td>
<td>134</td>
</tr>
<tr>
<td>4-5</td>
<td>Summary of stratigraphy and paleoenvironment of Cycle III volcanic rocks</td>
<td>145</td>
</tr>
<tr>
<td>Table</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>5-1</td>
<td>Trace element indicators of fractionation (after Frey et al. 1974)</td>
<td>153</td>
</tr>
<tr>
<td>6-1</td>
<td>Average compositions of Archean tholeiites (after Condie, 1976)</td>
<td>224</td>
</tr>
<tr>
<td>6-2</td>
<td>Average compositions of andesites (after Condie)</td>
<td>230</td>
</tr>
<tr>
<td>6-3</td>
<td>Effect upon trace elements of the eclogite melting model vs amphibolite melting for production of felsic volcanic liquids (after Glikson, 1976)</td>
<td>240</td>
</tr>
<tr>
<td>7-1</td>
<td>Chemical characteristics of calc-alkaline rocks</td>
<td>272</td>
</tr>
<tr>
<td>7-2</td>
<td>Chemical composition of rocks from marginal basins</td>
<td>273</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

figure

1-1  Index Map  \hspace{1cm} 2
1-2  Geological Map of the Confederation Lake Area*  \hspace{1cm} 2
2-1  Stratigraphic Map of the Confederation Lake Area*  \hspace{1cm} 10
2-2  Block diagram of geological structure of the Confederation Lake area  \hspace{1cm} 12
2-3  Stratigraphic section of the Confederation Lake area  \hspace{1cm} 60
3-1  Facies model for subaqueous ash flows  \hspace{1cm} 63
3-2  Subaqueous ignimbrites—Lost Bay  \hspace{1cm} 74
3-3  Subdivision of subaerial ignimbrites  \hspace{1cm} 75
3-4  Detailed Stratigraphy—Woman Lake tuff  \hspace{1cm} 79
3-5  L/W of pumice fragments—Woman Lake tuff  \hspace{1cm} 99
3-6  Geology of Cycle III—pyroclastic rocks within sector graben  \hspace{1cm} 123
4-1  Pre-folding reconstruction of Cycles I, II, and III  \hspace{1cm} 127
4-2  Map of Cycle I  \hspace{1cm} 133
4-3  Map of Cycle II  \hspace{1cm} 142
4-4  Map of Cycle III  \hspace{1cm} 149
4-5  Relationship of periodicity, volume of ejecta, and depth of magma chamber (after Smith, 1979)  \hspace{1cm} 157
5-1  Kd of various minerals  \hspace{1cm} 162
5-2  MgO vs CaO Cycles I, II, III  \hspace{1cm} 164
5-3  Na2O/K2O vs Na2O+K2O Cycle I, II, III  \hspace{1cm} 166
5-4  SiO2 vs log Zr/TiO2  \hspace{1cm} 168

*Figures 2-1 and 2-2 are in rear map pocket vol. II
<p>| Table 5-5 | Zr vs SiO₂ all cycles. | page 168 |
| Table 5-6 | Zr vs SiO₂ | page 169 |
| Table 5-7 | AFM all cycles | page 170 |
| Table 5-8 | Al₂O₃ vs MgO vs FeO* + TiO₂ cation percent all cycles | page 171 |
| Table 5-9 | Cr vs TiO₂ basalts all cycles | page 173 |
| Table 5-10 | REE patterns Cycle I basalts, intermediate volcanics, and felsic volcanics | page 176 |
| Table 5-11 | K₂O vs Na₂O Felsic volcanics all cycles | page 180 |
| Table 5-12 | Normative feldspar composition felsic volcanics all cycles | page 182 |
| Table 5-13 | REE patterns Cycle II basalts-andesites | page 187 |
| Table 5-14 | Log Rb vs Log Ba Cycle II felsic volcanics | page 190 |
| Table 5-15a | REE pattern Cycle II minor cycle felsic volcanics | page 190 |
| Table 5-15b | REE pattern Cycle II felsic top east limb | page 194 |
| Table 5-15c | REE pattern Cycle II intermediate volcanic west limb | page 195 |
| Table 5-15d | REE pattern Cycle II felsic volcanics | page 195 |
| Table 5-16 | REE patterns Cycle III basalts and associated rocks | page 202 |
| Table 5-17a | Log Ba vs Log Rb Cycle III felsic volcanics and Granodiorite | page 206 |
| Table 5-17b | Log Rb vs Log Sr Cycle III felsic volcanics and Granodiorite | page 206 |
| Table 5-18 | REE pattern Cycle III felsic volcanics and granodiorite | page 208 |
| Table 5-19 | SiO₂ histogram all cycles | page 211 |
| Table 5-20 | Y vs SiO₂ all cycles | page 214 |</p>
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-21</td>
<td>Y vs Zr all cycles</td>
<td>216</td>
</tr>
<tr>
<td>5-22</td>
<td>Cr vs SiO₂ mafic flows cycle II, III</td>
<td>219</td>
</tr>
<tr>
<td>6-1</td>
<td>Chondrite normalized REE patterns for Archean tholeiites (after Condie, 1976)</td>
<td>225</td>
</tr>
<tr>
<td>6-2</td>
<td>Petrogenetic grid for mantle derived basaltic rocks (after Green, 1971)</td>
<td>226</td>
</tr>
<tr>
<td>6-3</td>
<td>Chondrite normalized REE patterns for Archean andesites (After Condie, 1976)</td>
<td>236</td>
</tr>
<tr>
<td>6-4</td>
<td>REE pattern for melting of eclogite (after Arth and Hanson, 1975)</td>
<td>238</td>
</tr>
<tr>
<td>6-5</td>
<td>REE patterns for felsic volcanic rocks produced by several petrogenetic processes (after Hanson, 1978)</td>
<td>242</td>
</tr>
<tr>
<td>6-6</td>
<td>REE patterns for felsic volcanic rocks produced by melting greywacke (After Arth and Hanson, 1975)</td>
<td>243</td>
</tr>
<tr>
<td>6-7</td>
<td>The effect of fractional crystallization upon Sr, Rb, and Ba (after McCarthy and Robb, 1977)</td>
<td>245</td>
</tr>
<tr>
<td>6-8</td>
<td>REE patterns for production of tholeiitic liquids by varying degrees of mantle melting (after Arth and Hanson, 1975)</td>
<td>248</td>
</tr>
<tr>
<td>6-9</td>
<td>SiO₂ - CaO + MgO + FeO° - Al₂O₃ diagram (after Greig, 1927)</td>
<td>264</td>
</tr>
<tr>
<td>7-1</td>
<td>Calc-alkaline environment diagram (after Dykes, 1979)</td>
<td>276</td>
</tr>
<tr>
<td>7-2</td>
<td>Tectonic Reconstruction</td>
<td>280</td>
</tr>
</tbody>
</table>
figure page
6-7 The effect of fractional crystallization upon Sr, Rb, and Ba (after McCarthy and Robb, 1977) 244
6-8 REE patterns for production of tholeiitic liquids by varying degrees of mantle melting (after Arth and Hanson, 1975) 247
6-9 SiO$_2$-CaO + MgO +FeO* - K$_2$O + Al$_2$O$_3$ diagram (after Greig, 1927) 263
7-1 Calc-alkaline environment diagram (after Dykes, 1979) 275
7-2 Tectonic Reconstruction 279
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-1</td>
<td>Analyses of HST Chert</td>
<td>353</td>
</tr>
<tr>
<td>E-1</td>
<td>Analyses of cycle I metavolcanic rocks</td>
<td>357</td>
</tr>
<tr>
<td>E-2</td>
<td>Analyses of cycle II metavolcanic rocks</td>
<td>362</td>
</tr>
<tr>
<td>E-3</td>
<td>Analyses of cycle III metavolcanic rocks</td>
<td>375</td>
</tr>
</tbody>
</table>
## LIST OF APPENDIX FIGURES

<table>
<thead>
<tr>
<th>Appendix Figures</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-1 Poles to bedding outside graben</td>
<td>400</td>
</tr>
<tr>
<td>G-2 Poles to bedding inside graben</td>
<td>401</td>
</tr>
<tr>
<td>G-3 Lineations and fold axes inside graben</td>
<td>402</td>
</tr>
<tr>
<td>G-4 Lineations outside graben</td>
<td>403</td>
</tr>
<tr>
<td>G-5 Poles to foliation inside graben</td>
<td>404</td>
</tr>
<tr>
<td>H-1 Rare earth element mobility</td>
<td>406</td>
</tr>
<tr>
<td>(after Hellman et al, 1979</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER I

INTRODUCTION

1.1 Purpose

This thesis examines volcanological, stratigraphic, chemical, and temporal aspects of cyclical volcanism, that is the repetition of volcanic processes and rock types, through the Archean in the Confederation Lakes area, Ontario (Fig. 1-1). In this area metavolcanic rocks and less voluminous metasedimentary rocks of regional greenschist rank are in 3 cycles each consisting of a mafic base grading to a felsic top. The cycles are not underlain by ultramafic volcanic rocks, appear to be in the "greenstone group" of Anhaeusser (1971, p.61) and may represent an island arc in a relatively evolved stage of Archean volcanism. There are several concentrations of massive base metal sulphide minerals and one producing mine within the uppermost cycle and, gold was produced from 1938 to 1942 from chert horizons and quartz veins systems in volcanic rocks of the Middle cycle.

The purpose of this thesis is to characterize the three volcanic cycles in terms of:

1) regional stratigraphy
2) style of volcanism
3) petrography and chemical composition of the metavolcanic rocks
4) petrogenesis of the metavolcanic rocks
5) temporal evolution of the volcanic sequence

1.2 Location, Access, and Physiography

The Confederation Lakes area is about 100 km east-northeast of the town of Red Lake, District of Kenora and Patricia, northwest Ontario. It is between latitudes 51°00' and 51°15'N and longitudes 92°30' and 93°00'W and within the Trout Lake (52N) topographic map sheet.

Access to Confederation Lake is by road to South Bay Mine of Selco Mining Corporation at the Narrows of Confederation Lake. This road branches off Highway 105 south of Red Lake (Fig. 17). Access to most other lakes in the area is by float-equipped aircraft chartered at Red Lake or Ear Falls. There are three tourist lodges in the area and a settlement of about 300 persons at South Bay Mine.

The area has a maximum relief of 90 m with a few prominent hills. However, in general the area has subdued topography typical of the Canadian Shield. The amount of exposure is variable, but in general is 30 to 40 percent of the area; most bedrock is beneath 10 to 15 cm of moss.

Lithology and structure effect lake distribution. Leg Lake, Uchi Lake, Woman Lake and Narrow Lake are elongate parallel to strike and Leg, Uchi and Fly Lakes are along major faults. Drainage is via the Uchi and Wenasaga Rivers to Lac Seul and Lake Winnipeg.

1.3 Previous Work

In 1893, D.B. Dowling (1894) did a geologic
reconnaissance for the Geological Survey of Canada which
took him through Confederation and Fly Lakes. E.M. Burwash
(1920) travelled the North Bay of Confederation Lake and the
Wenasaga River and J.W. Greig (1928) mapped in the vicinity
of Woman and Narrow Lakes. Additional work by the Ontario
Department of Mines includes that of Bruce (1928), Harding
(1936), Thomson (1939) and Furse (1934). In 1938, J.D.
Bateman (1939, 1939a, 1940) mapped in the east part of the
area at one inch equals one mile and studied the gold
deposits which he suggested were concentrated about
granites.

The map area for this thesis is part of a reconnaissance
survey carried out by the Geological Survey of Canada from
1959 to 1961 (Duffell et al. 1963, Prest, 1963; Donaldson,
1969). A variety of geochemical studies based on material
collected during the above survey are reported upon by
Holman, (1963), Moxham (1965), and Emslie and Holman
(1966). Goodwin (1967) did pioneering whole-rock chemical
analyses and stratigraphic studies in the area.

Upon discovery of the orebody at the South Bay Mine in
1968, the Ontario Department of Mines started detailed
mapping of the Birch-Uchi belt, first by A.P. Pryslak
(Pryslak, 1970, 1970a, 1971; 1971a, 1972, 1972a) and later
by the author (Thurston et al. 1974, 1975, 1975a, 1975b;
Thurston, 1978). Pollock et al. (1972), Auston (1969) and
Touborg (1973) described the geology of the South Bay Mine.
and a limited area around it.

In 1975, the author participated in detailed mapping of Honeywell and McNaughton Townships (Johns and Thurston, 1975) and began a systematic compilation and reinterpretation of the south part of the Birch-Uchi belt, called the Confederation Lakes area. This is the specific area of this thesis (Thurston, 1975c, 1976; Thurston and Jackson, 1978).

Previous whole-rock chemical analyses and their application in mineral exploration is the subject of Davenport's work (1972) and that of Sopuck (1977). Seccombe (1973) examined sulphur isotopes and trace elements in the South Bay mine area. Sopuck (1971), Asbury (1975), Lalor (1970), and Koschal (1975) studied various aspects of the area in Masters theses and Falls (1974), Birnie (1972), Barclay (1976), Baker (1975), McAuley (1973), Berezowsky (1972) and Savory (1976) conducted relatively detailed studies in B.Sc. theses.

Barlow et al. (1976) performed a gravity survey which includes the thesis area. The author, in conjunction with F.W. Breaks of the Ontario Division of Mines (Thurston and Breaks, 1978), has suggested large scale thrusting along the Uchi-English River sub-province boundary south of the thesis area using a combination of geology and geophysics.

1.4 Field and Laboratory Work

Detailed mapping of Earngey, Birkett, Agnew and Costello
Townships was done by the author and assistants in 1973 and 1974 (Thurston et al. 1974, 1975a,b). Detailed mapping of Honeywell and McNaughton Townships was carried out with the author's supervision and active participation in 1975 (Johns and Thurston, 1975) while the author began mapping and compiling in the remainder of the area at a regional scale.

Samples were collected during the summers of 1973, 1974, 1975, 1976 and 1977. Mineralogy and textures were examined in over 400 thin sections; X-ray diffraction was used in some instances for determining mineralogy. Samples were analyzed by the Mineral Research Branch, Ontario Division of Mines, and by the author at the University of Western Ontario. Details of analytical techniques are described in Appendix D.
CHAPTER 2
REGIONAL GEOLOGY

2.1 General Statement.

The Confederation Lake area is within the Uchi sub-province of the Superior Province of the Canadian Shield (Ayres et al. 1971) and includes the south part of the Birch-Uchi belt of north trending metavolcanic and metasedimentary rocks (Goodwin, 1967), 32 km wide by 84 km long (Fig. 2-1)\(^1\). The Swain Lake fault (Goodwin 1967) is the north border of the area across which the rocks change in strike, and have more complex structures (Thurston, 1977). The area is bounded to the south by the English River subprovince, which has a greater proportion of metasedimentary rock and anatectically derived granitic rocks (Breaks et al. 1974). The area is bounded to the east and west by granitic batholiths of regional dimension. As all rocks described here are metamorphosed to the greenschist facies of regional metamorphism, the prefix meta will henceforth be understood to apply to all rock types.

Goodwin recognized two cycles of mafic to felsic volcanism, here termed Cycles II and III, and Pryslak later (1971, 1971a) recognized Cycle I, the lowest cycle. Cycle I trends north and dips east with the basalts at its base extending northward from Bear Lake to the east of Corless.

\(^1\) (Fig. 2-1 is in back pocket)
Lake (Fig. 2-1). The upper part of the cycle terminates at the east end of Spot Lake. The east part of Cycle I is exposed on the axis of an anticline at Leg Lake. The basalts at the base of Cycle II trend north and dip east from the south end of Woman Lake through Quartz Lake where they have a more easterly strike persisting to the west end of Narrow Lake. East of the synclinorial axis, basalts of Cycle II extend from Agnew Lake to the Bear Lake fault in Neepawa Bay of Uchi Lake. Rocks of Cycle III underlie the area between Lost Bay of Confederation Lake and the main part of that lake.

The area has folds with nearly vertical limbs the trace of the axial plane of a regional synclinorium trends south through the geographic center of the area flanked 13 km to the east by a regional anticlinorium (Fig. 2-2). West of the synclinorial axis, the rocks are a homoclinal succession, facing east. East of the synclinorial axis, west facings persist only part way through the sequence, giving way to many local reversals of dip and succeeded, in the area of Leg Lake, by a regional anticlinorium.

Thickness of the volcanic-sedimentary rock sequence is difficult to determine because of structural complexities east of the synclinorial axis. Nevertheless there is an estimated total thickness of 8500 m (Thurston, 1977) (Fig. 2-3). West of the synclinorial axis Goodwin (1967, p.85) has estimated a thickness of 7400 m.
Structure of the east part of the Confederation Lake area. The central synclinorium is on the west edge of the diagram and the Leg Lake anticlinorium is on the east edge.
2-3 Stratigraphic section of the Confederation Lake area with representative thickness. U-Pb radiometric ages are of rhyolites.
For ease of description, formations have been given informal alphabet designations rather than formal names as 1) the stratigraphy is tentative in nature, 2) the extent of the formations is not well known outside this area and 3) alphabetical designation provides the reader with a means of location within the stratigraphic section (Table 2-1).

Cycle I (Fig. 2-3) has a maximum thickness of 4800 m west of the fold axis. It is made up of formation A (Fig. 2-1a), largely mafic flows, both pillowed and massive; overlain by formation B, a wedge of greywacke with minor felsic tuffs and fine to medium pyroclastic rocks of intermediate composition; capped by formation D, about 100 m of marble and scattered lenses of massive pyrite and pyrrhotite sixty to seventy metres thick. Formation C, largely felsic pyroclastic rocks, occurs as a small pod interfingered with formation A at the southwest end of Narrow Lake on the west limb of the regional synclinorium and above formation A on the east limb. Formation C grades vertically and laterally on the east limb into arkosic wacke and feldspathic lithwacke called the Slate Lake series by Bateman (1939a).

A rhyolite from the upper part of Cycle I is 2959 Ma old according to a U/Pb age determination on zircons (Nunes and Thurston, 1979).

Cycle II, exposed west of the synclinorial axis, is composed of formation E, pillowed and massive mafic flows and their coarse grained intrusive equivalents, with
<table>
<thead>
<tr>
<th>Formation</th>
<th>Cycle</th>
<th>Principal Rock Types</th>
<th>Minor Rock Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>III</td>
<td>felsic lapilli tuff</td>
<td>felsic flows, tuff, intermediate flows</td>
</tr>
<tr>
<td>L</td>
<td>III</td>
<td>intermediate tuff and lapilli tuff</td>
<td>intermediate flows, tuff breccia</td>
</tr>
<tr>
<td>K</td>
<td>III</td>
<td>mafic to intermediate pillowed flows</td>
<td>hyaloclastic debris, massive variolitic flows, interflow sediment</td>
</tr>
<tr>
<td>J</td>
<td>II</td>
<td>marble</td>
<td>chert, oxide facies iron formation</td>
</tr>
<tr>
<td>H</td>
<td>II</td>
<td>felsic lapilli tuff</td>
<td>tuff, tuff breccia, porphyritic flows</td>
</tr>
<tr>
<td>G</td>
<td>II</td>
<td>intermediate lapilli tuff, tuff</td>
<td>argillite, chert, wacke, tuff breccia, and tuff</td>
</tr>
<tr>
<td>F</td>
<td>II</td>
<td>mafic flows</td>
<td>felsic tuff, mafic hyaloclastite</td>
</tr>
<tr>
<td>E</td>
<td>II</td>
<td>mafic and intermediate flows</td>
<td>intermediate and felsic tuff, cherty interflow units, oxide facies iron formation</td>
</tr>
<tr>
<td>D</td>
<td>I</td>
<td>marble</td>
<td>chert and sulphide facies iron formation</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>felsic lapilli tuff</td>
<td>felsic tuff</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>greywacke, argillite, intermediate lapilli tuff</td>
<td>felsic tuff</td>
</tr>
<tr>
<td>A</td>
<td>I</td>
<td>mafic flows, massive and amphibole phyrin</td>
<td>intermediate tuff and lapilli tuff, feldspar phyrin mafic flows</td>
</tr>
</tbody>
</table>
interdigitations of pillowed flows of intermediate composition and chemical metasediments, formation G, pyroclastic rocks of intermediate composition both in place and their transported, reworked equivalents, capped by formation H, felsic pyroclastic rocks including 100-500 m of welded ash flow (Savory, 1976; Thurston, 1979).

Formation F is small scale cyclical alternation of mafic flows and felsic tuff forming four repetitions of this rock association on the east limb of the synclinorium. The unit is approximately correlated with the middle portion of formation E on the west limb.

The cycle is topped by formation J, a 100 m thickness of stromatolitic carbonate rock with minor cherty lenses. This cycle has a maximum thickness of 6500 m and has an average thickness of 3640 m. East of the synclinal axis, formations G and H are submarine pyroclastic flows and formation J is oxide facies iron formation.

Two rhyolites from Cycle II are 2787 Ma old by a U/Pb age determination on zircons (Nunes and Thurston, 1979).

Cycle III is composed of formation K, pillowed and massive and generally epidotized, mafic and intermediate flows with a prominent variolitic unit; succeeded upwards by formation L, submarine pyroclastic flows and tuffs of intermediate composition; and formation M which is pyroclastic rocks of felsic composition. Most of formation M is within a fault bounded block containing a sequence of
dominantly felsic pyroclastic rocks called the Mine Series by Sopuck (1977) and their coeval felsic intrusions including a quartz-feldspar porphyry stock likened to an endogenous dome by Pollock et al. (1972). Average thickness of Cycle III is 3950 m.

A rhyolite and the rhyolitic quartz-feldspar porphyry stock are 2738 Ma old according to a U/Pb age determination on zircons (Nunes and Thurston, 1979).

The rocks of Cycle III are cut by sills and plugs of intermediate composition including sericite granodiorite, biotite granodiorite, and chloritic granodiorite. These intrusions have a prominent metamorphic foliation which is cut by unfoliated granite batholiths. The Perrigo batholith, consisting of four phases ranging in composition from hornblende monzonite through hornblende-biotite granite, and the Allison Lake batholith, which is largely pegmatitic muscovite granite are representative of these late granitic rocks.

The rocks of the Birch-Uchi belt were involved in a complex series of deformational and metamorphic events which are summarized in Table 2-2 (from Thurston and Breaks, 1978). The important events are:

1) The first folding, D1, which predates development of cleavage, produced isoclinal folds and nappes.
2) The first metamorphism, M1, is marked by the formation of inclusion trains preserved in staurolite, biotite,
andalusite, and almandine-porphyroblasts.

3) The main regional metamorphic event, \( M_1 \)A, produced the major foliation with a preferred shape orientation of chlorite, biotite, hornblende, muscovite, cordierite, almandine and sillimanite.

4) \( D_2 \), is the main regional folding, with rotation of \( M_1 \) porphyroblasts and intrusion of the late granitic rocks (Fig. 2-1).

Several other relatively minor events listed in Table 2-2 culminate in the development of major strike-slip faulting including the Bear Lake fault extending from Uchi Lake through Fly Lake eastward to Bear Lake. This strike-slip structure displaces, in a left lateral sense, Cycle III mafic rocks a horizontal distance of 1.5 km (Fig. 2-1).

Within the Uchi sub-province the Confederation Lakes area is a relatively proximal facies of volcanic rocks as determined from the following observations:

1) the presence of siliceous domal intrusions emplaced to high levels in the crust;

2) the presence of abundant coarse siliceous pyroclastic rocks;

3) the thick mafic section in the map-area relative to areas further north and south (Breaks et al. 1975; Thurston, 1977);

4) the presence of numerous intermediate syn-volcanic dikes cutting the pyroclastic rocks of intermediate
TABLE 2-2

Metamorphic and deformation events in the Uchi and English River subprovinces (After McRitchie and Weber, 1971)

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$S_0$</td>
<td>Original sedimentary and volcanic fabric.</td>
</tr>
<tr>
<td>$D_1$</td>
<td>Isoclinal folds in volcanic sequences and nappes in the Red L.-Bee L. areas.</td>
</tr>
<tr>
<td>$M_1$</td>
<td>Development of planar fabric preserved as inclusion trains in staurolite, biotite, and almandine and andalusite.</td>
</tr>
<tr>
<td>$M_1A$</td>
<td>Main regional metamorphic event. Development chlorite, biotite, hornblende, muscovite, cordierite, almandine, sillimanite. Migmatization of metasediments in English River Subprovince probably commenced during this event.</td>
</tr>
<tr>
<td>$D_2$</td>
<td>Regional folding, rotation of $M_1$ porphyroblasts associated with emplacement of granitic intrusions in Uchi volcanic sequence.</td>
</tr>
<tr>
<td>$M_2$</td>
<td>Matrix coarsening and development of main axial plane schistosity of biotite and muscovite parallel to $D_2$ folds. Further migmatization of metasediments in English River Subprovince; minor volumes of mobilize controlled by axial surfaces of mesoscopic $D_2$ folds.</td>
</tr>
<tr>
<td>$D_3$</td>
<td>Large scale $S$ folds.</td>
</tr>
<tr>
<td>$M_3$</td>
<td>Muscovite parallel to $D_3$ axial planes, plinitization of cordierite and andalusite.</td>
</tr>
<tr>
<td>$D_4$</td>
<td>Late stage development of mylonite on strike slip faults.</td>
</tr>
</tbody>
</table>
Retrograde muscovite and chlorite in shear zones of D₄.

Late transcurrent faulting, Bear Lake Fault.

Minor recrystallization associated with D₅.
composition of Cycle II;
5) the scarcity of metasedimentary rocks.

South of Confederation Lakes toward the English River sub-province, as defined by Ayres et al. (1971), the proportion of metasedimentary rocks increases, the thickness of the volcanic rock accumulation decreases, (Breaks et al. 1974, 1975), mafic sections contain only pillow lava with little if any recognizable hyaloclastic sections; felsic and intermediate pyroclastic rocks are usually thin-bedded, fine-grained tuffs, and the thickness and abundance of chemical sedimentary rock such as oxide facies iron formation becomes greater.

Breaks et al. (1974, 1975, 1976) note that the English River sub-province has a northern metasedimentary domain (immediately south of the Confederation area) succeeded to the south by a southern plutonic domain containing scattered fragments of rocks in the granulite facies of regional metamorphism with a minimum age of 3.3 Ga (Hinton and Long, 1979). The boundary between the Uchi and English River sub-provinces was placed by Wilson (1971, p.44) and by Breaks et al. (1974) at the Sydney Lake Cataclastic Zone. Breaks et al. (1975) and Thurston (1977) note that the metasedimentary rocks of the English River sub-province are the stratigraphic equivalent to the upper part of the Cycle I metavolcanic rocks of the Uchi-Confederation area and are probably also correlative with Cycles II and III. Thurston
and Breaks (1978) state that there is an abrupt increase in metamorphic grade south of the Sydney Lake Cataclastic Zone with isograds paralleling the zone for some distance south. Thurston and Breaks (1978) discuss the probable movement on this fault (see also Appendix I).

Hence lithologies of the Uchi sub-province and the English River sub-province represent a continuum from respectively, proximal dominantly volcanic; to distal increasingly sedimentary, time-equivalent units 2.8 Ga old (Krogh and Davis, 1971) deposited upon an older 3.3 Ga (Hinton and Long, 1979) tonalitic basement of higher metamorphic rank. Although the Sydney Lake Cataclastic Zone may represent a very early structure the available evidence indicates that it was active only during the deformation history of the area. Although it marks an abrupt change in metamorphic rank, it is not an abrupt lithological boundary.

2.2 Structural Geology

Rocks in the area generally strike north to north northwest, with the exception of a complex zone south of the South Bay Mine where strike varies from northeast to east. The Confederation Lake area is folded about a regional synclorinorum, the trace of the axial plane of which trends north through the upper part of Cycle III near Lake X in Dent Township (Fig. 2-1). West of the axis, facing directions are uniformly east, whereas east of the axis, the rocks of Cycles II and III face west until east of Lost Bay
on Confederation Lake where many reversals in facing direction occur producing small scale folds (Thurston et al. 1974). East of the Uchi Lake fault, there are many local reversals in facing direction in rocks of Cycle I, however east and west of the mafic flows and mafic to ultramafic intrusions centered on Leg Lake, alternating top determinations in intermediate and felsic pyroclastic rocks mark the Leg Lake anticlinorium. South of the South Bay Mine a syncline and an anticline are defined by the persistent presence of thin mafic flows (Fig. 2-1, 2-2).

Faults are marked by offset stratigraphy, zones of shearing or schistose rocks, aeromagnetic lineaments or gravity contours, silicification, carbonatization or talc-carbonate alteration. The most important faults in the area, from the point of view of magnitude of movement, are north trending and strike-slip. Movement on these faults must be early because they are offset by east trending faults, and where one of the north trending faults cuts the Okanose Lake batholith there is no evidence of mylonitization. Evidence from the Sydney Lake area to the south and west (Breaks et al. 1974) suggests that the zone of schistose rocks found on Uchi Lake represents a splay of the Sydney Lake Cataclastic Zone. This has been called the Uchi Lake fault (Thurston, 1978).

The Sydney Lake Cataclastic Zone and the Uchi Lake Fault appear to be thrust faults. This hypothesis is more fully
developed in Thurston and Breaks (1978) (Appendix I).

Brecciation and carbonatization of felsic rocks in the
Fly Lake area defines two irregularly north trending
faults. These faults are also apparent by stratigraphic
offset and discontinuities. Rocks on either side of these
two faults strike north, whereas between the two faults,
felsic volcanic rocks of Cycle III strike east to
northeast. Stratigraphically these two faults cut formation
M and the area between the faults is occupied by formation M
and hypabyssal intrusions. This pair of faults is assumed
to be normal and to define a graben, based on evidence
presented in Appendix G.

A northwest to west trending fault extends from Neepawa
Bay to Uchi Lake northwestward to Bear Lake in Knott
Township (Pryslak, 1971a) offsetting rocks of all three
Cycles, and is hence the latest fault in the area.

Secondary lineations form two sets, one trending N70W
plunging at 75 degrees, within Cycle III outside the graben
and a second set within the graben with a maximum at N64E
and a plunge of 46 degrees (Figs. G-1 to G-4 in Appendix G).

On the basis of the different strike, pattern of folding
and lineations and, the different kinds of felsic volcanic
rocks found within the graben compared to the remainder of
Cycle III, the graben is assumed to have developed during
Cycle III volcanism and is termed a sector graben (Williams,
1941).
CHAPTER 3

Geology of the Confederation Lakes Area

3.1 Cycle I, Formation A

3.1.1 Field Occurrence and Petrography

Basalt of Formation A is grey to green on fresh surface and weathers in shades of brown and green. Flows are 15 to 60 m thick east of Leg Lake and have concordant contacts with interflow tuff of intermediate composition although locally there is brecciation and inclusion of blocks of tuff in the basalt. The basalt flows are massive, slightly pillowed, or well foliated. The massive flows have no apparent primary features over outcrops 35 by 30 m and only equivocal hyaloclastite and pyroclastic zones are observable in thin section at low magnification. Massive flows grade laterally and vertically into pillowed flows north of Leg Lake and on the west side of the regional synclinorium where the regional metamorphism is amphibolite facies and the massive flows appear gabbroic. Pillowed flows, for example south of Wagner Lake and at Philchub Lake in Costello Township (Thurston et al. 1975) have pillows 0.6 by 0.2 m with selvages 2 to 4 cm thick. Inter-pillow material is quartz and calcite.

The basalt is equigranular to porphyritic with rounded hornblende phenocrysts 3 to 6 mm in diameter pseudomorphous after pyroxene. Metamorphic assemblages are listed in Table 3-1. The groundmass is fine grained ophitic to isgranular
### TABLE 3-1  Metamorphic Mineral Assemblages in Mafic Metavolcanics Earngey-Costello Townships area

<table>
<thead>
<tr>
<th>Facies</th>
<th>Mineral Assemblage</th>
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<tbody>
<tr>
<td>Amphibolite Facies</td>
<td>Plagioclase An25-35, hornblende, chlorite, carbonate</td>
</tr>
<tr>
<td></td>
<td>Hornblende, quartz, epidote, garnet, carbonate</td>
</tr>
<tr>
<td></td>
<td>Hornblende, plagioclase, biotite, chlorite, epidote, quartz, carbonate</td>
</tr>
<tr>
<td></td>
<td>Plagioclase, An25-35 hornblende, tremolite, biotite</td>
</tr>
<tr>
<td>Greenschist Facies</td>
<td>Albite, tremolite, epidote, chlorite, biotite, carbonate</td>
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<tr>
<td></td>
<td>Albite, tremolite, quartz, epidote, biotite, chlorite, carbonate</td>
</tr>
<tr>
<td></td>
<td>Tremolite, albite, hornblende, epidote</td>
</tr>
<tr>
<td></td>
<td>Chlorite, albite, carbonate, epidote</td>
</tr>
<tr>
<td></td>
<td>Biotite, albite, quartz, carbonate, chlorite, epidote</td>
</tr>
<tr>
<td></td>
<td>Albite, chlorite, epidote, quartz, carbonate</td>
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</tbody>
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plagioclase and amphibole (Oppenheim, 1964) (Plate 1a).
There are amygdular flows south of Philchub Lake in which
amygdules are 1 to 2 mm in diameter, consist of quartz and
calcite, and account for 1 to 2 percent of the rock. Basalt
of formation A is distinguished from basalt of formations E,
F, and K by the greater abundance of porphyritic flows with
both feldspar and pyroxene phryic varieties represented.
Formation A is overlain by formations B and C.

3.1.2 Leg Lake Sills

Cycle I mafic volcanic rocks are cut by several sills
and minor dikes of mafic and ultramafic rocks called the Leg
Lake sills (Thurston, 1977). They are differentiated bodies
exposed over a strike length of 7.8 km from Drake Lake in
the northeast part of Earngey Township to beyond the south
end of Leg Lake (Thurston et al. 1974). The Leg Lake sills
are concordant, but have clearly defined intrusive contacts
with some marginal chilling and small xenoliths of country
rocks. In addition, there are tabular inclusions within the
sills of 3 to 4 m long laterally discontinuous pieces of
felsic and intermediate pyroclastic rocks occur east of Leg
Lake and Lake W. Features indicative of ultramafic flows
such as polysutured texture (Pyke, 1978) are not present.

The sills are commonly separated from one another
by thin septa of metavolcanic and metasedimentary rocks.
The base of one sill extends the length of the east
shore of Leg Lake and northeastward for 3 km beyond the
PLATE I

a) Mafic flow of Cycle I, with coarse secondary plates of chlorite in a groundmass of fine grained granular epidote and chlorite and laths of plagioclase. Specimen 73-12-2182, crossed polars.

b) Lapilli tuff of intermediate composition, Cycle I. Coarse plates of hornblende and fine grained albite, epidote and biotite. Very fine grained aggregates of albite, epidote, hornblende and biotite represent relict pumiceous clasts (arrow). Specimen 73-12-2256, crossed polars.

c) Peridotite from the Leg Lake sills. Subhedral rounded grains of relict olivine, outlined by grains of magnetite, are now talc, tremolite, and carbonate. Specimen 73-12-194, plane light.

d) Laths of plagioclase in a mafic flow, now fine grained albite, epidote, and hornblende. Specimen 73-12-723, crossed polars.

e) Pumiceous lapilli tuff from the felsic part of Cycle I on the southwest part of Narrow Lake. Dark streaks are sericite rich devitrified glass between pumiceous lapilli. This locality was sampled for U-Pb age determination.

f) Dunite from Leg Lake sills. Relict olivine grains are now rounded aggregates of tremolite. Olivine grains are outlined by aggregates of talc with minor magnetite. Specimen 73-12-310, cross polars.
north end of Leg Lake. The sill is about 300 m thick and consists of a dunite to peridotite base 240 to 120 m thick succeeded upward by a gabbroic middle part about 100 m thick, and a dioritic upper part about 100 m thick. This first sill is succeeded upward by a second sill which has a 30 m thick tabular dunite base. A third sill has a 30 m thick tabular dunite base overlain by about 200 m of gabbro and subsequently 120 m of mafic flow and intermediate fine bedded tuff. There is a fourth sill, 300 m thick, of similar nature. Contacts between the ultramafic base of the sills and the surrounding supracrustal rocks were not observed.

Diorite parts of the sills weather in various shades of green to dark grey and are black on the fresh surface. One variety, however, has a white weathered surface with up to 30 percent green amphibole as 1 to 2 mm randomly scattered subhedral grains in a matrix of saussuritized plagioclase. Primary subophitic to ophitic textures are present (Plate 1d) in areas of greenschist facies metamorphism but obliterated by recrystallization of tremolite-actinolite to hornblende near the Perrigo Pluton (Fig. 2-1). Gabbr parts of sills have similar textures, grain size, appearance and mineralogy save for the near absence of quartz and a slightly high colour index.

Dioritic and gabbroic parts of the sills have poorly preserved primary mineralogy. Sites of plagioclase laths,
about 1 by 5 mm and An$_0$ to An$_5$ are partly to completely occupied by tightly packed anhedral grains of epidote from 0.01 to 0.02 mm in diameter or plates of epidote from 0.2 to 0.5 mm long. Plagioclase sites in places are also occupied by felted masses of acicular actinolite. Mafic minerals are tremolite, which is colourless to light green pleochroic, occurs as 2 by 3 mm grains, with associated 0.02 by 0.1 mm needles of anthophyllite. A few small areas of primary clinopyroxene are present as in specimen 73-12-723. Accessory minerals include epidote in plates 0.8 mm long and as very fine grained materials after plagioclase, sphene, iron-titanium oxides, and minor Chlorite. The rocks have an uniformly relict ophitic texture.

The ultramafic base of the Leg Lake sills constitute 10 to 15 percent of the total thickness, and vary greatly in thickness. Weathered surfaces are black, through grey to white, depending on the abundance of talc and carbonate minerals. At the south end of Leg Lake, these ultramafic rocks are mottled with blebs of dark green or black in a grey matrix. At the north end, both weathered and fresh surfaces are white to greenish white and soft. These rocks are serpentinized dunite and peridotite with recognizable cumulate texture and up to 5 to 10 percent primary minerals (Table 3-2). Spots on the fresh surface of the dunite are relict cumulate olivine grains up to 2 by 1 mm now occupied by serpentine, tremolite and talc. The intercumulus space
<table>
<thead>
<tr>
<th>TABLE 3-2 Mineral Assemblages in Metamorphosed Mafic and Ultramafic Rocks of the Leg Lake Sills</th>
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</table>

**Metagabbro and Metadiorite**

- Plagioclase, epidote, chlorite, tremolite, actinolite, sphene, sericite, carbonate, quartz
- Plagioclase, epidote, hornblende, sphene, chlorite, biotite, iron oxides, quartz
- Plagioclase, epidote, tremolite, carbonate, talc
- Plagioclase, epidote, actinolite, quartz, sphene, talc anthophyllite

**Metaperidotite and Metadunite**

- Talc, carbonate, iron oxides, chlorite
- Talc, carbonate, iddingsite, iron oxides, chlorite
- Serpentine, chlorite, carbonate, tremolite
- Serpentine, talc, carbonate, chlorite
is filled with anthophyllite and iron-titanium oxides as in specimen 73-12-194, chlorite as in 73-12-196, or talc as in 73-12-310 (Plate 1f). The dunite is cut by 1 to 5 mm thick, by 2 to 5 cm long veinlets of asbestiform amphibole which is greasy green in colour. Anhedral grains of magnetite are scattered through the rock but do not exceed 5 percent. Serpentinization is general at the north end of Leg Lake and to the northeast. Primary textures and mineralogy are best preserved to the south.

Peridotite in some outcrops has ten to fifteen percent green pyroxene phenocrysts, 2 to 5 mm in diameter. In thin section most pyroxene and all olivine are pseudomorphed by serpentine, tremolite, talc, and carbonate with or without opaque iron-titanium oxides. These minerals cluster in round areas 0.8 to 0.6 mm in diameter and account for seventy-five percent of the rock (Plate 1g). Cumulate textures are present but indistinct. Relict pyroxene is generally less than five percent of the rock, has very fine grained magnetite along cleavages and is pseudomorphed by magnetite and carbonate. Chlorite fills the intercumulus spaces. In some rocks, rounded serpentinized pseudomorphs of olivine are replaced at the edges or throughout by talc. Intercumulus chlorite is replaced by magnetite plus talc with large, 2 by 4 mm grains of dolomite replacing talc after pyroxene.

Dioritic and gabbroic dikes cut the sills of the basalts.
between sills. Contacts of the dikes are sharp with the sills and basalts having a 1-4 cm thick chill zone adjacent to the country rocks along the east shore of Lake W and the east shore of Uchi Lake in the bay 1 km northeast of the Uchi Lake Lodge. Primary mineralogical layering defined by small variations in the amphibole and plagioclase content, is present only rarely in these dikes.

3.2 Cyle I Formation B

3.2.1 Field-Occurrence and Petrography

Formation B occurs on both limbs of the regional synclinorium (Fig. 2-1, 2-1a). The formation is subdivided into member B₁, dominantly metasedimentary rocks overlying formation A on the west limb and intermediate pyroclastic rocks and metasediments on the east limb and the overlying member B₂, intermediate pyroclastic rocks on the west limb and metasediments formerly the Slate Series (Bateman, 1939) on the east limb of the synclinorium.

Formation B contains coarser fragments to the northwest on the west limb of the synclinorium in the Narrow Lake area, becoming finer and having appreciable admixed metasedimentary material to the south. On the east limb of the synclinorium, formation B is generally thinner than on the limb, and the formation generally fines upward from lapilli tuff to tuff.

Member B₁ on the west limb is 0 to 1500 m of wacke-argillite with minor amounts of felsic tuffs. The unit is
underlain by formation A, overlain by member B₂, and extends 6.5 km north from Bear Lake. They have not been examined in detail but appear to be 10 to 15 cm thick beds of feldspathic lithwacke grading upward into siltstone with 2 cm thick argillite tops on many beds. Graded beds and flame structures are the only primary structures observed.

On the east limb of the regional synclinorium, member B₁ is exposed on either side of Leg Lake. It is on top of formation A and is overlain by member B. On the east side, the maximum thickness is 240 m; on the west side, a few scattered septa 30 by 150 m are caught up in the Leg Lake sills. The south limit of member B₁ on the east side of the synclinorium is beyond the thesis map-area and the north limit is the Swain Lake fault (Fig. 2-1). They strike northeast from the south end of Leg Lake for fourteen km to west of One Island Lake in Costello Township (Thurston et al. 1975b) where it is cut off by the Perrigo Pluton. It reappears on the north side of the Perrigo Pluton, striking north for at least thirteen km.

Rock types east of Leg Lake are fine to very fine grained tuffs and lapilli tuffs. These very fine grained rocks are delicately bedded with individual beds from 0.5 to 1 cm thick. Graded bedding is common and recognizable in thin section by formerly glass rich, now hornblende-rich,

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2 Sandstone classification in Appendix A
bottoms (Plate 1b). More commonly tuffs consist of 5 to 10 mm thick beds of fine grained aggregates of saussuritic plagioclase, quartz, and tremolite–actinolite with 1 mm acicular hornblende porphyroblasts making up twenty percent of the rock. Subhedral feldspar up to 1 mm in diameter occurs in an aphanitic melanocratic matrix.

Intermediate tuffs occur at the top of member B1 east of Leg Lake. The tuffs are bedded on a scale of 0.5 to 4 cm, with variation in the proportions of quartz and hornblende serving to define the bedding (Plate 2b, c). Ten percent of the rock is felsic lithic fragments consisting of 0.3 to 0.4 mm grains of quartz, feldspar and hornblende in beds 0.5 cm thick of quartz-biotite rich metasedimentary material containing twenty percent biotite (73-12-84). In the best preserved examples of similar lithologies relict clinopyroxene is observed, with biotitic rims.

Lapilli tuffs of intermediate composition occur on the northernmost peninsula on the east side of Uchi Lake. This rock contains 2 to 3 cm by 1 cm rhyolite clasts which make up 10 percent of the rock in a fine grained matrix of oligoclase, quartz, hornblende, minor biotite, iron-titanium oxides, and epidote. The hornblende is poikiloblastic, up to 1 mm long, and has inclusions of quartz and feldspar.

Member B2 on the west limb of the synclinorium, with a maximum thickness of 2700 m, is the top part of Cycle I. It is exposed 15.5 km along strike from Bear Lake fault on the
south, north for 9.7 km to Narrow Lake where the strike becomes more westerly and eventually terminating against an intrusive contact at the west end of Narrow Lake (Fig. 2-1). Member B₂ is underlain by Member B₁ and overlain by formation D which is 30 to 90 m of thin bedded siliceous marble at central Narrow Lake correlative with quartzite and graphitic argillite at the south end of the lake. Locally formation B is overlain by metamorphosed felsic tuffs of formation C at the west end of Narrow Lake.

Rocks north of the south bay on Narrow Lake are thin to medium bedded intermediate lithic and crystal tuff, lapilli tuff and tuff breccia with twenty percent subrounded fragments up to 0.3 m long, but averaging 0.1 m in the long dimension in a fine tuffaceous matrix. On the scale of an outcrop 3 by 6 m, no bedding is recognizable (Plate 11a). The fragments are mainly essential holocrystalline lithic fragments of intermediate to felsic composition with no recognizable accidental fragments. In thin section, matrix and fragments are fine grained aggregates of quartz and feldspar and rounded felsic to intermediate lithic fragments which together make up twenty percent of the rock. As the rock is not bedded, is comprised of essential lithic fragments, does not have size or density grading and contains abundant matrix material it is considered to be a debris flow (cf Parsons, 1969).

A large area east and south of the Cycle I volcanic
PLATE 2

a) Intermediate-lapilli tuff with rhyolitic pumice fragments in a matrix of intermediae tuff and fine grained lapilli tuff. The rounded nature of the fragments, heterogeneity of fragment types and lack of primary structures such as bedding suggest the rock may be a debris flow. Location: shore of Spot Lake. Cycle I.

b) Rhyolite fine grained tuff of Cycle I at Leg Lake with graded bedding above slightly coarser dacitic tuff. Note also, flame structures above the coin.

c) Photomicrograph of Cycle I rhyolitic tuff fragments in epiclastic rocks immediately above the intermediate pyroclastic rocks on the east limb of the Leg Lake anticlinorium. Relict pumice (arrow) consists of a fine grained aggregate of albite, quartz, epidote, biotite and tremolite-actinolite. The framework of the rock is secondary plates of tremolite-actinolite, relict twinned volcanic plagioclase grains, now fine grained aggregates of albite and epidote. The matrix is acicular biotite and tremolite-actinolite. Specimen 73-12-84, crossed polars.

d) Cycle I felsic crystal tuff. Plagioclase phenocrysts (arrow) occur in a bedded fine grained aggregate of sericite, albite, epidote and quartz. Specimen 73-12-259, crossed polars.

e) Felsic crystal tuff from Cycle I on Narrow Lake. The matrix consists of a very fine grained aggregate of albite and quartz with interstitial biotite and sericite - large phenocryst is quartz. Specimen 77-401, crossed polars.

f) Limestone above Cycle I on central Narrow Lake. Photomicrograph of carbonate and quartz-rich interbeds. Quartz is fine grained aggregates. The carbonate is in large plates. Specimen 77-402, crossed polars.
rocks and on the east limb of the regional synclínorium is underlain by arenites, wackes, mudstones and clast supported conglomerate of the member B2. These sedimentary rocks underlie substantial parts of the map-area (Thurston et al. 1975b, 1975a; Johns, 1975). Weathered surfaces are brown and crumbly, therefore, primary structures are rarely observed. Beds of arkosic wacke and arkose 15 to 45 cm thick, grade upward into feldspathic lithwacke beds of equal thickness capped by 1 to 15 cm thick beds of argillite. Graded bedding is obvious in thin section but not in outcrop. Coarse grained wackes have grains in the 0.5 to 2 mm size range constituting ten to 30 percent of the rock set in a fine grained matrix. This rock has a disrupted framework of 10 percent clastic single quartz grains with undulose extinction averaging 0.5 to 1 mm in diameter and felsic metavolcanic fragments up to 2 by 3 mm in long dimension. Feldspar or lithic fragments can dominate and hence the rock becomes a feldspathic lithwacke, lithic arkosic wackes or arkosic wackes. The matrix is fine grained quartz and feldspar grains overgrown by biotite, muscovite, and chlorite nearly the same size as framework clasts. Occasionally the proportion of fine matrix decreases below 15 percent and the rock is properly termed an arenite.

Fine grained wackes have a disrupted framework dominated by felsic metavolcanic lithic fragments which are angular to
subangular 1.8-2 mm in the long dimension and consist of fine grained aggregates of quartz, albite, biotite, chlorites, and iron-titanium oxides. Lithic fragments make up at most 20 percent of the rock. Fifteen percent of the rock is detrital quartz grains possibly derived from a volcanic source as they are single unstrained grains, without subgrains, 1.8 to 2.0 mm in diameter and subangular to slightly rounded. The matrix is completely recrystallized fine grained, well rounded quartz and feldspar grains with slightly larger biotite, muscovite, and chlorite forming up to 30 percent of the rock. Andalusite is present in accessory amounts. Poikiloblastic cordierite, 1.8 to 2.5 mm forms up to 5 percent of the rocks (Table 3-3).

The arenites are the basal one third to one half of graded fining upward beds which range from arenite to wacke to mudstone. They weather to a crumbly brown surface and consist in thin section of a framework of sericitized albite plagioclase and quartz with minor K-feldspar and lithic fragments of felsic composition forming rounded clastic grains averaging 2 to 3 mm in size with accessory iron-titanium oxides, zircon and apatite with relatively little sericite, epidote and biotite forming a fine grained matrix.

Mudstone weathers brown to black and is in beds from 0.1 to 1 mm thick capping arenite-wacke sequences. The darker
TABLE 3-3  Metamorphic Mineral Assemblages in Metasedimentary rocks of Cycle I in Earngey-Costello Townships area

Greenschist Facies

a) Quartz, albite, biotite, with muscovite, andalusite, epidote
b) Quartz, albite, biotite with epidote, muscovite, chlorite
c) Quartz, albite, biotite with epidote
d) Quartz, albite, biotite, with muscovite, chlorite, stilpnomelane, epidote
e) Quartz, albite, biotite with muscovite, staurolite (relict)

Amphibolite Facies

a) Oligoclase-andesine, quartz, biotite with chlorite, cordierite
b) Oligoclase-andesine, quartz, biotite with muscovite, chlorite, garnet, cordierite, epidote
c) Oligoclase-andesine, quartz, biotite with cordierite, muscovite
d) Oligoclase-andesine, quartz, biotite with muscovite, cordierite
e) Oligoclase-andesine, quartz, biotite with muscovite, cordierite, garnet, sillimanite
f) Oligoclase-andesine, quartz, biotite, cordierite, muscovite, microcline
g) Oligoclase-andesine, quartz, biotite with muscovite, cordierite, andalusite, garnet
weathered surface relative to the other metasedimentary lithologies is a function of both fine grain size and an appreciable iron-titanium oxide content. Thin beds are simple argillaceous partings at the top of fining upward arenite sequences. Thicker beds have a blocky fracture and black to dark brown fresh surface. The rock is of variable proportions of 0.02 to 0.08 mm grains of quartz, albite, biotite, muscovite, epidote, and iron-titanium oxides with less than 20 percent rounded grains of quartz or lithic fragments.

The sequence corresponds to an A to E turbidite (Walker 1976, p.26) which implies a relatively proximal facies with graded wacke and arenite parts of the sequence representing rapid settling of grains from suspension, and argillites representing fine material gradually settling out after passage of the turbidity current.

3.3 Cycle I Formation C
3.3.1 Field Occurrence and Petrography

Formation C is a mappable unit only on the west limb of the regional synclinorium (Fig. 2-1a) where it is an isolated pod of tuffs 2400 m long by 300 m thick at the south end of Narrow Lake. It is is overlain by and interfingers with member B₂ on the west limb of the synclinorium and is overlain by member B₂ on the east limb. The Formation is underlain on the west limb by formation A, and on the east limb, where present, by member B₂. On the
east side of the regional synclinorium, formation C is a
less than 30 m thick felsic tuff on the shore of Lake Y.
East of Leg Lake a small area 30 by 90 m of finely bedded
felsic tuff occurs as a xenolith in mafic intrusive rocks.
The major rock types are felsic lithic and crystal lapilli
tuffs with bedding 2.5 to 3.5 cm thick consisting of
alternating pumiceous lapilli-rich and devitrified
glass-rich beds, lapilli tuff and tuff breccia (Plate Le).
The weathered surface is generally white to yellowish brown
and the fresh surface is white. Sample 75-1-259 is typical
and consists of thin (0.5 cm) bedded felsic lithic and
crystal tuff with 10 percent elliptical polycrystalline
aggregates of quartz 1 by 0.5 mm and ten percent rounded
felsic lithic fragments in a matrix of quartz, feldspar and
sericite 0.03 mm in diameter (Plate 2d). As the rock is
pumice rich with a tuffaceous matrix and does not have well
developed bedding or grading, and has some evidence of
development of a eutaxitic foliation (Plate IID), it is an
3.4 Cycle I Formation D
3.4.1 Field Occurrence and Petrography

A 90 m thick siliceous marble on the north shore of the
south part of Narrow Lake is uppermost Cycle I and
represents an hiatus in volcanism. The formation D marble D
is thin bedded with 5 to 10 mm thick quartz-rich beds
separated by marble beds of similar thickness.
Stratigraphically beneath and 90 m to the south across the lake, felsic and intermediate volcanic rocks are carbonate rich suggesting that the entire 90 m width of the lake is underlain by the limestone.

The marble weathers to a light tan colour and the quartz-rich beds weather white and have a greater relief than the marble. The marble is 0.5 mm thick bands of fine, 0.03 to 0.06 mm rounded clastic quartz grains with minor carbonate in a matrix of 90 percent coarse 0.2 mm, anhedral carbonate grains and 10 percent zoisite (Plate 2f).

Along strike, about 1.6 km to the southeast, a 69 m thickness of chert and graphitic metasedimentary rock described by Pryslak (1971) can be correlated with the marble.

The chert consists of fine grained recrystallized chert with beds a few metres thick of massive pyrrhotite, observed in poorly exposed pits on the north shore of Narrow Lake.

3.5 Geochronology

Twenty kilograms of thin bedded feldspar and quartzphyric felsic lapilli crystal tuff from Formation C was collected by P. Nunes of the Jack Satterly Geochronology Laboratory of the Royal Ontario Museum and the author for a U/Pb age determination on zircons. A slightly discordant minimum age of 2959 Ma using $\lambda_{235}=0.98485 \times 10^{-9}$ yr.$^{-1}$, $\lambda_{238}=0.15513 \times 10^{-9}$ yr.$^{-1}$ was obtained (Nunes and Thurston, 1978). Detailed analytical results and a concordia diagram
are in Appendix B.

3.6 Formation E

3.6.1 Field Occurrence and Petrography

Formation E is on both limbs of the regional synclini orium (Fig. 2-1a). On the west limb, these rocks have a maximum thickness of 2700 m, extending over a distance of 22.1 km from the Bear Lake fault in the south to the east end of Narrow Lake in the north; here the strike changes to an easterly direction. Formation E is underlain by the marble of formation D. It is overlain by mainly intermediate pyroclastic rocks of formation G.

Formation E is massive and pillowled coarse grained mafic flows, coarse grained sills, hyaloclastite, and minor pillowled flows of intermediate composition. There are also intercalations of oxide and sulphide facies iron formation, wackes and mudstone, chert, and fine grained, finely banded felsic tuff.

On weathered surface, mafic volcanic rocks of formation E vary from dark to light green in colour, with black and darker shades of green predominating in areas of amphibolite metamorphic facies or hornblende hornfels. Fresh surfaces are grey to green to black in colour in areas of greenschist grade.

Flows vary in thickness from 1 to 10 m, or in some instances, are monotonous pillowled sequences with no apparent base or top and a stratigraphic thickness of 150 m, bounded
by coarse-grained sills. Long 2-3 m thin, 0.3 m tube-like masses with quench textured edges are considered to be lava tubes. More conventional bun and balloon-shaped pillows with pillows averaging 30 to 40 cm by 20 cm are the most abundant pillow type. Pillow selvages are up to 2 cm thick and inter-pillow space is filled with spalled devitrified relict glass or crystallized chert with or without pyrrhotite and pyrite. Pillowed flows generally contain 25 to 30 percent carbonate filled amygdules. Varioles of the liquid immiscibility type (Gélinas et al. 1976) are found concentrated in the center of lava tubes in a few localities. Chlorite-rich devitrified glass pillow margins are succeeded inward by a spherulite-rich border zone and a microlite-rich inner zone (Dimroth et al. 1978).

Formation E on the east limb occurs as hyaloclastite plus flows of three types: a) porphyritic flows with relatively fine-grained felted groundmass containing 1-5 mm amphibole pseudomorphs (Plate 3b), b) flows, 30-60 m thick with a massive center and a pillowed top with a grain size in the massive part varying from 1-2 mm (east of Lost Bay appearing in part as unit 6a on Thurston et al. (1974) and c) thin, fine-grained usually pillowed flows with grain size up to 1 mm.

Massive flows and coarse-grained flows and sills are particularly abundant east of Lost Bay of Confederation Lake and in the Narrow Lake area (Fig. 2-1). They form ophitic
PLATE III

a) Cycle II variolitic pillowed mafic flow with Blake River type, liquid immiscibility varioles concentrated toward pillow center at the sharp end of the pencil. The pillow rim is at the lower right. Location: central part of Narrow Lake.

b) Amphibole phric mafic flows of Cycle II. Light areas of photomicrograph are aggregates of tremolite-actinolite with relict patches of clinopyroxene in light grey areas. Dark grey areas are aggregates of very fine grained epidote pseudomorphing plagioclase. Specimen 73-12-471, crossed polars.

c) Cycle III mafic flows on the road between Lost Bay of Confederation Lake and Uchi Lake. Isolated pillow breccia in a matrix of mafic hyaloclastite. Note chilled rim on the pillow below and to the left of the scale card. Short bars on scale card are equal to one cm.

d) Photomicrograph of mafic hyaloclastite. Dark areas are large relict glass fragments. Arrow variation in darkness of these fragments represent alteration fronts within the fragments. Mineralogy is fine grained sphene, chlorite, epidote, albite and iron-titanium oxides. Specimen 73-12-2822, plane light.

e) Subaqueous ignimbrites of Cycle II, Lost Bay of Confederation Lake. Pebby intermediate tuff to lapilli tuff forms the base of ignimbrite flow unit number II. Poorly developed crossbedding is parallel to the pencil.

f) Subaqueous ignimbrites of Cycle II, Lost Bay of Confederation Lake. Intermediate lapilli tuff with angular to subangular fragments of rhyolitic pumice in an ash matrix. Such bedding is sparse.
textured bodies 30 to 100 m thick with occasional xenoliths of the surrounding rock types forming thin septa within. Exceptionally, intrusive contacts are found, suggesting these coarse bodies are mostly sills.

The overall dimensions of individual flows and hyaloclastite units is difficult to establish because of extensive lateral variations. However, it appears that individual mafic hyaloclastites can be followed along strike for at least 300 m as fragments of mafic pillows in a matrix of fine mafic pillow debris and once glassy fragments (Plate 3c). Larger fragments have a prominent selvage covering at least part of their exterior. In many fragments, both with and without selvages, quartz or carbonate filled amygdules 5-10 mm in long dimension make up 5 percent of the rock.

The fragments of pillows average 0.3 mm in long dimension by 0.2 m and make up about two-thirds of the rock. The matrix is mafic hyaloclastite fragments with occasional accidental fragments such as 6 to 8 cm long clasts of jaspilitic iron formation or felsic pyroclastic rock. Some of the fragments are rimmed with an indistinct mass of very fine grained (0.002 mm) almost isotropic banded leucoxene, possibly derived by alteration of palagonite (Furnes, 1972, p.392), (Plate 3d). Matrix to the fragments is oval to rounded globules 0.25 to 2 cm in long dimension with zoning from a very fine grained exterior to a slightly coarser interior. The fine grained material of the globules is 0.6 to 0.2 mm
tremolite grains, in a matrix of epidote granules 0.02 by 0.02 mm which outline individual albite grains 0.12 by 0.02 mm. The tremolite accounts for 20 percent of the rock, the albite 60 percent of rock. Areas of chlorite after hyaloclastic fragments as large as 0.2 mm square make up the other 20 percent of the rock. The matrix to the globules is chlorite, epidote, albite and up to 10 percent calcite.

Chert and minor pyritic chert occupy the inter-pillow space. The zoned nature of the globules, the presence of a selvage on some of the pillow fragments, marking them as parts of pillows, and the squared-off, rectangular or plate-like (cf. Macdonald, 1972, p.104) fragments in the matrix, and the delicately zoned nature of some matrix fragments all point to a hyaloclastic origin for these rocks rather than, for example, a flow breccia (cf. Parsons, 1969).

Primary mineralogy is rarely preserved and there are only occasional examples of primary feldspars, heavily saussuritized, and rare armoured clinopyroxene grains in mafic hyaloclastites and coarse grained gabbros. Relict quench plagioclases with swallow-tail morphology and acicular grains of tremolite-actinolite pseudomorph quench crystals of olivine and pyroxene (Geliñas and Brooks, 1974; Bryan, 1972). In mafic volcanic rocks of the greenschist facies there are relict ophitic, subophitic, and intergranular textured flows with pseudomorphs of the
tremolite-actinolite series, saussuritized and sericitized plagioclase, sphene, opaque iron-titanium oxide, apatite, pyrite, leucoxene and rare quartz and biotite. Chlorite occurs after mafic minerals and after plagioclase.

Magnetite octahedra from 0.5 to 1.5 mm in diameter are common as an accessory mineral generally concentrated at pillow margins in isogranular to ophtic textured matrix. The flows grade laterally and vertically into broken pillow breccia (Carlisle, 1963).

Pillowed flows of intermediate composition occur sporadically through formation E, but are usually distinguishable only on the basis of chemical analysis from their neighbouring mafic flows. The greatest thickness and abundance of intermediate flows and attendant sills within formation E occur on the east limb of the regional synclinorium and, in the Narrow Lake area on the west limb of the regional synclinorium. Here the formation thins to the southeast. Coarse grained sills tend to occur toward the base of formation E, and hyaloclastite toward the top. Intercalations of iron formation occur one third of the way above the base on the west limb.

Flows of intermediate composition are abundant through the whole of Cycle II with pillowed flows intercalated with mafic massive flows along the south shore of Narrow Lake (75-1-282). Intermediate flows occur along the east shore of Narrow Lake (75-1-408a), in the lower part of the Lost
Bay section below the HST (Baker, 1975) and, massive
amygdular and feldspar phryic variants are also found in the
Lost Bay section. In outcrop, intermediate flows are
difficult to distinguish from mafic flows. Observed
differences are thinner selvages on pillows, up to 1 cm
rather than 2 to 3 cm, and lighter green fresh surface for
the former plus a spatial association with felsic
metavolcanic rocks and a tendency toward lighter grey
weathered surfaces than mafic flows. The abundance of
intermediate flows is understated on the map and sections,
but may be more correctly estimated from random geochemical
sampling such as that done by Goodwin (1967). He estimated
the proportion of andesite, which would almost entirely
consist of flows, to be 8.3 percent of the "Lower Acid"
section (Goodwin, 1967), i.e. the upper part of Cycle II.
Higher proportions of dacites and rhyodacites were tabulated
by Goodwin for this section but an unknown amount of this
would be pyroclastic in character rather than intermediate
flow.

3.7 Formation F

3.7.1 Field Occurrence and Petrography

Formation F occurs only on the east limb of the
synclinorium where it is 11 km long and about 975 m thick in
the area east of Lost Bay of Confederation Lake (Fig. 2-1).
It is underlain by formation E and overlain by formation G.
It is correlative with oxide facies iron formation occurring
part way through formation E on the west limb, and is the four-fold cyclical repetition of mafic flows and hyaloclastite overlain by felsic tuff. Each of these cycles is from 60 to 120 m thick.

Individual flows are rarely more than 6 m thick and more commonly 3 m thick or less in the HST area (Baker, 1975). In the HST area broken and isolated pillow breccia (Carlisle, 1963) and hyaloclastic debris (Rittman, 1962, p. 82) are 3 to 10 m thick. In thinner flows, small pillows on the order of 10 cm by 6 to 8 cm are common, perhaps a reflection of minor FeO and TiO₂ content (J.B. Fridleifson, 1977, pers. comm.). The mineralogy and textures in thin section of the mafic flows are similar to those observed in formation E.

The felsic tuffs consist of fine grained fining upwards tuff beds 15 to 30 cm thick, with the tuffs consisting mainly of relict glass shards consisting of albite plagioclase, epidote and quartz and occasional small lithic fragments, grading from 1 to 2 mm shards at the base of beds to 0.1 mm shards at the top of beds. One of these small scale cycles is capped by the Hill-Sloan-Tivey quartz "vein" (Thompson, 1938) a 1 m thick unit.

The Hill-Sloan-Tivey "vein" (HST), is a generally conformable band of quartz rich material. This extends for 2950 m and is conformable with the
volcanic rocks and has an average width of 57 cm ranging from 40 cm to 1 m. Baker (1975) notes it is underlain by felsic air fall tuffs 15 to 25 cm thick fining upward beds in layers about 3 m thick. It is everywhere overlain by mafic pillow lava or massive to bedded hyaloclastite. The HST quartz horizon is laminated parallel to strike.

Quartz-rich laminae varying from 2 mm to 2 cm thick are separated by more mafic, thinner 0.1 to 1.5 m laminae. Quartz-rich laminae are 75 to 90 percent sutured irregular crystallized quartz grains averaging 0.5 mm in diameter. The remaining 10 to 25 percent of the rock is carbonate and untwinned albite. Muscovite occurs as small grains in more mafic laminae along with carbonates and iron oxides. Both calcite and ankerite occur. The calcite appears to be replacing quartz as irregularly shaped grains associated with fractures in quartz grains. Ankerite is replacing quartz in selected areas. Tourmaline occurs as 0.1 mm isolated and clustered acicular grains associated with sericite, but occasionally single needles crosscut the laminae. Pyrite is small subhedral to euhedral grains preferentially distributed in the quartz adjacent to the wall rock. Numerous quartz veins cut underlying felsic tuffs but not the HST quartz horizon. On the basis of sedimentary structures, and chert texture, this horizon is more correctly termed the Hill-SloaneTivey chert (Appendix C).
3.8 Formation G

3.8.1 Field Occurrence and Petrography

Formation G is on both sides of the regional synclinal axis. West of the axis it has a maximum thickness of 5400 m between Narrow Lake and Woman Lake in Goodall and Skinner Townships (Pryslak, 1972, and pers. comm. 1976). It is underlain by formation E on both sides of the synclinorium and on the west side of the synclinorium it is overlain by formation H, a minor accumulation of felsic metavolcanic rocks toward the top of Cycle II. On the east side of the synclinorium it is overlain by formation H or J. The Bear Lake fault is the south limit of formation G from which it trends north for a distance of 9.8 km where the strike deviates slightly west to continue for a further 6.5 to 8 km to the Swain Lake fault.

East of the synclinal axis, formation G extends from Neepawa Bay of Uchi Lake, through Lost Bay of Confederation Lake, to the north part of the Uchi Lake fault. It is also centered upon Honeywell Lake. The south limit is in the English River terrain (Breaks et al. 1975) and to the north it is terminated by the Swain lake fault.

Formation G weathers to various shades of medium and light green to grey and white. There is little correspondence between colour of the weathered surface and metamorphic rank with white surfaces predominating in areas of greenschist facies, and various shades of green common in
higher grade areas. The abundant rock types in formation G are intermediate lapilli tuff and lapillistone. This rock is angular to slightly rounded lapilli, over 50 percent of which are pumiceous fragments, 20 to 30 percent lithic fragments and 10 percent accidental fragments, that is, mafic volcanic rocks, iron formation, and less commonly, well bedded felsic to intermediate tuff fragments and clasts of vein quartz. On the basis of chemical analysis of 2-3 kg bulk samples of medium to fine grained lapilli tuff with similar petrography (Table E-2), and comparison of colour index, the essential fragments are rhyodacite through to andesite, with a predominance of the more siliceous types. The rocks have 10 to 20 percent fine tuffaceous matrix with some relict glassy shards but mostly consist of fine lithic grains.

On the shore of Lost Bay of Confederation Lake Formation G has several sequences which grade upward from coarse unbedded intermediate lapilli tuff and pyroclastic breccia to fine grained parallel bedded pumiceous lapilli tuff and tuff. Beds are 2 to 4 cm thick. The fragments consist of subangular to rounded felsic pumice fragments with subordinate felsic lithic fragments in a sparse ash matrix (Table 3-4). The ash matrix contains abundant poorly rounded, fractured quartz and feldspar phenocrysts. Occasional 0.1 to 0.3 m thick interbeds of ash occur in the coarse grained rocks (Plate IV-a) but in general coarse grained rocks
PLATE IV

a) Subaqueous ignimbrites of Cycle III, Lost Bay of Confederation Lake. Intermediate lapilli tuff with inter-bed of tuff. This photo is of rock a few metres up section from that of Plate III f.

b) Subaqueous ignimbrite of Cycle II on the west limb of the fold on northern Narrow Lake. Sandy pumice tuff of Yamada (1973) is near the coin. Slightly coarser material is below the coin with subangular pumice fragments of low relief. This material is equivalent to that on the east limb lying above the material in photo III a.

c) Subaqueous ignimbrite of Cycle II on Lost Bay of Confederation Lake. The uppermost part is massive to finely laminated tuff is to the right of the knife. Underlying material to the left of the knife is slightly coarser.

d) Subaqueous ignimbrite of Cycle II on Lost Bay of Confederation Lake - sawn slab of pumiceous clast toward the base of unit I. Note vesiculated nature of clasts. Largest clast is 2 cm from left to right. Matrix includes many broken plagioclase crystals.

e) Subaqueous ignimbrite in Cycle II on Lost Bay of Confederation Lake. Pumice rich upper part of unit IV, consisting almost entirely of pumiceous clasts in an ash matrix. Note the fingerprint like, devitrification texture of the pumice clast to the right of the label and in the upper right. Specimen 73-12-1010, plane light.
are chaotic, not bedded but which grade upward, into the fine grained layers. The coarse to fine sequences are 30 to 300 m thick (cf. Fig. 3-1).

Alternations between pumiceous lapilli tuff and pumice-free tuffs are conspicuous (Plate IV-b). Pumice clasts decrease in abundance upward and bedding is defined by subtle variations in the relative abundance of subhedral 2 to 5 mm feldspar crystals and slightly rounded quartz crystals. Above this, tuff containing mostly pumiceous clasts, grades upward, becoming finer grained and more regularly bedded. Pumiceous clasts are smaller and less abundant; crystalline debris, shards and clastic nonvesicular lithic fragments are more frequent; laminations are thinner (Plate IV-c), on the order of 0.5 cm. Parallel laminations over a lateral extent of 5 to 10 m can be observed. Convolute bedding caused by soft-sediment deformation is present in one 0.3 m thick layer. Parallel laminated fine to ultrafine grained tuff caps the Lost Bay succession (Plate IV-c). Five to 10 m thick sections with bedding on the order of 0.5 to 1 cm thick are common. No pumice is present among the relict shards and crystalline debris.

The fining upward sequences are occasionally disturbed by the occurrence of 1 to 6 m thick beds of 1-10 cm rounded clasts of pumice occurring just below the fine grained, finely laminated tuff of the top.
3-1 Facies model (Yamada, 1973) for subaqueous ash flows. Close to the eruptive site (right) chaotic pumiceous conglomerate occur, outward from this bedding is better developed, and a sequence of massive graded tuff with abundant blocks of pumice to very fine grained thinly laminated tuff occurs.
Exposure in the Lost Bay section is erratic, but there are at least seven of the sequences which fine-upwards in various stages of completeness (Figure 3-2). The lateral exposure is limited to the north, and to the south these rocks wedge out (Thurston et al. 1974).

In the Narrow Lake section tuffs 3 to 6 m thick are unbedded, ungraded felsic lapilli tuff to pyroclastic breccia with eighty percent angular pumiceous clasts in a matrix of felsic ash and broken feldspar crystals. At 2 to 6 m intervals these coarse grained rocks are capped by 2 to 15 cm thick finely laminated of felsic tuff beds 1 to 2 cm thick. There is chaotic, unbedded, felsic pyroclastic breccia with subangular to rounded felsic pumice fragments with rare felsic lithic fragments and occasional accidental fragments in 10 to 20 percent matrix. This becomes less chaotic with distinct tuffaceous upper parts developed toward Narrow Lake.

Primary mineralogy is generally not preserved. Primary zoned clinopyroxene phenocrysts occur in the lithic fragments of a lapilli tuff (73-12-14 and 73-12-487). Unaltered plagioclase crystals occur in occasional samples of intermediate crystal and lithic lapilli tuff (73-12-489 and 73-12-2141). Mineral assemblages consist of plagioclase, mainly albitic, with epidote, quartz, biotite, sericite, chlorite, tremolite actinolite with accessory magnetite, sphene, zircon, carbonate, and hornblende.
3-2 Detailed geology of the Lost Bay area. To the west of the minor cycles of major cycle II there are seven (roman numerals) subaqueous ignimbrites, with minor airfall material above ash flow IV. The arabic numerals and letters refer to photographic plates. As no good exposures of one complete ignimbrite are available, composite documentation of textures is presented by using exposures from several of the essentially similar rocks.
Figure 3-2: Subaqueous Ignimbrites, Cycle II, Lost Bay.
Relict pumice has uncollapsed slightly elliptical vesicles forming 40 percent of the fragment. Vesicles are generally filled with quartz, and carbonate with or without chlorite. The rock is a fine grained felted mass of chlorite, tremolite-actinolite, epidote, albite, quartz and white mica with relict quartz and plagioclase, phenocrysts.

Pumiceous fragments are usually subangular, irregular in shape, and composed of a fine grained aggregate of albite with epidote inclusions, quartz, sericite, tremolite-actinolite, sphene, opaque iron-titanium oxides, porphyroblasts of epidote. The pumiceous nature of the clasts is recognizable in elongate areas of quartz or quartz and feldspar surrounded by chlorite or epidote (Plate IV-d,e). These define relict long-tube pumice along with ragged wispy terminations on fragments, very irregular outlines and even rounded bubble type pumice (Plate IVe) samples 73-12-773, 1010) (cf. Fiske, 1969).

Relict angular glassy fragments (73-12-1010) are typified by extremely fine grained, less than 0.02 mm, closely packed aggregates of epidote with albite forming the whole of 1 to 2 cm angular fragments. Lithic fragments (Table 3-4) consist of secondary minerals similar to those in the pumice fragments. The tuff fraction consists of less than 2 mm relict glassy rock fragments, now fine grained recrystallized quartz and feldspar, relict glass shards, now fine grained aggregates of biotite, epidote and carbonate.
<table>
<thead>
<tr>
<th>ROCK TYPES</th>
<th>TYPE AND ABUNDANCE</th>
<th>FRAGMENTS</th>
<th>ORIGIN</th>
<th>SIZE</th>
<th>SHAPE</th>
<th>SORTING</th>
<th>MATRIX</th>
<th>STRUCTURAL FEATURES</th>
<th>FIELD RELATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lagilli tuff to tuff breccia</td>
<td>60 to 80 percent blocks and lagilli, listed in order of abundance</td>
<td>Essential: 1, 2, 3, 4, 5; accessory: 6</td>
<td>1 and 2; average 3-5 cm; maximum 15-30 cm</td>
<td>1 and 2; subangular to rounded; 3-5 cm</td>
<td>Generally nonsorted, although occasional interbeds of ash are present</td>
<td>10 to 40 percent; consisting of fine relict ashy fragments, some phyllosilicates, and albite pseudomorphs with about 25 percent broken quartz and feldspar phenocrysts.</td>
<td>1: Lateral extension over 15 m minimum; 2: Convex upward with respect to underlying unit; 3: Massive unbedded; 4: Occasional tuff breccia; 5: Overlap of tuff breccia and underlying unit; 6: Tuff breccia matrix.</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Breccia one third of each tuff unit.</td>
</tr>
<tr>
<td>Lagilli tuff and tuff</td>
<td>20 to 60 percent lagilli and tuff, listed in order of abundance</td>
<td>Essential: 1, 2, 3, 4, 5; accessory: 6-10</td>
<td>1 and 2; average 3-5 cm; generally 5-10 cm</td>
<td>1, 2, and 3; subangular to slightly rounded</td>
<td>Generally alternating 1 to 3 cm thick mirror and glassy phenocrysts of quartz and feldspar.</td>
<td>40 to 70 percent consisting of relict shards and broken phenocrysts of quartz and feldspar.</td>
<td>1: Lateral extension; 2: Medium to thin bedded; 3: Concentration of tuff fragments; 4: Tuff intercalations downward.</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tuff intercalates upward of massive tuff.</td>
</tr>
<tr>
<td>Tuff</td>
<td>Rare faceted phenocrysts with broken phenocrysts.</td>
<td>Essential: 1-2 cm</td>
<td>Rounded</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tuff one third of each tuff unit.</td>
</tr>
<tr>
<td>Fine tuff</td>
<td>Occasional plagioclase phenocrysts.</td>
<td>Essential: 1-3 mm</td>
<td>Subhedral</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tuff intercalates upward of fine tuff unit.</td>
</tr>
</tbody>
</table>
and broken subhedral quartz and plagioclase crystals.

Genetic Implications

The presence of abundant pumice, reverse size grading, normal density grading and lack of well developed bedding suggests that these deposits are the product of pyroclastic flow eruptions (cf. Sparks et al. 1973) and that they are submarine pyroclastic flows (cf. Lajolie, 1979), (Table 3-5).

Similar deposits have been described by Yamada (1973) who developed a facies model for subaqueous ignimbrites (Fig. 3-1). Utilizing this facies model, the coarse units at Mosier Lake represent a proximal facies, those at Narrow Lake a slightly more distal environment, and Lost Bay a relatively distal facies.

3.9 Cycle II Formation H

3.9.1 Field Occurrence and Petrography

Cycle II felsic volcanic rocks of formation H are disposed on both sides of the regional synclinorium intercalated with and overlying the pyroclastic rocks of intermediate composition, formation G. Maximum thickness is 400 m in Dent Township (Pryslak, 1970) on the west side of the synclinorium and in Goodall Township (Pryslak, 1972) to the north the formation has an aggregate thickness of 540 m. Lateral extent of the felsic rocks in formation H is much the same as the mafic rocks of this Cycle II, formation E but they are not continuous.

The felsic volcanic rocks of formation H are overlain by
<table>
<thead>
<tr>
<th><strong>TABLE 3-5 Characterization of Subaqueous Versus Subaerial Ignimbrites</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SUBAQUEOUS</strong></td>
</tr>
<tr>
<td><strong>Bedding:</strong> Well bedded relative to subaerial deposits with chaotic unbedded material proximal to vent and well bedded in the distal environment. (Yamada, 1973)</td>
</tr>
<tr>
<td><strong>Grading:</strong> Fining upward of fragments and matrix with occasional reverse size grading resulting in pumice-rich uppermost beds. (Yamada, 1973; Fiske and Matsuda, 1964)</td>
</tr>
<tr>
<td><strong>Fragment Size:</strong> Fragment and matrix grain size generally less than in the subaerial environment. (Sheridan, 1971; Walker, 1971)</td>
</tr>
<tr>
<td><strong>Sorting:</strong> Sorting is greater in this environment, particularly in the distal facies. (Yamada, 1973; Fiske and Matsuda, 1964)</td>
</tr>
<tr>
<td><strong>Welding:</strong> Welding is not well developed, although it has been observed in the subaqueous environment. (Frances and Howells, 1973)</td>
</tr>
<tr>
<td><strong>Recrystallization:</strong> Vapor phase recrystallization of pumice and ash matrix is not generally observed. (Frances and Howells, 1973)</td>
</tr>
<tr>
<td><strong>Fragment Type:</strong> Accessory fragments constitute up to ten percent of the unit.</td>
</tr>
<tr>
<td><strong>SUBAERIAL</strong></td>
</tr>
<tr>
<td><strong>Bedding:</strong> Ranges from massive, unbedded in the proximal environment to poorly bedded in the more distal environment. (Lajoie, 1979)</td>
</tr>
<tr>
<td><strong>Grading:</strong> Normal density grading, reverse size grading very common. (Sparks et al., 1973)</td>
</tr>
<tr>
<td><strong>Fragment Size:</strong> Fragment and matrix grain size is generally greater than in subaerial environment. (Sheridan, 1971; Walker, 1971)</td>
</tr>
<tr>
<td><strong>Sorting:</strong> Less well developed. (Sparks et al., 1973)</td>
</tr>
<tr>
<td><strong>Welding:</strong> Welding is commonly observed in subaerial ash flows. (Ross and Smith, 1960; Sparks et al., 1973)</td>
</tr>
<tr>
<td><strong>Recrystallization:</strong> Vapor phase recrystallization of pumice and matrix, fumarolic alteration, and granophoric recrystallization are observed in this environment in conjunction with the degree of welding. (Smith, 1960)</td>
</tr>
<tr>
<td><strong>Fragment Type:</strong> Accessory fragments are rare.</td>
</tr>
</tbody>
</table>
formation J, which is chemical sediment. Formation H
weathers white to grey with occasional examples being buff
or light apple green in colour. The fresh surface is
commonly vitreous in lustre and usually has a conchoidal
fracture. Primary mineralogy is not preserved (Table 3-6).

Rock types on the west side of the synclinorium are
tuff, lapilli tuff and minor tuff breccia. In the area
between Narrow Lake and Woman Lake in Goodall Township thin
bedded 0.5 to 3 cm tuff forms a unit up to 60 m thick. This
tuff has fine, 0.1 by 0.15 mm, relict shards now quartz,
albite, chlorite and sericite, and coarser subangular
lapilli of 3 to 10 mm with epidote, chlorite, and opaque
iron-titanium oxide constituting 10 percent of the rock.
The thin-bedded tuff in some instances is solely relict
shards and fine, less than 3 mm lithic fragments, fining
upward to very fine quartz, and albite after shards at the
top in delicate bands 5 to 10 mm thick. Lithic fragments
are felsic, subangular to well rounded, and do not have a
grain size or colour change toward their margin (Plate
V-a). The matrix is a felsic to intermediate lapilli tuff
with 10-20 percent angular to wispy relict pumice fragments
of epidote, chlorite, albite, plagioclase, and quartz. The
coarser grained rocks are in layers 2 to 5 m thick succeeded
upward by a few cm of finely laminated tuff (Plate V-a).
These are interpreted as proximal ignimbrites on the basis
of the pumiceous nature of the coarse clasts, lack of
TABLE 3-§  Metamorphic Mineral Assemblages in Felsic Metavolcanic rocks of Cycle II, Earngey-Costello Townships

Amphibolite Facies

Plagioclase, quartz, microcline, actinolite

Greenschist Facies

Albite and quartz with: microcline, biotite, epidote, carbonate
Albite and quartz with microcline, muscovite, biotite, chlorite, epidote, carbonate
Albite and quartz with microcline, biotite, chlorite, epidote, carbonate
Albite and quartz with microcline, biotite, tremolite, epidote, chlorite
Albite and quartz with microcline, chlorite, muscovite, epidote
Albite and quartz with microcline, muscovite, chlorite, stilpnomelane, epidote, carbonate
Albite and quartz with microcline, tremolite, chlorite, epidote
Albite and quartz with microcline, muscovite, biotite, epidote, carbonate
a) Subaqueous ignimbrites of Cycle II, north bay of Narrow Lake. Rhyolitic tuff breccia to lapilli tuff on the right is overlain by fine grained, finely bedded tuff. These represents deposition from a glowing avalanche and glowing cloud parts respectively of an ash flow.

b) Subaerial ignimbrites of Cycle II, Woman Lake. Lower partly welded part of the lower of two flow units in the Woman Lake tuff. The large square and the triangular clast are undeformed lithic fragments. Partly recrystallized pumice fragments from dark wavy areas draped around the lithic fragments; the light colored matrix is glass-rich ash.

c) Subaerial ignimbrites of Cycle II, Woman Lake. Upper densely welded part of the lower flow unit. Pumice, the dark clasts, is enriched in the upper part of the unit.

d) Detail of plate 5c showing the flame-like terminations on some pumice fragments.

e) Note mafic lapillus to the left of the lens cap in the upper flow unit of the Woman Lake tuff in the upper partly welded zone.

f) Layer 3 of the upper flow unit of the Woman Lake tuff has faintly bedded fine grained lapilli tuff forming in the uppermost part. Bedding trends from top to bottom of the photo to the right of the lens cap.

At the top of formation H a white weathering felsic tuff to lapilli tuff with a semi-vitreous lustre occurs at Woman Lake Narrows. This was studied first by Savory (1976) and then in more detail by Thurston (1979). It has a maximum thickness of 300 m, extends along strike for 12 km, and is called the Woman Lake Tuff (Thurston, 1979). It is tuff, lapilli tuff and minor tuff breccia. Clasts are of felsic pumiceous lapilli and bombs and fiamme. The lapilli and bombs vary from uncollapsed vesicular relict glass with quartz and feldspar phenocrysts (Plate VIa), now fine grained recrystallized quartz and feldspar. Felsic lithic fragments are largely relict non-vesicular glass with feldspar phenocrysts, now fine-grained quartz and feldspar with accessory epidote and sericite and, no accidental clasts. The fiamme are almost entirely quartz. The matrix is relict glass shards, devitrified to aggregates of quartz, feldspar, epidote and sericite (Plate I, App. Ic). The Woman Lake Tuff can be subdivided into a base and top as the base contains larger, slightly more mafic, more vesicular pumice (Plate V-c, d), than the top which has more feldspar phenocrysts (Table 3-7, Fig. 3-3, Fig. 3-4, Table 3-8). The base and the top are separated by 15 cm of unbedded tuff. Both base and top have a massive unbedded, ungraded, lapilli tuff to tuff breccia in which pumice increases in abundance
TABLE 3-7  Detailed Stratigraphy of the Woman Lake tuff

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TOP

12 m  unwelded felsic airfall tuff, lapilli tuff, minor tuff breccia

a) uppermost 1.5-3 m felsic tuff breccia with 20-30% pumice, 10-15% lithic fragments, unbedded in ash matrix.

b) lower 9-10 m airfall tuff 6 to 8, 4 to 60 cm thick normally graded tuffs with 3-5 mm feldspar and quartz grains and lithic clasts (25%) in an ash matrix.

4.5 m  unwelded felsic lapilli tuff (20% pumice avg. 2 cm x 1 cm)

2 m  unwelded felsic lapilli tuff

a) uppermost 25-30 cm bedded parallel laminated ash

b) 1.8 m felsic lapilli tuff with 20-30% 2 cm x 2 cm pumice fragments.

100-200 m  welded felsic lapilli tuff (unit 2)

a) uppermost 0.2 m parallel bedded felsic tuff

b) unwelded felsic lapilli tuff 2 m thick with 20-30% 1 cm x 2 cm pumice.

c) 47.8 m partly welded to welded felsic lapilli tuff (a distinctive 1 m thick unit with 10% mafic lapilli occurs towards the top of this section).

50 m  welded felsic lapilli tuff (unit 1)

a) uppermost 3 m - up to 45 cm x 4 cm pumice clasts (50%) in an ash matrix.

b) remainder of unit - 5 cm x 5 mm pumice clasts in an ash matrix with rare lithic clasts (clasts form 38% of mid. portion)

c) a 30 cm thickness about 1 m above the base is locally vitrophyric.

1 m  unwelded felsic crystal lithic airfall tuff

thin-bedded (2-8 cm) normally graded with sparse lapilli.

BOTTOM
Subdivision of subaerial ignimbrites after Sparks et al. (1973). Layer 1 is thinly cross laminated base surge material. Layer 2 is the buld of the deposit from the glowing avalanche, sub-divided into layer 2a, the initial poorly graded material a few meters thick and 2b which forms over 90 percent of the thickness of the unit. Layer 2b has normal density grading with lithic fragments concentrated toward the base and pumice toward the top and reverse size grading as pumice fragments are often larger than the lithic fragments. Layer 3 is unbedded fine tuff deposited from the glowing cloud.
Fig 3-4 DETAILED STRATIGRAPHY OF THE WOMAN LAKE TUFF
TABLE 3-8 SUMMARY OF MODAL DATA, WOMAN LAKE TUFF

Proportions of lithic fragments, pumiceous fragments, phenocrysts, and shards in the Woman Lake Tuff:

<table>
<thead>
<tr>
<th></th>
<th>Pheno-crys</th>
<th>Lithic</th>
<th>Pumice</th>
<th>Glass</th>
<th>Number of Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Mean</td>
<td>Range</td>
<td>Mean</td>
<td>Range</td>
</tr>
<tr>
<td>Top:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper unwelded</td>
<td>-</td>
<td>Nil</td>
<td>60.0-100.0</td>
<td>80.0</td>
<td>40-00</td>
</tr>
<tr>
<td>Upper partly-welded</td>
<td>0.4</td>
<td>0.0-7.0</td>
<td>3.0</td>
<td>33.0-37.0</td>
<td>36.5</td>
</tr>
<tr>
<td>Welded</td>
<td>2.6</td>
<td>7.0-20.0</td>
<td>13.0</td>
<td>20.0-39.0</td>
<td>34.5</td>
</tr>
<tr>
<td>Base:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Welded</td>
<td>0.5</td>
<td>3.1-3.6</td>
<td>3.5</td>
<td>21.1-29.0</td>
<td>24.4</td>
</tr>
<tr>
<td>Lower partly-welded</td>
<td>0.8</td>
<td>17.6-45.5</td>
<td>31.6</td>
<td>3.1-15.0</td>
<td>8.5</td>
</tr>
<tr>
<td>Lower unwelded</td>
<td>0.9</td>
<td>11.0-27.9</td>
<td>19.1</td>
<td>5.0-23.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Size of lithic and pumiceous fragments:

Pumice: Top:
- Lower
  - Largest: 40.0 x 3.0 cm
  - Smallest: 0.5 cm
  - Mean: 2 cm
- Upper
  - Largest: 7.0 x 2.0 cm
  - Smallest: 0.5 cm
  - Mean: 3 cm

Base:
- Upper pumice-rich portion
  - Largest: 38.0 x 2.5 cm
  - Smallest: 0.05 x 1.0 cm
  - Mean: 2.0 x 0.2 cm
- Remainder of unit
  - Largest: 5.3 x 2.5 cm
  - Smallest: 2.0 x 0.3 cm
  - Mean: 2 cm

Lithic: Top:
- Upper 100 m (avg.)
  - Largest: 2 cm
  - Smallest: 0.2 cm
  - Mean: 0.5 cm
- Lower 20-50 m (avg.)
  - Largest: 3 x 2 cm
  - Smallest: 0.5 cm
  - Mean: 0.5 x 0.8 cm

Base:
- Upper 40 m
  - Largest: 20 cm
  - Smallest: 0.5 cm
  - Mean: 0.8 x 0.5 cm
- Lower 10 m
  - Largest: 2 cm
  - Smallest: 0.2 cm
  - Mean: 1 cm
and size upward, (Table 3-8) followed by a thin tuffaceous upper part.

The matrix in the lowermost 10 to 30 m of the base and the uppermost 30 to 60 m of the top is flattened relict glass shards now equigranular fine grained quartz and feldspar with minor epidote and sericite. At only one locality, both matrix and clasts are a uniform relict glass with a black weathered and fresh surface 2 to 3 m above the base of the tuff. There are no identifiable clasts or individual grains in the matrix over a stratigraphic interval of 3 to 6 m.

In the middle part of the Woman Lake Tuff, i.e. the upper part of the base and the lower part of the top, relict shards can not be recognized; instead the matrix is oriented axiolites of fine quartz and feldspar with phenocrysts of granophyric intergrowths of quartz and albite. Fine quartz filled fractures trend perpendicular to bedding in this stratigraphic interval. Megascopically, the matrix is foliated in the central part of the Woman Lake Tuff with the foliation passing around pumiceous fragments more conspicuously than around lithic fragments. (Plate V-b).

The length/width of pumice clasts versus stratigraphic position measured after the method of Peterson (1961, Fig. 3-5), is greatest in the middle of the Woman Lake Tuff where elongation of clasts is extreme and they are mostly polycrystalline aggregates of quartz and vesicles are
3-5 Length/width for pumice fragments in the Woman Lake tuff versus stratigraphic position, indicating the greatest deformation toward the center. Arrows indicate the range of the measurements, made after the method of Peterson (1961) by Savory (1976).
FLATTENING RATIO OF PUMICEOUS CLASTS IN THE WOMAN LAKE TUFF

Figure 3-5
missing and epidote increases slightly. The upper 30 m and lower 30 to 60 m of tuff contain pumice clasts in which clasts and vesicles in clasts are only slightly elongated; they consist of relict glass now fine grained quartz, feldspar, sericite, epidote and minor carbonate, with occasional feldspar phenocrysts.

Spherulitic intergrowths of feldspar are uncommon within lithic fragments in the middle part of the Woman Lake Tuff. In the upper part, branching fractures up to 6 cm wide by 0.5 m long trend generally perpendicular to strike. The fractures are filled with angular fragments of country rock and a chloritic relict glass mesostasis.

The lack of bedding, presence of abundant pumice, reverse size grading, normal density grading (Table 3-7), lack of accidental clasts and a tuffaceous upper part suggest that the base and top are both ignimbrite flows, each representing one eruptive event (Sparks et al. 1973). Within the base of the Woman Lake Tuff, layer 1 of Sparks et al. 1973 (Fig. 3-4) is the thin bedded tuff (Table 3-6). In the top of the Woman Lake Tuff, layers 2a, and 2b are the main component with the uppermost 12 m (Table 3-6) representing layer 3 of Sparks et al. (Plate V-f, VI-a).

The above textural changes in the matrix, and textural and mineralogical changes in the pumiceous clasts, coupled with the consistent stratigraphic control, the ash flow origin of the unit, lack of high degree of strain of the
nearby mafic flows, and analogy with younger rocks (Anderson, 1969; Leonard, 1979; Geijer, 1913; Ross and Smith, 1961; Snyder, 1962) suggest that the Woman Lake Tuff can be subdivided into a central highly welded zone, flanked above and below by a partly welded zone and an unwelded base and top (Table 3–9). The boundary between the lower partly welded zone and the central welded zone occurs toward the top of the basal eruptive unit (Appendix G–c) therefore the Woman Lake Tuff is a single compound cooling unit (Smith, 1960) of two flows from two eruptive events.

The isolated area in which, over a small thickness, the unit appears wholly glassy, is a basal vitrophyre by analogy with younger welded units (Smith, 1960; Ross and Smith, 1961). The conversion of the glassy matrix in the central welded zone is considered, by analogy with younger units (Anderson, 1969; Geijer, 1913; Ross and Smith, 1961; Snyder, 1962) to be vapor phase recrystallization to Torske’s (1975) snowflake texture. The foliation, present only in the matrix, which passes around lithic fragments is interpreted as eutaxitic foliation.

Granophyric intergrowths of albite and quartz in the welded zone of the Woman Lake Tuff represent granophyric recrystallization as described by Smith (1960). The relict glass filled fractures perpendicular to strike are fumarolitic alteration as it is confined to the upper part of the tuff. The intensity of recrystallization and weathering lead to the
<table>
<thead>
<tr>
<th>UNWELDED</th>
<th>PARTLY WELDED</th>
<th>WELDED</th>
<th>BASAL VITROPHIRE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MATRIX</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash: Relict shard shapes visible in plane light as elliptical irregular areas filled with secondary fine grained quartz, feldspar, sericite, and epidote.</td>
<td>Relict shards flattened as in unwelded zone and bent around pumice and lithic fragments; replaced by similar secondary mineralogy.</td>
<td>Shards not discernable. Replaced by development of fine oriented axiolites of quartz and feldspar. Cut by hairline quartz-filled fractures perpendicular to bedding. Phenocrysts of granophyric intergrowths of quartz and albite in most highly welded zone.</td>
<td>Shards not discernable.</td>
</tr>
<tr>
<td>Phenocrysts: Abundant feldspar phenocrysts, subhedral, often broken, occasional corroded quartz phenocrysts.</td>
<td>Broken subhedral feldspar phenocrysts. No change in quartz phenocrysts.</td>
<td>Phenocrysts extensively sericitized, rotated, and surrounded by a sericite-free halo 0.5 mm wide.</td>
<td>Not observed.</td>
</tr>
<tr>
<td>Lithic Fragments: 2 mm fragments, generally aphyric relict glass now fine grained quartz and feldspar, concentrated toward the base of Units 1 and 2.</td>
<td>Unchanged from unwelded zone.</td>
<td>Occasional development of spherulitic textured feldspar clusters.</td>
<td>Not observed.</td>
</tr>
</tbody>
</table>

**CLASTS**

| | | | |
| Pumice: Lapilli and block size relict glass replaced by fine grained feldspar, quartz, sericite, epidote, and chlorite. Relict vesicles sometimes filled with quartz, slightly flattened (Plate VI-a) | Greater flattening (Figure 3-5). Replacement of relict glass by feldspar, quartz, sericite, and slightly greater amounts of epidote and chlorite than in unwelded zone. Shards of eutaxitic texture around pumice. | Extensive elongation of clasts replacement of relict glass by fine poly-crystalline quartz development of fiamme morphology (Appendix C, Plate 1) | Entirely replaced by secondary mineralogy with clast boundaries obscured by recrystallization. |
| Lithic: Lapilli size angular fragments. Relict glass with feldspar phenocrysts. Glass replaced by fine grained secondary mineralogy as above. | Shards develop good eutaxitic foliation above lithic fragments. No textural change. | | |
| | | | No textural change. |
conclusion that the Woman Lake Tuff represents a subaerial ignimbrite (Table 3-5).

East of Lost Bay, thin and medium bedded felsic tuff, 0.5 to 30 cm bed thickness, and intercalated with mafic flows and hyaloclastites to give an aggregate thickness of 106 m. Grain size grades uniformly upward. In some instances the upper fine grained part of beds appears megascopically to grade into chert, but microscopically (73-12-17-130) the chert is very fine grained quartz, albite, and epidote, with grain size of 0.05 to 0.1 mm and in the same proportions as the coarser part of the bed. There are no relict shards and only a few angular lithic fragments. Bedding is defined by grain size changes and minor variation in the proportion of sericite and biotite. These are air fall tuffs, based upon the presence of bedding, the uniform fining upwards character, and the lack of accidental fragments.

The uppermost 400 m of formation H on Lost Bay is considered to be dominantly felsic lapilli tuff and tuff. Microscopically the rocks are angular relict glass fragments (73-12-1010) now consisting of very fine grained chlorite, epidote and opaque iron-titanium oxide, former pumiceous lapilli with wispy terminations, with a foliation that may be long tubes as it is not present in the matrix, and consisting of very fine grained epidote, and albite. The matrix is vermicular textured epidote, albite and quartz
after glass shards. Reverse grading and double grading is visible in some outcrops similar to Yamada's (1973) sandy pumice tuff division. The thin bedded felsic tuff is common in the east facing part of Cycle II on the west shore of Uchi Lake.

3.10 Cycle A Formation J
3.10.1 Field Occurrence and Petrography

Formation J is above the Woman Lake Tuff of formation H and is a 60 m thickness of finely laminated calcite, 0.5 to 10 mm thick with inter-beds of quartz and organic rich, silty material now consisting of black opaque material and tremolite-actinolite. Areas of coarse, 2 to 5 mm recrystallized calcite form irregular knots not exceeding 10 percent of the rock. The wavy form of the carbon-rich laminae is assumed on the basis of its form and distribution to mark the presence of stromatolites (Henderson, 1975, pers. comm. H. Hoffman, 1980) (Plate W1-b).

3.11 Cycle III, Formation K
3.11.1 Field Occurrence and Petrography

Cycle III, the youngest of the three cycles, is on both limbs of the regional synclinorium (Fig. 2-1). On the west limb, formation K, mafic flows and associated coarse grained intrusive rocks are the base of the cycle, and are 3400 to 5500 m thick. The formation is mapped for 31.4 km from the south to the north boundary of the area and is known to extend a further 1.8 km north to the Swain Lake fault.
a) Subaerial ignimbrite of Cycle II on Woman Lake. Upper unwelded part of the upper flow. Relatively undeformed, unrecrystallized rhyolite pumice fragments outlifed by wispy chlorite.

b) Hand specimen of stromatolitic carbonate capping cycle II on Woman Lake. White areas are sparry recrystallized carbonate, dark curved linear elements are fine grained carbonate and organic material. Scale card marked in cm.

c) Varioles occur in a massive flow unit with no discernable pillow structure. Varioles are light coloured rounded bodies. Lighter rim is a metamorphic phenomenon.

d) Coalescene of varioles is seen in detail here, coin is 23.5 mm in diameter.

e) Photomicrograph of Cycle III varioles including a plucked out vesicle in lower left, and the matrix in the upper right. Note the sharp contact between variole and matrix. Specimen 77-450, crossed polars.

f) Cycle III basalt on Lost Bay of Confederation Lake with spalled relict glass filling the inter-pillow space.
south limit has not been well defined (Breaks et al. 1975). On the east limb of the regional synclinorium formation K is 2250 m thick and extends from Fly Lake in the south to the Swain Lake fault, a distance of 37 km. It is underlain by felsic tuffs and the stromalitic carbonate which forms the upper part of Cycle II, and is overlain by intermediate and felsic pyroclastic rocks of formation L, Cycle III.

The weathered surface of formation K varies in colour from dark to light green to white and is dark green or light green to white on the fresh surface. Its lower part is pillowed flows, assumed to be relatively thin as no massive flow centers are present. Individual flows up to 60 m thick outcrop on the shore of Lost Bay of Confederation Lake. Pillows are elliptical to bun shaped with 1 to 4 cm thick selvages, commonly with small, 1 to 2 mm, plagioclase phenocrysts and microspherulitic quartz and plagioclase intergrowths 2 to 3 mm in a relict glass matrix. Twenty percent is amygdules. Chert and spalled glass fragments form inter-pillow debris (Plate VI-f). Broken and isolated pillow breccia (Carlisle, 1964) occur as irregular bodies 90 m thick with a minimum length of about 150 m at scattered localities on Lost Bay. Textures in the massive flows are ophitic to intergranular, or isogranular (Oppenheim, 1964) or variolitic.

A variolitic part up to 90 m thick, possibly a single flow, occurs 460 to 580 m above the base of formation K.
This has a lateral extent of at least 14 km from Fly Lake to the south contact of the Okanese batholith on the east limb and, about 16 km on the west limb of the regional synclinorium. Varicles average 1.5 cm in diameter and range from 0.5 cm to 5 cm; they form 20 to 100 percent of the rock. They are a vitreous white center set in a dark brown fine-grained mafic matrix. As they become more abundant they form layers of coalesced varicles up to 2 m thick. Variations in the abundance of the varicles indicate some type of flow differentiation (Plate VI-c).

Individual varicles commonly have an intensely saussuritized outer rind 1 to 2 mm thick surrounding a core of alternating acicular albite and quartz with branching intergrowths of clinzoisite arranged in a radial pattern (Plate VI-c). Toward the rim the varicles have a greater concentration of clinzoisite, minor chlorite, biotite, carbonate and leucoxenè. The central core of the varicles is generally medium grained anhedral quartz sericite, and carbonate with a polygonal texture (Plate VI-e). The variole to matrix boundary is sharp and the matrix mineral assemblages suddenly predominate at the variole rim.

There are quench textures in the form of skeletal clinzoisite, perhaps after calcic plagioclase (Gelinas and Brooks, 1974), belt buckle feldspars and swallow-tail microlites. Coarse branching dendritic aggregates of quartz and albitic plagioclase give way outward from the center of
the variolé to a radiating acicular texture followed by a clinozoisite and chlorite-rich border zone. The matrix is chlorite needles after quench pyroxenes and relict plagioclase in a felted mass (Bryan, 1972; Gelinás and Brooks, 1974).

On the basis of the large size of the varioles, lack of association with pillow rims, irregular shape, and apparent contrast in composition the variolites correspond to the Blake River type of Gelinás et al. (1976).

They are distinguished from felsic flows by the presence of pillows, greater density, lack of conchoidal fracture, massive appearance and lack of quartz in the weathered rind. There is more than 25 percent epidote, whereas epidote is less abundant in felsic flows.

Plagioclase is uniformly albite and contains small 0.01 to 0.03 mm subhedral light green grains of epidote which make up a maximum of 30 percent of the albite grain; alternating epidote is in very fine (0.01 mm) anhedral granules which form 90 to 100 percent of plagioclase grains. The mafic minerals present vary from coarse anhedral poikilitic plates of augitic clinopyroxene, 5 to 10 mm in size, to coarse 5 mm poikiloblasts of feathery tremolite-actinolite, and chlorite. Chlorite is rarely the dominant mafic mineral. Carbonate is present in some samples replacing other phases or randomly forming 1 to 3 mm anhedral grains. More commonly it is confined to veins, or
is present in amygdules possessing quartz rims and carbonate cores. Other phases present in veinlets include epidote, quartz, stilpnomelane, biotite and sericite.

In the lower part of formation K, on Bobajo Point of Confederation Lake, flows are present with light green to white fresh surface. They are composed of an epidote-rich assemblage consisting of 40 percent zoisite and clinozoisite, 40 percent albite, 15 percent tremolite-actinolite, and 5 percent carbonate, trace chlorite. Carbonate is more abundant in interpillow spaces, on the edges and outermost 4 to 5 cm of individual pillows with the pillow interiors consisting of chlorite, tremolite-actinolite, plus albite. Plagioclase has small 0.01 mm scattered grains of epidote within it but large 0.1 to 0.3 mm anhedral flakes of zoisite appear to replace most of the mafic minerals with up to 20 percent chlorite or tremolite in some examples. Carbonate varies from trace to 15 percent as anhedral grains replacing earlier phases or filling amygdules.

In the Settting Net Lake area Ayres has noted (pers. comm. L.D. Ayres, 1974) pods, veins and pervasive areas of epidote, quartz, and magnetite, with or without pyroxene, in single mafic flows beneath an impermeable chert bed. This phenomenon increases in intensity as the chert is approached. Ayres attributes it to hydrothermal or fumarolic alteration, beneath an impermeable chert cap.
rock. Water dominated greenschist facies alteration of oceanic basalts described by Humphris and Thompson (1978) produces similar epidote-rich assemblages. The widespread distribution of the epidote-rich assemblages throughout formation K, and the lack of epidotized mafic flows in formations A and E, supports the interpretation that this assemblage is of pre-regional metamorphic alteration.

3.12 Cycle III Formation L

3.12.1 Field Occurrence and Petrography

Formation L extends from east of North Bay of Confederation Lake southward to Fly Lake, a distance of 30 km; the thickness is approximately 2,000 m (Fig. 2-1). It is dominantly tuff with minor intercalated flows. The tuff part is intermediate to felsic in composition (mean SiO$_2$ = 67 percent, $n$=18; pers. comm. V. Sopuck, 1976) and differs from the overlying coarse grained felsic tuffs and flows of formation M felsic volcanic rocks in that it is relatively fine, glass-rich with common devitrification spherulites (Lofgren, 1971; Kesler and Weiblen, 1968).

It is dominantly intermediate flows at the base through lighter weathering felsic, dominantly pyroclastic rocks, in its upper part. In general the rocks have a black through light green or grey weathered surface and a white to black fresh surface. Intermediate flows occur in the vicinity of Lake X in Agnew Township and along the shore of the bay on the west side of Lost Bay of Confederation Lake. The flows
are massive to slightly foliated in hand specimen with occasional spherulites; the spherulites vary in size from 1 mm to 2 cm. No pillows were observed. The flows have an intergranular texture (Oppenheim, 1964) with the mineral assemblages listed in Table 3-10. Relict primary albite phenocrysts are clouded with 0.01 mm subhedral grains of epidote scattered throughout. The mafic minerals are chloritic aggregates making up 15 to 25 percent of the rock and fine-grained plagioclase generally interstitial 1 to 2 mm plagioclase euhedral (sample 73-12-2793).

The pyroclastic rocks are intermediate to felsic tuff and lapilli tuff with minor tuff breccia. Typically, the outcrop surface has alternating beds of aphanitic black weathering material which is fine-grained glassy tuff and fine-grained sandy textured coarse tuff. Spherulites are common throughout (Plate VII-a). The rock (73-12-2481) is 1 to 5 mm subangular lithic fragments of quartz, albite, chlorite, biotite, sphene, and epidote, surrounded by relict pumice fragments composed of very fine grained (.02 mm) biotite, chlorite, epidote, and lenticles of quartz and albite. Pumiceous fragments have ragged terminations and are typically 5 to 10 mm long by 2 to 3 mm wide and up to 20 percent of the rock. The texture is eutaxitic as there is evidence of compaction and partial welding (Ross and Smith, 1961).
TABLE 3-10 Metamorphic Mineral Assemblages in Intermediate Metavolcanics Cycle III, Earngey-Costello Townships area

Amphibolite Facies

Plagioclase, hornblende, quartz, biotite, epidote, chlorite, tremolite
Hornblende, biotite, quartz, plagioclase, cummingtonite
Plagioclase, hornblende, epidote, chlorite, carbonate, quartz, biotite
Plagioclase, hornblende, chlorite, epidote, quartz, biotite
Plagioclase, hornblende, quartz, chlorite, biotite, epidote, carbonate
Plagioclase, hornblende, quartz, chlorite, epidote, biotite

Greenschist Facies

Albite, tremolite, biotite, chlorite, muscovite
Albite, chlorite, carbonate, biotite, epidote
Albite, tremolite, epidote, biotite, chlorite, carbonate
Albite, epidote, chlorite, biotite, muscovite, K-feldspar
Albite, biotite, epidote, carbonate
Albite, tremolite epidote, carbonate
Albite, chlorite, sericite
Biotite, epidote, albite, carbonate, chlorite, tremolite
Biotite, albite, epidote, stilpnomelane

All assemblages are quartz bearing.
PLATE 7

a) Cycle III, felsic pyroclastic rocks. Spherulite in a spherulitic felsic tuff. Spherulite is radiating albite, epidote, and quartz with minor sericite. The matrix, formerly glass shards, has the same mineralogy with a higher colour index. Specimen 73-12-2481, crossed polars.

b) Cycle III felsic pyroclastic rocks felsic lapilli tuff on Confederation Lake south of the South Bay Mine.

c) Photomicrograph of quartz-feldspar porphyry forming the endogenous dome at the South Bay Mine. The plagioclase phenocrysts in the lower left is somewhat sericitized and quartz phenocrysts are strained. The matrix is sericite, epidote, albite and quartz.

d) Cycle III felsic pyroclastic rocks on Fly Lake south of the South Bay Mine. Note the light coloured rim on the larger fragments. The matrix is not ash but progressively smaller fragments. The unit is interpreted as pyroclastic fall back breccia or a subaqueous ash flow.

e) Granophyric granodiorite of map unit 7. A granophyric plagioclase and quartz occur in the upper left surrounded by quartz and feldspar phenocrysts in a fine grained groundmass of quartz, feldspar, epidote, biotite and amphibole.
In some instances, tuffs contain large spherulites up to 1 cm in diameter; the spherulites are concentrated in 1 to 5 cm thick beds separated by spherulite free beds of roughly equivalent thickness. Spherulites are radiating very fine grained (0.01 mm) acicular albite, quartz, and epidote in a matrix of albite, quartz, biotite and epidote. Epidote, biotite, quartz, and albite in fingerprint-like swirls is interpreted to be a devitrification texture (cf. Ross and Smith; 1961). Masses consisting of greater than 90 percent epidote, quartz, biotite, and stilpnomelane between spherulites is also interpreted as a devitrification texture. The spherulites generally have a smooth elliptical outline suggesting they are not the low temperature vapor phase crystallization phenomenon which produces irregularly shaped spherulites in ignimbritic rocks (Ross and Smith, 1961) (73-12-2886): rather they represent conventional devitrification processes.

Along the west shore of Lake X in Agnew Township over a thickness of about 300 m and a lateral extent of about 6 km, formation L includes a large proportion of tuff breccia with highly epidotized fragment. It is 10 to 40 percent rounded clasts averaging 15 to 20 cm in long dimension and, 60 to 90 percent glass-rich crystal tuff with occasional pumiceous fragments. Clast-matrix contacts vary from sharp to gradational suggesting that an alteration event was post-depositional. The matrix is spherulitic tuffaceous
material similar to that described above with up to 10 percent broken quartz phenocrysts. Bedding is 1 to 2 m thick and in combination with pumiceous fragments suggest the rock is a subaqueous ash flow (cf. Parsons, 1969, p.298-300).

3.13 Cycle III, Formation M

3.13.1 Field Occurrence and Petrography

Most of formation M is in a fault bounded block which trends in a northerly direction from the south edge of the map-area to slightly north of South Bay Mine, a distance of 16 km. This formation is equivalent to the "Mine Series" of Sopuck (1977). The structural trend of lithologies outside the block is generally north. Within the block northeast trends predominate. Minor occurrences of north trending felsic tuff are east of the fault bounded block. Formation M, the top of the stratigraphic section, is underlain by the intermediate to felsic metavolcanic rocks of Formation L, Cycle III. Thickness is difficult to estimate as marker beds have only limited extent but maximum thickness is estimated as 2,200 m (Thurston, 1979a).

The felsic volcanic rocks of formation M are about 1500 m of rhyolite flows and associated hyaloclastites and brecciated flows (terminology of Dimroth and Rocheleau, 1979) succeeded upward by about 1000 m of tuff, lapilli tuff and tuff breccia, considered to be dominantly ignimbrites and, 150 m of debris flows and air-fall pyroclastic rocks
capped by 45 m of mafic flows (Fig. 3-6). Above this mafic flow there is a complex of mainly felsic flows and local accumulations of pyroclastic rocks interpreted as a collapsed endogenous dome at the South Bay Mine (Pollock et al. 1972). The approximate boundary between the interpreted dome of South Bay Mine and the ignimbrites to the south is the north end of Fly Lake (Fig. 3-6).

Weathered surfaces vary from light green through grey and white. Fresh surfaces are grey to white. Generally most rocks are aphanitic, although quartz can be observed in the weathered rind. Mineral assemblages in the felsic volcanic rocks are largely secondary in origin (Table 3-5). Saussuritized primary plagioclase occurs as 5 to 10 mm phenocrysts in the quartz-feldspar porphyry at the South Bay Mine.

Fine grained felsic tuff with bedding from 2 to 3 mm up to 3 cm thick occurs in the vicinity of the quartz-feldspar porphyry dome and south along the west shore of Fly Lake. The tuff is 0.1 to 1 mm grains of angular to subangular quartz and albite with minor interstitial chlorite, white mica, albite and epidote. The tuffs, where bedding can be seen, are plane bedded. South of the mine, fine grained tuffs are interbedded with lapilli tuff which consists of one-half to two-thirds ash matrix with millimeter to centimeter size complex amoeboid shaped fragments with varying proportions of fragments to matrix. As these
fragments are irregularly shaped and in some instances have a more intensely saussuritized rim relative to the fragment center, the author interprets them to have been hot glassy fragments derived from underlying felsic flows (cf. Dimroth, 1975) (Plate VII-d).

Many fine grained felsic tuffs consist of alternating beds of relict glass lenticles 0.2 by 0.01 mm in beds 1 to 2 cm thick separated by beds of relict glass and pumiceous fragments up to 1 to 2 mm in size. The formerly glass-rich beds contain 10 to 40 volume percent of 2 to 5 mm spherulites of acicular quartz and albite, separated by a chlorite, sericite, and epidote matrix. Development of spherulites in glass-rich volcanic rocks is a reasonably rapid process at elevated temperatures (Kesler and Weiblen, 1968), on the order of 1 to 2 days at 900°-1000°C for andesitic glasses. The slower diffusion rate in rhyolitic glass relative to the andesitic glasses referred to by Kesler and Weiblen and the lower temperature involved in these airfall deposits would not radically increase the time necessary for formation.

Massive and porphyritic felsic flows are in close association with the quartz-feldspar porphyry dome and to the south along Fly Lake. The flows have a massive to porphyritic interior overlain by autoclastic breccia of 0.1 to 0.5 mm angular lithic fragments composed of fine grained quartz, albite, and sericite in a matrix of straight-sided
fragments with similar mineralogy and assumed to be hyaloclastic fragments (cf. Macdonald, 1972, p.105). Stratiform sphérolitic zones are associated with zones of crackle brecciated flows in the mine area. Felsic flows in the Fly Lake area are generally massive, commonly with 1 to 5 mm quartz and albite phenocrysts in a fine grained quartz, albite, sericite groundmass. Irregular sphérolite-rich zones are interspersed with massive parts of flows. The sphérolites are surrounded by light brown weathering epidote-rich relict glass. Flow banding presently consisting of 0.5 to 2 cm spaced parallel cracks is observed occasionally on Fly Lake.

The part of formation M interpreted as ignimbrites typically consists of tuff breccias to lapilli tuffs 10 to 20 cm thick. A peculiar rock on an island in the south part of Fly Lake is felsic tuff breccia with 40 percent angular to rounded felsic lithic fragments generally with a very irregular shape resembling fusiform bombs (cf. Macdonald, 1972, p.127). These fragments are in a matrix composed of small, 10 to 15 mm angular to subangular essential felsic lithic, 20 percent pumiceous fragments and ash-size matrix. Rims 0.5 to 1 cm wide on the larger fragments are lighter coloured than the fragment interior.

In a typical exposure from this area, layer 1 of Sparks et al. (1973) is not found. Layer 2a, 0.5 to 0.8 m thick, consists of 20 to 30 percent pumiceous essential felsic
lapilli and blocks, and 5 to 10 percent essential felsic lithic fragments in a felsic ash matrix. This is succeeded upward by layer 2b of Sparks et al. (1973) consisting of 20 to 50 percent essential pumiceous felsic bombs, commonly subrounded, but occasionally angular in a matrix of 20 percent lapilli of felsic pumice fragments and 30 percent felsic tuff. Reverse size grading is commonly conspicuous with the uppermost 0.3 m of a 3 m thickness consisting of more than 75 percent pumiceous bombs 0.2 to 0.3 m. Layer 3 of Sparks et al. (1973) is generally present and about 15 m thick and unbedded.

The layers have reverse size grading of pumiceous fragments and pumice-rich tops. Normal density grading with relatively scarce lithic fragments is toward the base; a lack of stratification, and a poor development of welded textures in pumiceous fragments suggest the rocks are ignimbrites (cf. Sparks et al. 1973).

The 152 m thickness of air-fall tuff and debris flows above the ignimbrite consists of: 1) heterolithic intermediate to felsic lapilli tuff to tuff breccia containing subrounded intermediate and felsic pumiceous and lithic fragments of many rock types with no sign of welding, size grading, density grading, or bedding. Sand size clastic quartz, chlorite and feldspar form a fine matrix constituting 10 to 15 percent of the rock. On the basis of the heterolithic character, the scant matrix, and lack of
primary structures, it is considered a lahar (cf. Mullineaux and Crandell, 1962).

A 3 to 6 m thickness of well-bedded felsic tuff with less than 5 percent rounded felsic lithic bombs about 20 cm in long dimension caps the felsic sequence. Bomb sag structures and a bedded nature suggests it is an air fall tuff.

Coarse pyroclastic rocks of intermediate composition occur just east of South Bay Mine at Lost Bay on Confederation Lake (77-428) where there is a coarse breccia of 10 to 20 percent angular to subangular scoriaceous fragments up to 15 cm (average 7-10 cm), 60 percent angular bomb and lapilli sized lithic fragments and, 20 to 40 percent matrix of lapilli tuff and tuff with 3 to 10 mm subangular fragments. Fragments and matrix are of the same composition, with a tendency for fragments to be slightly more chloritic. It is unsorted and unbedded over thicknesses of 10 m in individual exposures which occur intermittently over 300 m of stratigraphic thickness. The rock is lenticular with a thickness of 550 m and thins rapidly over 1 km north and 2 to 5 km south. The monolithic character of the fragments and the matrix, the lack of bedding, limited lateral extent, lack of interbedded fine grained tuffaceous rocks, lack of accidental fragments, and close spatial relationship to the endogenous dome of quartz feldspar porphyry at the South Bay Mine suggest that this is

In summary, formation M is in the north largely flows
and a dome collapse breccia associated with a quartz-
feldspar porphyry dome. To the south, it is ash flow
deposits succeeded upward by air fall tuffs.

3.14 Metamorphosed Felsic to Intermediate-Hypabyssal
Intrusions

There is a diversity of rock types, all of which
represent a hypabyssal environment, which vary in
composition from granitic to quartz diorite, and which
occur as small stocks, sills and minor dikes. They all have
exsolution textures in the feldspars and, the more siliceous
types are distinguished from their extrusive equivalent by
more abundant sericite and extrusive textures. They
generally cut formations of cycle III.

3.14.1 Hornblende Quartz Diorite

A sill of hornblende quartz diorite occurs on Uchi Lake
at the mouth of Leg Creek. The stock is intrusive into the
metamorphosed diorites of map unit 6 and formation A and
covers an area of about 1.25 km$^2$. It extends roughly
parallel to strike over a distance of 3.3 km and varies in
width from 213 m to 365 m. The sill weathers black to dark
brown, and the fresh surface is generally dark green to
black to dark brown. It has 10 percent phenocrysts of quartz
up to 2 to 3 mm in size, 10 to 15 percent plagioclase
phenocrysts and 20 to 30 percent mafic phenocrysts less than
1 mm in size. They are in a fine grained groundmass. Mafic phenocrysts vary irregularly through the stock from 2/3 biotite, 1/3 hornblende to entirely hornblende. The hornblende-rich part of the rock host 25 to 30 percent, slightly chloritic hornblende phenocrysts, phenocrysts of saussuritized, 20 percent granophyric plagioclase, which has some Carlsbad twins and small 0.1 mm, granules of potash feldspar and rods of epidote, 10 percent phenocrysts of anhedral quartz, in a fine grained groundmass of granophyric plagioclase and quartz, with minor epidote, carboate, opaques and, about 1 percent scattered flakes of stilpnomelane. Texturally this rock is dominated by a preferred shape orientation of mafic minerals and plagioclase laths.

3.14.2 Granophyric Granodiorite

This rock name was used by A.P. Pryslak (personal communication, 1973) to describe a number of metamorphosed felsic stocks in Dent and Mitchell Townships. Within the map area, the term is applied to grey to buff weathering felsic rocks consisting of 1 to 2 mm plagioclase phenocrysts in a fine phaneritic to aphanitic groundmass. At the north end of Found Lake in Agnew Township it is intrusive into formation K and, on the small peninsula at the north end of this lake, is cut by granitic rocks of Okanse Batholith. The major difference between this rock and the quartz-feldspar porphyry dome at South Bay Mine is a lesser amount
of quartz phenocrysts in the former.

The major occurrences of this rock type are: (1) a stock 4.8 km long by 390 m wide, east of the south end of Fly Lake, and 670 m wide just south of the channel between Lost Bay and the main part of Confederation Lake. 2) a complex, multi-phase stock east of Pound Lake in Agnew Township which consists of a more mafic, that is, dioritic phase and granophyric granodiorite. 3) a sill which extends from the west shore of Lost Bay northward for 24.9 km to a point west of Pound Lake for a width ranging from 180 m to 400 m.

The rock is 50 percent granophytic intergrowths of optically continuous plates and vermiciform pods of quartz, with plates and long sinuous areas of sericitized albite. An additional 40 percent is 1 to 2 mm phenocrysts of saussuritized plagioclase and quartz in a matrix of optically continuous quartz (Plate VI-e). Five to 10 percent of the rock is sericite, biotite, and opaque iron-titanium oxides all interstitial to intergrowth quartz and feldspar.

Some phases of the granophytic granodiorite, in particular the south part of the stock east of Fly Lake and large parts of the Pound Lake stock, have less than average quartz phenocrysts and two generations of plagioclase phenocrysts. Plagioclase laths about 2 mm by 0.3 mm comprise between 5 and 10 percent of the rock and a second group of phenocrysts varying from 0.6 to 1 mm by 0.2 mm form
about 60 percent of the rock. Theselatter phenocrysts have
saussuritized central zones with a 0.01 to 0.02 mm clear
albite rim. Potash feldspar grains about the same size as
the smaller plagioclase grains are 10 percent of the rock.
Finer anhedral grains of quartz and albite are the matrix
and about 15 percent of the rock. The remainder is
aggregates of chlorite, minor biotite, opaque iron oxides
and sericite.

In general, the colour index and type of mafic
mineralogy in the granophytic granodiorite varies with the
rock type which it intrudes. At the north end of the Fly
Lake stock the accessory minerals are 5 percent muscovite
with minor biotite and in this instance the rock is
intrusive into intermediate and felsic metavolcanic rocks.
The south end of this stock is surrounded by mafic flows of
formation K and correspondingly the colour index increase
from 5 to 15 and the mafic minerals are chlorite and minor
biotite. The sill, which extends north from Lost Bay to
west of Pound Lake in Agnew Township, is almost wholly
chloritic granodiorite with 20 percent of the rock
sericitized plagioclase and quartz phenocrysts averaging 1
mm by 0.1 mm but occasionally as large as 2 to 3 mm by 0.2
mm in a matrix of granophytic plagioclase, potash feldspar,
quartz, chlorite and opaque iron oxides. Within the base of
the sill there are two 30 m thick lenses of quartz-feldspar
porphyry. The base of the sill at the north end contains a
similar 30 m by 490 m sill of quartz-feldspar porphyry. Small sills of quartz-feldspar porphyry are also found toward the top of the sill at the north end. The quartz-feldspar porphyry appears to be slightly later than the granodiorite.

The chloritic granophyric granodiorite in the sill consists 10 to 15 percent of 2 to 3 mm quartz phenocrysts and 10 to 15 percent equant to subhedral sericitized plagioclase phenocrysts of similar size, generally rimmed with myrmekitic intergrowths of quartz and albitic plagioclase in a matrix of plagioclase, quartz, potash feldspar, chlorite and opaque iron oxides.

3.14.3 Porphyritic Rhyolite

This rock, locally known as (Thurston et al. 1974; Pryslak, 1971) quartz-feldspar porphyry is a siliceous, intrusive rock, rhyolitic in composition, which is spatially associated with the Cycle II volcanic rocks. Its principal features are abundant, 20 to 40 percent, quartz phenocrysts 0.06 to 0.2 mm in diameter and generally subordinate amounts, 10 to 15 percent, of albite phenocrysts of similar size in grey to white weathering massive to slightly foliated rock. Scattered through the matrix, especially in the less altered varieties, there is 10 percent 0.1 mm rounded euhedral feldspar phenocrysts and trace amounts of 0.1 mm grains of epidote (Plate 7c). Secondary calcite cements, fractured quartz phenocrysts.
A major occurrence of this rock type is a sill 122 m thick which extends for 1,600 m along the west shore of Asin Bay of Fly Lake. An extension of this sill, offset right-laterally, continues southward outside the map-area. A small sill 1,220 m long by 120 m wide is 300 m east of the NW corner of Earngey Township. This occurrence has a chilled, phenocryst-free margin and is intrusive into metavolcanic rocks.

These sills of rhyolite porphyry are spatially related to a large body of rhyolite porphyry in Dent Township, called the Mine Porphyry, which is generally dome-like in plan view. This body is 800 m by 2,000 m.

On the basis of a limited number of thin sections, it would appear that the second generation of plagioclase phenocrysts is more abundant, the matrix is more sericitic, the larger first generation plagioclase phenocrysts are commonly fractured and the cracks filled with sericitic material, and chlorite appears as a constituent of the matrix (about 1 percent) as the South Bay orebody is approached, suggesting that these changes are a mineralogical expression of the ore-forming event (Sopuck, 1977).

The flows of formation M are generally separated from the Mine Porphyry by the dacite breccia of Pollock et al. (1972) which has been interpreted here (formation M) as a dome collapse breccia. The Mine Porphyry has a foliation
varying from the regional tectonic foliation which is parallel to the margins of the intrusion. Fragments of the Mine Porphyry a few cm on-a-side in a matrix of Mine Porphyry, termed ghost breccia (J. Wan pers. comm. 1974) may represent the fragmental carapace of a volcanic dome (Macdonald, 1972).

On the basis of the above points, Pollock et al. (1972, p.303) and Asbury (1975, p.7, 8) conclude that the Mine Porphyry is an endogenous dome. The sills within the map-area however appear to be either minor offshoots of the main dome or, in the instance of the Lost Bay sill, differentiates of the granophyric granodiorite, given the close spatial association and similar petrography. Therefore this would tend to support a close temporal relationship between the granodioritic rocks and the rhyolite porphyry.

Numerous thin, 3 cm to 10 m dikes of rhyolite quartz porphyry are within formation H. They are generally massive and weather white to buff. Ten to 20 percent albite or quartz and feldspar phenocrysts in the range 1 to 2 mm generally subhedral to euhedral are set in an aphanitic groundmass. These rocks cut all unmetamorphosed granitic rocks, but they have a tendency to be concentrated in the eastern two thirds of Earngey Township. They generally have a chilled margin from 2 mm to 2 cm thick and rarely, a foliation parallel to the margin of the dike. This is
evident in particular on an outcrop of re-worked intermediate pyroclastics at the southeast corner of Lost Bay, where the alignment of chlorite grains in the dike define a foliation. In some places the dikes have been contaminated with 5 to 10 percent of 0.5 to 1 mm rounded to angular xenoliths of the surrounding rock types.

The groundmass of the dikes is 0.01 to 0.02 mm rounded anhedral, grains of quartz and feldspar defining a hypidiomorphic granular texture. The proportion of quartz to feldspar is generally 1:4. Scattered, 0.1 to 2 mm, grains of subhedral biotite and subordinate muscovite occur throughout the groundmass forming 5 to 10 percent of the rock accompanied by trace amounts of sphene, opaque iron titanium oxides and epidote. The phenocryst population is variable with 3 to 5 percent quartz, phenocrysts in the rhyolite prophyries, whereas the feldspar porphyries consist of similar size phenocrysts of orthoclase and plagioclase. Both are commonly slightly saussuritized, and generally the plagioclase is An$_{20-30}$ in unaltered cores of phenocryst, forming a maximum of 10 percent of the rock. Compositionally these rocks are biotite-micro quartz monzonites which have mineral assemblages of greenschist facies metamorphism.

One dike on the east shore of Leg Lake is a biotite micro granophyric quartz monzonite, although it was mapped in the field as an aphanitic felsite. The dike is 50
percent granophyric oligoclase laths 0.6 by 0.2 mm and 20
percent subhedral equant potash feldspar grains, 20 percent
anhedral 0.3 mm grains of quartz, 5 percent subhedral grains
of muscovite and 1 to 2 percent epidote plus and accessory
sphene, carbonate, chlorite and pyrite.

3.15 Unmetamorphosed Felsic to Intermediate Intrusions.

There are four major bodies of unmetamorphosed granitic
rock in the map-area; the Okanse batholith centered on
Okanse Lake, the Perrigo batholith, centered on Perrigo
Lake, the Costello Lake stock, west of Costello Lake and the
Allison Lake batholith. These batholiths are relatively
simple consisting of two or three phases, in distinct
contrast to those found elsewhere in the Shield (Ziehlke,
1975, and Ayres, 1974). Mapping of the granitic area is not
however as detailed as that of the remainder of the area,
and this conclusion is tentative. The various phases are
mappable on the basis of composition, abundance and
character of mafic minerals, and presence and character of
phenocrysts.

3.16 Geochronology

A Cycle III porphyritic felsic flow from the east shore
of Fly Lake in Dent Township outside the fault bounded block
was sampled by the author and P. Nunes of the ROM for U/Pb
geochronology on zircons. An age of 2739 ± 50 My has been
determined for this material (Nunes and Thurston, 1979).
Although slightly discordant, a sufficient number of points
are available (Appendix B) to suggest that this represents the age of crystallization of this rock.

A radiometric age determination by the U/Pb method on zircons from the rhyolite-porphyry endogenous dome from the South Bay Mine within the fault bounded block is 2740 Ma. This is believed to be the age of crystallization of the porphyry based upon recalculation of the 2800 Ma age in Krogh and Davis (1971) using the newer decay constants (see appendix B).

Structural interpretation (appendix G) suggests that rocks within the fault bounded block are younger than rocks outside the block. Therefore, the zircons of the porphyry are inherited, or the age on the porphyry body has a larger error associated with the data than the more recent analyses.
CHAPTER 4

Physical Volcanology

4.1 Cyclical Volcanism

4.1.1 General Statement

A cycle is defined as: "A series of events or changes that are normally, but not inevitably, considered to be recurrent and to return to a starting point, that are repeated in the same order several or many times at more or less regular intervals and that operate under conditions which at the end of the series are the same as they were at the beginning" (AGI, 1972). Cyclical volcanism is the repetition of volcanic rocks, in an Archean context, this has generally referred to the repetition of mafic to felsic sequences of rocks (Goodwin, 1967, 1968).

Anhaeusser (1971) examined cyclicity in Archean volcanic rocks and described its occurrence on four scales:

1) mini-cycles: measured in centimetres or parts thereof, e.g. greywacke-argillite couplets or felsic tuff-chert couplets.

2) minor-cycles: measured in metres, tens of metres, hundreds of metres, for example parts of Cycle II where basaltic andesite to rhyolite cycles take place over about 150-m intervals.

3) major-cycles: "a few hundred to many thousand of metres" thick, for example the cyclical volcanism of Ayres (1977).

Cyclicity on this scale occurs in the Norseman area of
W. Australia (Doepel, 1965; quoted by Glikson, 1976) and in
the Bulawayan Group of Rhodesia (Bliss and Stidolph, 1969).

4) Super-cycle: includes the whole of a volcanic-
 sedimentary pile and may change from ultramafic to
tholeiitic to calc-alkaline to alkaline and includes
thousands of metres of stratigraphy.

In the Abitibi metavolcanic-metasedimentary belt of the
Canadian Shield, Pyke (1978) and Jensen (1979) have
described the three-fold recurrence of a volcanic super
cycle involving basaltic komatiite succeeded in time by
high Fe and high Mg tholeiitic basalts through tholeiitic
rhyolites to calc-alkaline basalts through rhyolites.
Archean volcanic cycles of this magnitude appear to be
unusual in their stratigraphic thickness and chemical
variety. A further compilation of examples of the various
scales of volcanic cyclicity is listed in Table 4-1.

Speculation as to the causes of super cycles versus
major cycles involves consideration of the following
parameters with respect to supercycles:

1) A komatiite through calc-alkaline rhyolite super-cycle
involves production of komatiitic liquids by 30 to 50
percent melting of mantle source (Arndt, 1977) with no
clear evolutionary path between the komatiitic and the
overlying tholeiitic suites of lesser degrees of partial
melting (Condie, 1978). Both suites have distinct
intermediate differentiates (Arndt, 1975).
<table>
<thead>
<tr>
<th>Area</th>
<th>Units (permasaged) (after Wilson et al., 1971)</th>
<th>S. Africa (Carnivorous, etc.)</th>
<th>N. Australia (Gibbsford)</th>
<th>Canada Subprovince</th>
<th>Labrador Subprovince</th>
<th>Abitibi Subprovince</th>
<th>Gold Subprovince</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scale of cyclicity</td>
<td>major cycle</td>
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<td>major cycle</td>
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<td></td>
<td>units, super cycle</td>
<td>major cycle</td>
<td>super cycle</td>
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</tbody>
</table>

Reference:
- Anneser, 1971
- Bliss & Stedolph, 1969
- Doogeal, 1965
- Hubert, 1976
- Ayres, 1977
- Blackburn and Groves, 1978
- Pyke, 1978
- Jensen, 1976
- this work
- Nichols, pers. comm., 1978
2) Super-cycles of the Abitibi sub-province appear to have evolved in a relatively short space of time (Nunes et al. 1978) late in the Archean.

3) Super-cycles appear on the basis of limited data (Pyke 1978; Jensen, 1978a, 1979; Dimroth and Rocheleau, 1979) to be the product of mafic volcanism from regionally extensive fractures followed by siliceous volcanism from areally restricted centers. In major cycles, the volcanism is on about the same scale as the mafic volcanism both emanating from areally restricted volcanic centers (Ayres, 1977; Thurston et al. 1978).

Wilson et al. (1974) based upon Canadian and Australian examples postulated a four fold division of Archean volcanic succession as follows:

<table>
<thead>
<tr>
<th>Unit Name</th>
<th>Main Rock Types</th>
<th>Intrusive Rocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper cyclic</td>
<td>basalt through rhyolites</td>
<td>small ultramafic plugs</td>
</tr>
<tr>
<td>Middle felsic</td>
<td>intermediate pyroclastics</td>
<td>Layered gabbro- pyroxenite-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>peridotite</td>
</tr>
<tr>
<td>Middle basic</td>
<td>tholeiitic basalts</td>
<td>Large gabbro sills</td>
</tr>
<tr>
<td></td>
<td>minor intermediate</td>
<td>Large ultramafic sills</td>
</tr>
<tr>
<td>Lower basic</td>
<td>Mg basalt, no amygdules</td>
<td></td>
</tr>
</tbody>
</table>

This schemes does not appear to adequately represent
the extent of ultramafic volcanism found in the South African Shield (Viljoen and Viljoen, 1969; Anhaeusser et al. 1969).

4.1.2 Cyclicity in the Confederation Lake Area

Cyclicity in the lithologies of each cycle in the Confederation Lake area is on the scale of Anhaeusser's (1971) major cycle with respect to all three cycles. Cyclicity on the minor-cycle scale occurs in Cycle II on the east limb of the regional synclinorium where cycles ranging from basaltic andesite to rhyolite occur over a stratigraphic interval of about 900 m.

Anhaeusser's (1971) type of mini-cycles are of course observed in thin bedded rhyolitic tuffs with cherty tops of 5 to 10 mm thick beds and in the form of greywacke-argillite couplets, particularly in member B2. Mini-cycle scale cyclicity is present in numerous tuff beds within Cycle II which have chert rich tops, and virtually all the bedded volcanic and sedimentary units such as the HST chert.

The three major cycles are defined by progression from a mafic base through to a felsic top. Cyclicity in a minor cycle scale is present as:

1) discrete Fe enrichment cycles ranging from basalt to andesite in formations A, E and K, respectively cycles I, II, and III.

2) 4 cycles in formation F which range from basaltic
andesite flows through to rhyolite tuffs.

3) In the upper part of formation H on the east limb fining upward subaqueous ash flows are repeated seven times.

4) In formation H on the west limb, two ignimbrite flow units are found (Thurston, 1979) representing repeated subaerial eruption.

5) Repeated eruption of thick felsic flows in formation M occur associated with the dome of Cycle III.

4.2 Facies Variation and Paleovolcanic Reconstruction

4.2.1 General Statements

Stratigraphic units have been defined on the basis of composition; facies variation is defined by textures, primary structures and structure sequences reflecting mechanism of extrusion or emplacement. Facies in mafic flows are based upon vesicularity, volcanic structure such as pillows, breccias, and layered aquagene tuffs or hyaloclastite, and thickness variations of the mafic unit as a whole. The presence of accidental fragments, the degree of alteration and the type of sedimentary structures in the hyaloclastites also serve to define facies. In intermediate flows, facies analysis is based upon: volcanic structures, and relationship to mafic flows. In an example from the Abitibi belt, Dimroth and Rocheleau (1979) observed that as intermediate flows are more viscous than basalts, they tend to be concentrated toward the volcanic center relative to less viscous, more widespread basalts.
In felsic flows, facies are defined by volcanic structures such as ribboning, brecciation, and position with respect to subvolcanic domes. In pyroclastic rocks, facies are defined by grain size, textures of fragments and matrix, and sedimentary textures and structures.

Pyroclastic eruptions have been classified by Walker (1973) by two parameters:

1) the dispersal index (D) i.e. the area enclosed by the 0.1 Tmax isopach where Tmax is the maximum thickness at source and

2) the fragmentation index (F) which is the weight percent of particles finer than 1 mm at 0.1 Tmax.

Using these parameters Walker subdivides pyroclastic deposits into four types:

1) Strombolian (small F and $D < 5 \text{ km}^2$)
2) sub-Plinian (small F and $D \approx 100 \text{ km}^2$)
3) Plinian (larger F than 2) $D > 500 \text{ km}^2$)
4) Surtseyan (large F)

Sparks et al. (1973) and Sparks and Wilson (1976) and Wilson (1976) describe the characteristic of the Plinian eruption type in terms of a larger F than 1 and 2 above and a larger D.

Mechanical analyses of consolidated Archean metavolcanic rocks and estimates of dispersal of products of single eruptions in Archean terrain are difficult to make and of uncertain reliability but it is still possible
to roughly classify the pyroclastic rocks of the Confederation Lake area. Ash flows are generally considered to be the result of the gravitational collapse of a gas-charged Plinian eruption column (Wilson and Sparks, 1976) containing lithic fragments and the products of vesiculating felsic magma-shards, pumice and crystals (Sparks, 1978).

Calderas are commonly associated with voluminous eruptions of ash and pumice. Therefore the following review of caldera associated volcanism is provided; summarized from Smith and Bailey (1968) and Williams (1941).

The term caldera is defined by Williams (1941) as "large volcanic depression, more or less cirquelike in form". A portion of Williams' classification of calderas with modifications by Smith and Bailey is as follows:

Type 2 calderas are associated with differentiated volcanoes accompanied by voluminous eruptions of pumice and ash, and have been termed Krakatoan by Williams.

Williams and Mc Birney (1979, p.207) have further subdivided Williams (1941) classification of calderas with the Valles type representing "foundering ... along arcuate fractures independent of pre-existing volcanoes as a consequence of and simultaneously with a discharge of colossal volumes of siliceous pumice...".

Stages of caldera activity are described by Smith and
Bailey (1968) with respect to structural, volcanic, and plutonic events, divided into seven stages (Table 4-2).

4.3 Reconstruction of Facies

In order to visualize facies and thickness relations within the Confederation Lake area a pre-folding reconstruction (Fig. 4-1) has been made. As a part of the volcano extends out of the area and into the Birch Lake area this has been included in order to show the facies relations more clearly.

4.3.1 Cycle I Confederation Lake Area

Formation A is mainly pillowed, poorly vesiculated and as a whole thickens to the north in the area of north Corless Township. However, the presence of andesitic flows south of the Bear Lake fault in the upper part of formation A, and the southward thickening of formation B, all suggest a source area for Cycle I volcanism to the south in the area now occupied by granitic intrusions (Fig. 2-1). (see summary Table 4-3).

On the east limb of the regional synclinorium, Cycle I is exposed in the core of the Leg Lake anticlinorium east of Uchi Lake (Fig. 4-2) with pillowed mafic flows with no hyaloclastic debris, and numerous massive and porphyritic flows with pillowed tops and minor aquagene tuff at the top (Dimroth, 1975, flow type f) with interbeds of finely laminated intermediate and felsic tuff. The presence of tuff interbeds between relatively thin flows on the east
Figure 4-1: Reconstructed Pre-folding Cross-section Showing Relationship of Cycles.

Birch Lake Section Largely Didagrammatic. (Lies to the north, outside the area)
<table>
<thead>
<tr>
<th>Stage</th>
<th>Structural Events</th>
<th>Volcanic Events</th>
<th>Sedimentary Events</th>
<th>Plutonic Events</th>
<th>Duration in the Valles Caldera</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Regional tumescence and propagation of ring and radial fractures with possible apical graben subsidence.</td>
<td>Eruptions due to leakage along radial or ring fractures.</td>
<td>Fracture of the volcanic highland.</td>
<td>Compositional zonation in magma chambers. Increasing magma pressure. Minor intrusion</td>
<td>$&lt; 4 \times 10^5$ yrs.</td>
</tr>
<tr>
<td>II</td>
<td>--------</td>
<td>Major ash-flow eruption. 50-500 mi.³</td>
<td>--------</td>
<td>Degassing and skimming of zoned top of chamber.</td>
<td>$&lt; 10$ yrs. est.</td>
</tr>
<tr>
<td>III</td>
<td>Caldera collapse.</td>
<td>Overlap with stage II in some calderas.</td>
<td>Avalanches and slides from caldera walls.</td>
<td>Disequilibrium.</td>
<td>$&lt; 10$ yrs est.</td>
</tr>
<tr>
<td>IV</td>
<td>--------</td>
<td>Minor pyroclastic eruptions and lavas on caldera floor is some calderas.</td>
<td>Caldera fill; talus, avalanches, slides, fans, lake deposits.</td>
<td>Consolidation of magma caught in ring fractures; residual ring dikes. Progressive recovery of equilibrium. Beginning of minor ring intrusion.</td>
<td>$10^5$ yrs.</td>
</tr>
<tr>
<td>V</td>
<td>Resurgent doming</td>
<td>Possible ring-fracture volcanism and/or eruption or intrusion in dome fractures</td>
<td>Caldera fill continues; lake overflows and caldera is breadth.</td>
<td>Rise of central pluton and perhaps a ring-intrusion stage.</td>
<td>$10^5$ yrs.</td>
</tr>
<tr>
<td>VI</td>
<td>Possible regional tumescence and reopening of ring fractures.</td>
<td>Ring-fracture volcanism. Possible stage II eruption of next cycle.</td>
<td>Caldera fill continues, late lake sediment. Erosion of fill. Fill &gt; erosion.</td>
<td>Final emplacement and differentiation of ring intrusions. Possible stoping by central pluton.</td>
<td>$8 \times 10^5$ yrs; $10^5$ yrs.</td>
</tr>
<tr>
<td>VII</td>
<td>--------</td>
<td>Terminal fumarolic and hot spring activity (hydrothermal alteration)</td>
<td>Erosion; Erosion &gt; fill.</td>
<td>Crystallization of major plutons. Possibly a major oro forming stage.</td>
<td>$&gt; 10^5$ yrs.</td>
</tr>
<tr>
<td>CYCLE</td>
<td>FORMATION</td>
<td>THICKNESS (m)</td>
<td>DOMINANT ROCK TYPE</td>
<td>MINOR ROCK TYPE</td>
<td>DEPOSITIONAL ENVIRONMENT</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
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<td>----------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>I A</td>
<td>west limb of fold</td>
<td>966-2496</td>
<td>mafic flows, massive flows, amphibole phric flows</td>
<td>pillowed mafic flows, intermediate tuff, lapilli tuff, feldspar phric mafic flows</td>
<td>subaqueous flows. Unit thins to S. Lower portion of unit removed by granitic intrusions</td>
</tr>
<tr>
<td>B</td>
<td>west limb of fold</td>
<td>0-1487</td>
<td>greywacke, argillite</td>
<td>felsitic tuff</td>
<td>slightly coarser to the S. On the east limb, coarsens south to the conglomeratic facies of the English Riv. subprovince.</td>
</tr>
<tr>
<td>C</td>
<td>305-322</td>
<td>felsic lapilli tuff</td>
<td>felsic tuff</td>
<td>minor thickness and lateral extent (2km.) due to incomplete preservation. Suggestive of ash flow eruption in shallow subaqueous or subaerial environment. Proximal equivalent of metasediments listed above.</td>
<td>spherulites, flattened fiamme, abundant relic flattened shards:</td>
</tr>
<tr>
<td>B</td>
<td>925-2776</td>
<td>intermediate lapilli tuff</td>
<td>felsic tuff</td>
<td>coarsens to the south and east.Varies from unbedded pumiceous tuff breccia to parallel laminated tuffs fining upward and northward. Great lateral extent vs thickness (16km vs 1800m) suggests downslope movement of breccia. Monolithic close to source, heterolithic downslope. Transition from vent facies in S. to distal facies in N. marked by increase in rounding &amp; proportion of pumice, number of exotic fragments, and decrease in bedding thickness.</td>
<td>abundant pumice, heterolithic, fining upward thickbedded to massive in proximal environment</td>
</tr>
<tr>
<td>D</td>
<td>Narrow Lake</td>
<td>0-61</td>
<td>marble</td>
<td>chert &amp; pyrite</td>
<td>subaqueous, shelf environment?</td>
</tr>
</tbody>
</table>
4-2 General geology of Cycle I. Square pattern underlain by Cycle I, contacts after Fig. 2-1.
limb only and lack of hyaloclastic debris suggests that the east limb is relatively more distal from a source than the west limb in that hyaloclastic debris is usually relatively close to the volcano (cf. Dimroth et al. 1977) and the lack of tuff interbeds in formation A on the west limb and greater thickness of formation A there suggests that the west limb is more proximal.

Within formation B on the west limb, thin-bedded crystal lithic airfall tuffs of intermediate composition assumed to be relatively distal, occur interbedded with coarse conglomeratic pumiceous ash flow deposits assumed to be relatively proximal based on thickness of the unit on this limb relative to the east limb. This intermixing of styles and products of eruption and proximal and distal facies implies more than one source area. Most units are only a few tens of metres thick, therefore the source area is relatively distant. The lack of welding, and abundant pumice, suggest a relatively shallow subaqueous eruptive environment for the air fall eruptions. The depositional environment is relatively deep water given the interfingering of abyssal wackes and pyroclastic rocks.

4.3.1.2 Eruption type and Environment of Deposition

The following observations with respect to Cycle I bear on the eruption type and environment of deposition:

Formation A

1) Lack of vesiculation in the basalt flows
2) large pillows
3) lack of abundant hyaloclastic debris
4) thin widespread nature of the unit
Pyroclastic units, formations B and C
1) conglomeratic intermediate ash flow units with abundant pumice
2) thin-bedded fine-grained rhyolitic tuffs
3) mafic flows and abundant dikes.

Eruption of the mafic flows represented quiet effusions from a shield volcano based upon the reconstructed shape of the volcano (fig. 4-1) and the lack of alternating flow-pyroclastic sequences. Conventionally, vesicularity is taken to indicate a relatively shallow depth of submarine extrusion (Jones, 1969). However data from Project Famous (Bryan and Moore, 1977) indicates that vesicularity in basaltic rocks is also a function of the content of K2O and SiO2. Therefore, although the Cycle I mafic flows are not very vesiculated, a relatively shallow water depth for the volcano of less than 500 m is postulated based on the presence of the overlying pyroclastic rocks (cf. McBirney, 1963; McBirney and Murase, 1971; Sparks, 1978).

4.3.1.3 Large Scale Reconstruction

The ash flow deposits south of Narrow Lake may represent continued eruption from a poorly focused edifice. This is based upon the rather uniform thickness
and great lateral extent of formation B.

Preserved evidence of a stratovolcano in Archean terrains usually consists of a thick proximal mafic section with interdigitated pyroclastic rocks. Thickening of the mafic flow accumulation with pyroclastic units is not as apparent in shield volcanoes. The lack of evidence for a thick central edifice, that is a stratovolcano, could represent erosion of the thicker section, or it may not be present in the exposed section. Pyroclastic activity from a shield volcano during the early stages of volcanic activity is known from the Valles caldera (Smith and Bailey, 1968) where relatively widespread ash flows are related to an early tumescent stage (Table 4-1).

Depth below water of eruption of member B1 must have been less than 500 m, the maximum depth for explosive activity (cf. Mc Birney, 1963, Mc Birney and Murase, 1971; Sparks, 1978).

4.3.2 Cycle II Confederation Lakes Area

4.3.2.1 Reconstruction of Facies

On the west limb of the regional synclinorium formation E consists of pillowed basaltic (Chapter 5) flows with intercalated andesites, both of which are moderately vesicular (25-30 percent). There are many gabbroic sills intercalated with the flows. Cycle II as a whole is thickest at Narrow Lake. On the east limb of the fold formation E is also pillowed, the extent of andesitic
volcanism is reduced (Johns, 1976) vesiculatity is in the range of 10 to 15 percent. (Fig. 4-3, Table 4-4).

Above formation E is a thick accumulation of intermediate subaqueous to subaerial pyroclastic flows of formation G. On the west limb, tuff breccia and lapilli tuff composed of pumiceous essential fragments is in beds about 3 m thick overlain by 5 to 10 cm thick bedded massive tuff units. Coarse beds appear to fine upward. Several occurrences of sandy pumice tuff and pumice tuff (Yamada, 1973) are on the west limb, generally fining upward into thin-bedded intermediate tuffs. On the east limb, the subaqueous ash-flow model of Yamada (1973) is more fully documented with seven fining upwards units 150 to 300 m thick which also fine southward away from an assumed volcanic center. Pumice and shards of this phase of activity are rounded to angular without re-entrant angles, perlites, or in situ brecciation, and appear to be the product of magmatic explosive activity (cf. Dimroth, 1977; Sparks, 1978).

The presence of pumiceous tuff breccia overlain by finely laminated tuff in the Narrow Lake area is analogous to a telescoped A-E turbidite sequence (Bouma, 1962). This documents a relatively proximal environment (cf. Fisher, 1979). Conversely the gradually fining upward nature of the subaqueous ash-flows of the east limb represent a more distal environment (cf. Yamada, 1973; Fisher, 1979).
4-3 General geology of Cycle II. Dot pattern underlain by Cycle II, contacts after Fig. 2-1.
<table>
<thead>
<tr>
<th>CYCLE</th>
<th>FORMATION</th>
<th>THICKNESS (m)</th>
<th>DOMINANT ROCK TYPE</th>
<th>MINOR ROCK TYPE</th>
<th>DEPOSITIONAL ENVIRONMENT</th>
<th>ENVIRONMENTAL INDICATORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>E west limb of fold</td>
<td>2100-3623</td>
<td>mafic flows, intermediate flows, felsic tuff, mainly:pillowed.</td>
<td>intermediate and felsic tuff, cherty interflow units, oxide facies iron formation</td>
<td>subaqueous flows, unit thins to S and E; overlies exhalative units of cycle I, represents migration northward of volcanic center. Fumarolic epidotization more intense where interflow sediments more prominent in section. Proximal: variolites more common, amygdules more abundant. Interflow sediments common. Distal: Fewer andesitic units interflow sediments, variolites, smaller pillows, fewer amygdules</td>
<td>pillow, amygdules, variolites, andesitic flows</td>
</tr>
<tr>
<td>G</td>
<td>distal facies west limb of fold</td>
<td>0-1106</td>
<td>intermediate lapilli tuff, tuff</td>
<td>argillite, chert, wacke</td>
<td>grades to south into finer more thin bedded, rounded pumiceous clasts, argillite interbeds</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>proximal facies Confederation Lake</td>
<td>483-2816</td>
<td>intermediate lapilli tuff</td>
<td>tuff breccia &amp; tuff</td>
<td>proximal (vent) facies: subaqueous pumice flows rare interbedded pillow ed flows, all on the flanks of a stratovolcano</td>
<td>tuff breccia units reverse and normally graded fining upwards into thin bedded tuff, abundant pumice. Monolithic fragment population similar composition of coarse &amp; fine fractions, presence of sulphide clasts.</td>
</tr>
<tr>
<td>H</td>
<td>proximal facies Woman Lake</td>
<td>0-724</td>
<td>felsic lapilli tuff</td>
<td>tuff, porphyritic flows</td>
<td>subaerial intensely welded fining upwards ignimbrite sheets. To the N &amp; S it passes into unwelded units assumed to be subaqueous.</td>
<td>eutaxitic texture; fiamme, intensely welded with replacement of fiamme by silica, snowflake texture</td>
</tr>
<tr>
<td>CYCLE</td>
<td>FORMATION</td>
<td>THICKNESS (m)</td>
<td>DOMINANT ROCK TYPE</td>
<td>MINOR ROCK TYPE</td>
<td>DEPOSITIONAL ENVIRONMENT</td>
<td>ENVIRONMENTAL INDICATORS</td>
</tr>
<tr>
<td>-------</td>
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<td>--------------------------</td>
</tr>
<tr>
<td>H</td>
<td>transported facies</td>
<td>640-1086</td>
<td>felsic lapilli tuff</td>
<td>tuff, tuff breccia</td>
<td>transported subaqueous equivalent of the above unit. Subaqueous ash flows with normal and reverse graded units. Four fining upwards units present 30-150 m thick</td>
<td>pumiceous fining upward and distally reverse and normal grading, sulphide clasts</td>
</tr>
<tr>
<td></td>
<td>Lost Bay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Confederation Lake</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II J</td>
<td>Woman Lake</td>
<td>91-152</td>
<td>marble</td>
<td>chert, oxide facies iron formation</td>
<td>shallow submarine stromatolitic marble overlain by chert. Relatively proximal exhalative origin on west limb where marble occurs. Distal iron formation on east limb.</td>
<td>stromatolites in carbonate</td>
</tr>
<tr>
<td>II F</td>
<td>Lost Bay, Confederation Lake</td>
<td>122-183 each mafic flow</td>
<td>felsic tuff, hyaloclastite</td>
<td>proximal subaqueous flows thin to north and south of Lost Bay product of satellite cone of main stratovolcano. Total of 7 units, each about 60 percent mafic flows, remainder intermediate to felsic pyroclastics. Often strongly altered. Capped by 1-2 m. exhalative units. Overlain by the transported felsic pyroclastic rocks.</td>
<td>abundant hyaloclastic debris and pillow flows. Beds of air fall tuff tuff breccia. Exhalative units:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Formation F on the east limb is intercalated with and overlays formation E, and is thin 10 m pillowed mafic to intermediate flows with 20 to 30 percent vesicles and abundant interpillow chert overlain by 1 mm to 1 m thick beds of air-fall felsic tuff. The tuff is well sorted with occasional lithic fragments about 2 mm giving way upward to exclusively ash size particles at the top of each fining upward bed.

An intensely welded rhyolite ignimbrite overlays the intermediate to felsic subaqueous ignimbrites on the west limb (Savory, 1976; Thurston, 1979).

A volcanic center is postulated to have existed in the area of Narrow Lake based upon the increased thickness of formation E, the greater abundance of gabbro sills there, and the apparent restriction of andesite flows to the area of a volcanic center (Dimroth and Rocheleau, 1979). The proximal subaqueous ash flows analogous to A-E turbidites of Narrow Lake succeeded to the south by more distal facies based upon Yamada's (1973) model also supports the existence of a center in that area.

The minor cycles on the east limb, given the chemical dissimilarity of Cycle II basalts (Chapter 5), the thin bedded, fine grained character of the tuffs, represents a possible satellitic source, or different conditions of transport or volcanism at the same source.

4.3.2.2 Eruption Type and Environment of Deposition
Abundant pillows in the basalts of Cycle II affirm the subaqueous nature of its lower part. Water depth would have been relatively shallow, based upon the presence of 20 to 30 percent vesicles in the pillows (cf. Jones, 1969). The overlying intermediate pyroclastic rocks suggest a water depth of less than 500 m. (cf. Mc Birney, 1963; Mc Birney and Murase, 1971; Sparks, 1978). They are also suggestive of a relatively proximal shallow water environment solely by analogy with other subaqueous ash flows (Yamada, 1973; Fiske, 1963).

The welded ash-flow capping Cycle II on the west limb has intensely welded shards, silica replacement of fiamme, vapor phase recrystallization of K feldspar to snowflake texture (cf. Torske, 1975) which are indicative of a subaerial deposition. Welding is, of course, possible in the subaqueous environment (Francis and Howells, 1973), but the intensity of recrystallization of the pumiceous lapilli and the degree of welding of the shards suggest that the unit was definitely deposited subaerially (pers. comm. M. Howells, 1977).

A stromatolitic carbonate overlies the welded rhyolite tuff indicative of deposition in the photic zone of a marine environment (Playford and Cockbain, 1976). The available information suggests that maximum depth for growth of the organisms is 100 m in the clearest ocean water and 50 m in average ocean water (Brock, 1976).
Cycle II volcanic activity commenced with quiet effusions of non-viscous magma from a shield volcano. Later pyroclastic activity is classified by Walker's (1973) parameters as follows:

Coarse fragments, blocks, bombs and lapilli make up a substantial part of the base of each ash flow therefore, qualitatively, F is relatively small. Dispersal is on the order of 500 km². Dispersal was calculated by assuming a depth of infolding derived from Thurston and Breaks (1978), and Gupta et al. (appendix G) of about 4 km and the lateral extent for cycle II from Thurston (1977), assuming that volcanic rocks did not overlie adjacent granitic areas. Therefore, it is concluded that the ash flows of the middle part of Cycle II in the vicinity of Narrow Lake on the west limb and Lost Bay on the east limb are the product of Plinian eruptive activity (cf. Sparks et al. 1973). The fine vitric crystal tuffs capping each of the minor cycles in formation F are the product of Plinian ash fall activity relatively distal to the volcanic center as they are fine grained, and finely bedded (cf. Fisher, 1979).

Distribution of ash-flows suggests that slopes were less than 10° as ash flows do not usually deposit upon greater slopes at least in the subaerial environment (Bond and Sparks, 1976). The thinly laminated tuffscapping many of the coarse units of the ash-flows are deposited from the turbulent dust cloud observed above many ash flows (Bond
and Sparks, 1976; Sparks et al. 1973; Fisher, 1979).

In the model presented by Sparks et al. (1973) Plinian activity is commonly followed by an effusive phase. Scattered units mapped as quartz and feldspar phryic felsic flows on the shores of Woman Lake and several basaltic flows between Woman and Narrow Lakes represent the effusive phase of activity.

The welded ash-flows forming the upper part of Cycle II on the west limb (Savory, 1976; Thurston 1978) have prominent reverse grading of pumiceous clasts, great lateral extent and large degree of fragmentation (F=50).
Therefore it may represent the renewal of sub-plinian activity (cf. Sparks; et al. 1973).

4.3.2.3 Large Scale Reconstruction

The alternation of massive and pillowed flows in Narrow Lake which form a rapid thickening of the section possibly represents the basaltic part of a shield volcano.
Continued eruption of the intermediate to felsic part of Cycle II represents large volumes of predominantly ash and pumice suggestive of the early stages (Table 4-1) of caldera activity.

The overall sequence of lithologies in formation G of Cycle II, pumice blocks in unwelded ignimbrites, grading of fragment size laterally and vertically, presence of reverse grading, all suggest that the Plinian phase (Sparks et al. 1973) was of the Krakatoan type (Williams, 1941). In this
type of caldera, the collapse of the volcanic edifice is the result of the collapse of the roof of the magma chamber. The caldera collapse is a relatively final event—there is no resurgence involving caldera filling, doming, etc. such as described by Smith and Bailey (1968) for the Valles type caldera of the resurgent type, in that preserved caldera-fill sequences are not found in the area examined.

4.3.2 Cycle III Confederation Lake Area

4.3.3.1 Reconstruction of Facies

Formation K is predominantly pillow flows with local lenses of broken pillow breccia, layered and massive aquagene tuff. The lack of massive flows is an indication of relatively rapid rate of extrusion or relatively distal facies (Dewit and Stern, 1978). An opposing view is offered by Lonsdale, 1977). Thickening of the unit northward on both limbs of the fold suggests that the eruptive center is between Swain Lake, north of the thesis area, and Confederation Lake. The greatest thickness of intermediate to felsic pyroclastic rocks is in the vicinity of Lake "X" (Fig. 4-4, 2-1). As well, a substantial part of the section in the thesis area is composed of tuff breccia with epidotized rounded to angular pumiceous bombs in a spherulitic ashy matrix, suggesting proximity to an eruptive center and retention of heat necessary to form spherulites (cf. Lofgren, 1971, 1971a).
4-4 General geology of cycle III. Square pattern underlain by cycle III; contacts after Fig. 2-1.
The fault bounded block in which most of the products of Cycle III felsic volcanism are found is best termed a volcanic sector graben after (Williams, 1941, p.243).

This is based upon the fault-bounded nature of the block (fig. 2-1), the differing structural trends within it (fig. 2-1), and different fold pattern and lineations within the feature (Appendix G; Asbury, 1975) relative to the area outside the block. A synvolcanic age for the block is suggested by the fact that most units of formation M are restricted to the block and the different structural pattern within the block (Appendix G) requires subsidence on the boundary faults, volcanism confining most formation M units to the block, then regional folding.

To the south of the thesis area, but within the fault bounded sector graben in the area of Fredart Lake, the presence of several domical bodies of quartz feldspar porphyry which grade into welded lapilli tuff and felsic flows are suggested by Colvine (A.C. Colvine, pers. comm. 1979) to represent several local centers of felsic volcanism along the sector graben. Within the sector graben in the thesis area, formation M is characterized by coarseness and pumice rich nature of the pyroclastic ejecta, lack of bedding, and presence of fragments with re-entrant angles (cf. Dimroth, 1977) suggesting magmatic explosive activity and local dome collapse origin for the formation (cf. Parsons, 1969). The larger proportion of
flows to pyroclastic rocks also suggests proximity to a volcanic center.

4.3.3.2 Eruption Type and Environment of Deposition

Vesicularity of the pillowed mafic flows of formation K approaches 20 percent. Vesicularity alone would indicate water depth to be only a few hundred metres but the presence of zonation of vesicularity within individual pillows indicates a depth of approximately 350 m (cf. Jones, 1969).

Formation L is poorly welded. Given the fact that formation K pillow lavas are clearly submarine and the magmatic explosion origin of the overlying felsic pyroclastic rocks, a shallow submarine origin is proposed for formation K in spite of the observed eutaxitic textures (Table 4-5), as no greater development of welding or recrystallization is found.

This eruptive event was succeeded by the foundering of the sector graben. Later eruptive activity within the graben consisted of the development of a group of subvolcanic endogenous domes including the one below the South Bay Mines orebody at Confederation Lake (Pollock et al. 1972) and several to the south (pers. comm. A.C. Colvine, 1979).

Local magmatic explosions resulted in the production of breccia units of restricted lateral extent and more extensive rhyolitic flows within formation M.
<table>
<thead>
<tr>
<th>CYCLE</th>
<th>FORMATION</th>
<th>THICKNESS (m)</th>
<th>DOMINANT ROCK TYPE</th>
<th>MINOR ROCK TYPE</th>
<th>FACTES ANALYSIS AND DEFOSITONAL ENVIRONMENT</th>
<th>ENVIRONMENTAL INDICATORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>III K</td>
<td>Confederation Lake 'X'</td>
<td>1030-1667</td>
<td>mafic to intermediate pillow flow</td>
<td>hyaloclastic debris, massive &amp; variolitic flows</td>
<td>proximal facies subaqueous flows. Thickest section at Washagomi Lake. Thins to S. Overlies shield volcano of cycle II, separated by exhalative carbonate from cycle II. shield volcano.</td>
<td>amygdules, hyaloclastite units, pillows, variolites, with spherulitic crystallization features, fumarolic alteration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>724-2574</td>
<td>intermediate tuff &amp; lapilli tuff</td>
<td>intermediate flows, tuff breccia</td>
<td>proximal shallow water subaqueous unit. Proximal aspect indicated by presence of flows, dikes, coarseness of fragments, thick bedding in coarse pyroclastics. Presence of spherulites and textures indicating partial welding suggest minimal transport. Lack of textures of intense welding suggest subaqueous welding rather than subaerial. Violent plinian eruption brings about initial collapse of sector graben.</td>
<td>relict glass, spherulites, fumarolic alteration of bombs, thick bedding, partial welding.</td>
</tr>
<tr>
<td>N</td>
<td>(Sopuck, 1977)</td>
<td>2200</td>
<td>felsic lapilli tuff &amp; tuff breccia</td>
<td>felsic flows, tuff, intermediate flows</td>
<td>Proximal vent breccias derived from phreato- explosive activity in a fault bounded mont or sector graben. Result of resurgent caldera activity. Subaqueous environment.</td>
<td>fragments with re-entrant angles, abundant pumice, spherulites, partial welding, volcanogenic massive sulphide bodies.</td>
</tr>
<tr>
<td></td>
<td>porphyry dome</td>
<td>0-1828</td>
<td>quartz-feldspar porphyry</td>
<td>argillite overlie dome locally</td>
<td>endogenous dome of rhyolitic composition</td>
<td>phenocryst free margins, flow-aligned marginal zone, grades into partially welded upper zone (Asbury, 1975) presence of ghost breccia</td>
</tr>
</tbody>
</table>
Cycle III eruptive activity involves resurgence of volcanic activity after Plinian or sub-Plinian activity. It is thus more closely allied to the resurgent type caldera exemplified by the Valles caldera (Smith and Bailey, 1968), rather than the Krakatoan type.

Following Smith and Bailey's (1968) analysis of stage by stage development of resurgent cauldrons the following analogies can be drawn as (shown in Table 4-6).

4.4 Time Constraints on Volcanism

Data on the periodicity of volcanism in general and cyclical volcanism in particular is scarce. Smith and Bailey (1968) have reviewed the chronology of volcanic events during the various stages of the caldera cycle model they proposed, indicating as shown in Table 4-2 that the whole cycle from stage I to VII took less than $1.4 \times 10^6$ years. Smith (1979) reviewed the problem of periodicity in detail using data from many major ash flow eruptions. In his model, a large high level magma chamber gradually differentiates developing a high Si, volatile-rich most fractionated upper portion, a "dominant volume" of relatively constant composition and a lower portion which forms a zone in which the silicic magma is mixed with underlying more primitive perhaps basaltic magma which provides, by new injections of basalt, a continuing source of heat for the system. Ash flow eruptions display pronounced chemical and mineralogical zonation (Hildreth,
<table>
<thead>
<tr>
<th>Stage No.</th>
<th>Structural Event</th>
<th>Volcanic Event (general case)</th>
<th>Volcanic Event Uchi-Confederation area</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Regional tumesence and propagation of ring and radial fractures with possible apical graben subsidence</td>
<td>eruptions due to leakage along fractures</td>
<td>not recognized</td>
</tr>
<tr>
<td>II</td>
<td>---</td>
<td>ash-flow eruption</td>
<td>cycle III intermediate-felsic pyroclastic rocks</td>
</tr>
<tr>
<td>III</td>
<td>caldera collapse</td>
<td>overlap with stage II</td>
<td>intrusion of granodiorite sills etc. along fractures</td>
</tr>
<tr>
<td>IV</td>
<td>---</td>
<td>minor pyroclastic eruptions on caldera floor</td>
<td>not recognized</td>
</tr>
<tr>
<td>V</td>
<td>Resurgent doming</td>
<td>eruptions associated with domes</td>
<td>breccias and flows associated with quartz-feldspar porphyry dome at South Bay</td>
</tr>
<tr>
<td>VI</td>
<td>Regional tumesence &amp; re-opening of ring fractures</td>
<td>ring fracture volcanism</td>
<td>ash flow material filling graben south of Confederation Lake</td>
</tr>
<tr>
<td>VII</td>
<td>---</td>
<td>fumarolic and hot spring(activity</td>
<td>formation of South Bay Mine orebody</td>
</tr>
</tbody>
</table>
1979) with small volume systems erupting fragments of the underlying mafic magma (Sparks et al., 1977). The volume of erupted ash-flows provided Smith a means of estimating the volume of the original magma chamber. The process of crystal fractionation as a differentiation mechanism takes time, given the high viscosity of siliceous magmas and variables such as water content, phenocrysts size, etc. taken into account by Rose et al. (1979) in order to estimate the time taken for phenocrysts to form and sink in the magma chamber; permitting an estimate for the residence time of the magma chamber in the upper crust of in excess of $10^4$ years for the Los Chocoyos ash flow in Guatemala. Smith's (1979) study, utilizing data of this sort and geochronologic control, suggested that periodicity is a direct function of magma chamber size (Fig. 4-5).

4.4.1 Confederation Lakes Area

In the Confederation Lakes area a minimum volume estimate for Cycle II ash-flow activity, both submarine and subaerial is approximately 2600 km$^3$ making no allowance for deformation, past or present porosity corrections, or erosion. The products of cycle II magmatism are assumed to be confined to the thesis area and the Birch Lake area (Thurston, 1977); the depth extent is about 4 km based on reasoning presented in Thurston and Breaks (1978) and Gupta et al. (Appendix I), and average thickness is derived from fig. 2-1. Using Smith's (1979) approximations, the length
Figure 4-5: Relationship of volume of magma and volcanic periodicity after Smith, 1979
of time represented by Cycle II felsic volcanism is on the order of between $10^6$ and $10^7$ years. U/Pb age determination on zircons of Cycle I, II and III rhyolites (Appendix B) gives a time interval of about 167 Ma for accumulation of Cycle II and 55 Ma for accumulation of Cycle III volcanic rocks. In estimating the volume of magmatism of each cycle, it was assumed that the eruptive products spread no further than the two limbs of the major fold. Therefore much greater volumes undoubtedly existed. Using Smith's (1979) approximations it is possible that Cycle II magmatism represents production from a large magma chamber over a protracted time period. Cycle III involves an approximate minimum volume of 500 km$^3$ of felsic volcanic rocks which does not match as well with Smith's (1979) model, but the uncertainties of volume estimation are greater.

Ludden (1977) from volume data and geochronology estimates the production rate of Piton de la Fournaise at 3.9 to 6.3 m$^3$/sec, a much more rapid rate of volcanism than suggested by the Smith (1979) model. Elston et al. (1973) document the existence of three volcanic cycles ranging from andesite to rhyolite terminated by basaltic andesite which took place over a time interval of 18 m.y., again a rapid rate of volcanism.

Given the similarity of Archean and younger volcanic products, the processes giving rise to them must be
basically similar. The existence of extremely fractionated rhyolites with high LIL element abundances in cycle III (Chapter 5) suggests that compositional gradients existed in Archean magma chambers analogous those described by Hildreth (1979) for younger rocks. This implies the existence of felsic magma chambers over long periods of time in the Archean, suggesting that Smith's (1979) estimates may have some validity in an Archean context.
CHAPTER 5

Chemical Composition of the Rocks

5.1 General Statement

Major elements are defined as those present in rocks in amounts of greater than 0.1 percent; minor elements are those present in amounts ranging from .05 to 0.1 percent and trace elements are those present in lesser amounts. Trace and minor element variations have recently been used to attempt to understand differentiation processes in igneous systems. Central to the understanding of trace element distribution is the partition coefficient concept (Gast, 1968) expressed as:

$$K_d = \frac{C_m}{C_o}$$

$K_d$ = partition coefficient

$C_m$ = concentration of trace element in mineral

$C_o$ = concentration of trace element in liquid

Also useful and important are the mathematical modelling of igneous processes by Neuman et al. (1954), Shaw (1970) and Arth (1976). Important also is the fact that given trace elements substitute in particular structural sites of given minerals primarily as a function of valence and ionic size (Jensen, 1973). A compilation by Frey et al. (1974) indicates which elements readily partition (large $K_d$) into which important rock forming minerals (Table 5-1). Variations in elements such as Ni for example will usually indicate whether olivine is
<table>
<thead>
<tr>
<th>Indicators of Plagioclase Removal</th>
<th>Indicators of Clinopyroxene Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Decrease of:</strong></td>
<td><strong>Decrease of:</strong></td>
</tr>
<tr>
<td>Sm/Eu</td>
<td>Sc</td>
</tr>
<tr>
<td>Sm</td>
<td>V</td>
</tr>
<tr>
<td>Eu</td>
<td></td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Indicators of Olivine and Chromite Removal</th>
<th>Indicators of Degree of Crystallization</th>
</tr>
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<tbody>
<tr>
<td><strong>Decrease of:</strong></td>
<td><strong>Increase of:</strong></td>
</tr>
<tr>
<td>Cr</td>
<td>Y</td>
</tr>
<tr>
<td>Co</td>
<td>Zr</td>
</tr>
<tr>
<td>Ni</td>
<td>La</td>
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<td></td>
<td>Ce</td>
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<tr>
<td></td>
<td>Lu</td>
</tr>
<tr>
<td></td>
<td>Hf</td>
</tr>
</tbody>
</table>

(after Frey et al. 1974)
fractionating or has been left behind in a residue during partial melting. The so-called incompatible elements are those elements which, because of their ionic radii and valency, do not readily substitute in major minerals of the mantle, or of the lower crust, and are strongly enriched in the liquid relative to co-existing major minerals (Frey et al. 1978). Therefore elements such as Zr, Y, Nb, Hf, and the rare earth elements (REE) serve as indices of the degree of fractionation and partial melting and other petrogenetic mechanisms.

The REE form a special class of incompatible elements as all but Eu always have a valence of +3, and, as Z increases from 57 to 71, the ionic radius decreases. Therefore, these elements substitute into mineral structures mainly as a function of their size and provide valuable insight into events in the magma chamber (Fig. 5-1). For example, if garnet is in the residue of a partial melting event, heavy REE abundances will be low in any resulting melt. In terms of fractionation, if clinopyroxene is fractionating it will have the effect of preferentially raising the abundance of the light REE in any sample of the magma at that point.

Analytical results are listed in separate tables for the mafic and intermediate to felsic portion of each cycle (Appendix E). Analytical methods and precision are discussed in Appendix D. Tabulated with the analytical
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Analytical results are listed in separate tables for the mafic and intermediate to felsic portion of each cycle (Appendix E). Analytical methods and precision are discussed in Appendix D. Tabulated with the analytical
5-1 Kd of various minerals for the rare earths. Abbreviations: Bio = biotite; Hyp = hypersthene; Cpx = clino-
pyroxene; Hbl = hornblende; Ap = apatite; Gpt = garnet; Zr = zircon; after Hanson, 1978.
data are CIPW norms calculated by the method of Johannsen (1939).

The validity of the following discussion is directly dependent upon the isochemical nature of possible premetamorphic halmrolytic and diagenetic reactions and the iso-chemical nature of the greenschist facies metamorphism (Thurston and Breaks, 1978). Secondary alteration processes do not appreciably affect the so-called immobile elements: Ti, Zr, Y, Nb, Ce, Ga and Sc (Frey et al. 1968; Herrmann et al. 1974; Ferrara, 1976). These processes do affect the major elements and mobile trace elements such as Rb, Sr, P, Th, U (Floyd and Winchester, 1978) to varying degrees however (Coish, 1977; Andrews, 1977).

In order to combat the problems of major and trace element mobility two approaches have been utilized. Firstly in an effort to avoid small areas of alteration, 235 whole and partial analyses have been compiled from all previous workers in the area (Goodwin, 1967; Lalor, 1970; Birnie, 1972; Pryslak, personal communication, 1975; Johns, 1976; and Thurston, 1978). An additional 122 rocks have been analysed for this study. All have been plotted on APM diagrams (A=Na2O+K2O; F=FeO*; M=MgO all in wt. percent) and the modified APM projection of Jensen (1976) (A=Al2O3 F=FeO* + TiO2 M=MgO all in cation percent) to ascertain the presence of igneous trends. Secondly a suite of 73 of the above 122 samples were analysed for a number of trace
elements and the rare earth elements (REE) which are relatively resistant to alteration (Condie, 1976; Sun and Nesbitt, 1978; Condie et al. 1977). In the following section, major element trends are, wherever possible, discussed in conjunction with data for the immobile elements.

5.2. Metasomatism

Differentiation of basaltic rocks results in increasing FeO* (total iron expressed as FeO) content of olivine and pyroxene and a concomitant increase in the ratio FeO*/FeO* + MgO (Carmichael, Turner and Verhoogen, 1974). However, when this is plotted against Ti or Cr, both elements sensitive to differentiation in basaltic rocks, atypical non-igneous trends with much scatter result for basalts from this study area. Sea-floor metamorphism of greenschist facies rank can result in addition of MgO or CaO reflected in modal chlorite and epidote respectively (Humphris and Thompson, 1978).

Figure 5-2 has the field of chlorite and epidote rich mid-ocean ridge basalts (MORB) after Humphris and Thompson (1978) and data points for the basalts from Confederation Lake. Samples with greater than 15 percent chlorite or greater than 5 to 10 percent large, greater than 0.1 mm epidote grains not pseudomorphs after plagioclase are in or near the chlorite and epidote fields of Humphris and Thompson (1978) respectively. Humphris and Thompson's
study resulted in the delineation of relatively small fields for the two alteration types possibly because of a restricted number of samples. The results on Figure 5-2 suggest that the chlorite and epidote fields are larger for basaltic rocks of this study. It is evident from the foregoing that Mg metasomatism is the most probable cause of the erratic results obtained in using FeO*/MgO as a measure of differentiation. Therefore TiO₂ content has been chosen as the index of differentiation rather than FeO*/MgO.

Alkalies are notoriously susceptible to alteration during devitrification (Ross and Smith, 1961), and metamorphism (Andrews, 1977; Coish, 1977; Amstutz and Patwardhan, 1974; Humphris and Thompson, 1978; Condie, 1976). Of the related incompatible elements, Rb is usually enriched (Condie, 1976; Hart, 1969), during metamorphism. Sr and Ba show little or no change (Condie, 1976; Hart, 1969), and are relatively fixed during metamorphism. On a plot of Na₂O/K₂O vs Na₂O+K₂O Miyashiro (1975) has defined an upper limit (line A-A' on Fig. 5-3) for fresh basaltic rocks based upon a study of ophiolitic basaltic rocks. The basaltic rocks of this study define approximately vertical trends with most parts above line A-A' on Fig. 5-3. This distribution is considered to indicate large scale addition of Na and probable decrease in K. The net effect being a decrease in Na₂O + K₂O.
5-2 MgO vs CaO (weight Percent) for basalts from all three cycles. Field of chlorite and epidote rich samples from Humphris and Thompson (1978a). a= Cycle I, b= Cycle II, c= Cycle III.
Figure 5-2
5-3 $\text{Na}_2\text{O}/\text{K}_2\text{O}$ vs $\text{Na}_2\text{O} + \text{K}_2\text{O}$. The curve separates the upper field of altered basalts from fresh basalts defined by Miyashiro (1975) from a study of ophiolitic basalts. $a=$Cycle I, $b=$Cycle II, $c=$Cycle III.
Plots of SiO₂ vs Zr/TiO₂ (Fig. 5-4), SiO₂ vs Zr (Fig. 5-5) and Zr vs Y (Fig. 5-6) have igneous trends (Floyd and Winchester, 1978) suggesting: a) little Si metasomatism; and b) that immobile elements serve as useful measures of fractionation.

5.3 Cycle I Mafic Volcanic Rocks

5.3.1 Major and Trace Element Abundances

Mafic volcanic rocks of Cycle I are olivine normative (Table E-1) tholeiitic basalts (Fig. 5-7a, 5-8). These rocks are typical Archean tholeiitic basalt with lesser Ti and greater Fe and Mg than modern MORB. TiO₂ plotted against Cr separates two groups (Fig. 5-9a). Each group is in approximate stratigraphic order from bottom to top. The stratigraphically lowest samples have lesser Ti and greater Cr content which is consistent with Ti content increases and Cr content decreases as differentiation proceeds. A concomitant enrichment in Fe, P₂O₅ and the large ion lithopile (LIL) elements Nb, Zr and Y occurs within each group accompanied by a decrease in Cr and Ni. Ni, however, does not have smooth trends where plotted against Ti, possibly as a result of the large Kd of Ni for sulphide relative to silicate minerals (Cawthorn and McCarthy, 1977) and subsequent removal of the sulphide minerals. There is a general decrease upwards in Al, Ca and a probable decrease in Sr. Zr has an upward increase in those samples in which the Zr has been determined by XRF. The decrease
5-4 $SiO_2$ vs Log $Zr/TiO_2$ after Floyd and Winchester (1978). The fields are as shown by Floyd and Winchester:
- AB is alkalic basalts, hawaiites, mugearites, trachybasalts;
- sub AB is subalkaline basalts (tholeiites and high alúmina);
- B + TB + N is basanites, trachybasanites, nephelinites; A is andesites, D + RD is dacites and rhyodacites, R is rhyolites;
- TA is trachy andesites; T is trachytes; Ph is phonolites; C + P is commendites and pantellerites. Dashed Iine is the field of altered oceanic basalts of Floyd and Winchester (1978).
5-5 Zr vs SiO₂. Solid line encloses most cycle III samples. Samples outside this line include matrix III, variolite pairs and intrusive rocks from cycle III. Dashed line encloses basalts and rhyolites from Cycle I.
Figure 5-5

5-5 Zr vs SiO₂. Solid line encloses most cycle III samples. Samples outside lines include matrix-variole pairs and intrusive rocks in cycle III. Dashed line encloses basalts and rhyolites from cycle I.
Figure 5-6

5-6 Zr vs SiO$_2$ Cycle III samples only.
Figure 5.7

5.7 a, b, c AFM diagram for all cycles A is Na$_2$O, K$_2$O, F is FeO* M is MgO, all in weight percent.
a is cycle I, b is cycle II c is cycle III
The line dividing tholeiitic and calc-alkaline rocks after Irvine and Baragar (1971)
5-8a, b, c Cation plot after Jensen (1976). All parameters in cation percent. The sloping line separates the field of tholeiitic rocks from calc-alkaline rocks, the vertical line separates the above from rocks of komatiitic affinity. Detailed explanation of the various fields on the diagrams is presented by Jensen (1976). The dividing line between tholeiitic and calc-alkaline field after Irvine and Baragar (1971), with the calc-alkaline field below the curved line. a=Cycle I, b=Cycle II, c=Cycle III.
5-9 Cr vs TiO₂ in weight percent: trend lines join samples within separate Fe enrichment cycles. A is basalts of Cycle I, b is basalts of Cycle II, c is basalts of Cycle III. In 5-9b, the stratigraphically lowest group of basalts forms the left trend line and the highest stratigraphically the right trend line. Points off the trend lines of low Cr concentrations are due to poor precision in Cr analyses and lack of room for extension of individual trend lines. On 5-9c, upper trend line and associated points lie below the variolite unit, the other trend line represents samples above the variolite unit.
Figure 5-9
in Ca and Al suggest that plagioclase is being fractionated; the increase in Ti and Fe and decrease in Mg indicate that a mafic silicate phase is also fractionating (Table E-1). Relatively constant Ti/Nd indicates that an oxide phase is not fractionating.

Nb, Ba, and Ti have been enriched stratigraphically upward by a factor of almost 2 suggesting a minimum of 50 percent fractional crystallization. The decrease in Ni coupled with this suggests that the fractionating phases are plagioclase and olivine. The elevated Sc and V abundances in samples 77-4233 and 77-473 suggest that the late stages of iron enrichment (Fig. 5-9, Ti vs Cr) are marked by clinopyroxene accumulation (Frey et al. 1974).

5.3.2 Abundances of Rare Earth Elements

Analytical results are normalized to the chondritic values of Haskin et al. (1968) on the standard rare earth plot developed by Coryell et al. (1963) to eliminate the effect of variable abundances of elements with odd and even atomic numbers (Fig. 5-10). Patterns for the basalts of Cycle I are flat to slightly enriched in the light REE with abundances in the 12 to 20 times chondrites range and are similar to those of other Archean tholeiites (Fryer and

3 Samples are described in Appendix F. Analytical results are listed in Appendix E. All rare earth element plots are for samples in the 77 series.
5-10 REE patterns for Cycle I volcanic rocks. Vertical axis refers to chondrite normalized values (Haskin, 1968). Sample numbers refer to results listed in Table E-1.
Jenner, 1978; Arth and Hanson, 1975; Condie, 1976). The similar pattern with variations in absolute abundance implies that neither amphibole nor clinopyroxene are the cause of the abundance variations as fractionation of these phases would alter the pattern and the abundances. The more fractionated samples are stratigraphically higher. The positive Eu anomaly is because of either mafic phase fractionation, plagioclase accumulation or alteration (cf. Sun and Nesbitt, 1978). The former is favoured given the consistent nature of the phenomenon. Sample 77-416 differs from the other two samples as it is more enriched in light REE and Eu. The sample is from a cross cutting dike in the intermediate pyroclastic rocks of Cycle I and may represent more highly fractionated material. However given the similarity of Zr, Y, Sr, Ba, Y, and Nb contents of sample 77-416 relative to other Cycle I basalts, the light REE enrichment could be caused by mobility of the light REE during alteration (Hellman and Henderson, 1977; Menzies, et al. 1977).

5.4 Cycle I Metavolcanic rocks of Intermediate Composition

5.4.1 Major and Trace Element Abundances

These metavolcanic rocks are andesitic in composition (Table E-1). They are calc-alkaline and quartz normative. Compared to the tholeiitic basalts, the suite comprising samples 77-418, 77-419, 77-474 and 77-475 upon which
detailed analytical work has been done, has more Al, P, K, and Na and has similar amounts of Ti and lesser Fe, Mg, and Ca. Within this four sample group, increasing Si is accompanied by decreasing Fe, Mg, Ca, Sc and V, with more or less constant Al and Ti. These variations within the andesites are consistent with some plagioclase fractionation, but not enough to decrease the Al content, and fractionation of an Fe, Mg rich mafic phase. The decrease of Sc and V with increasing Si content suggests clinopyroxene fractionation. The rocks of this group have paradoxically more Cr, Ni and Zr than the most fractionated basalts.

5.4.2 Abundances of Rare Earth Elements

The REE pattern for samples 77-419 and 77-474 are enriched in light REE (60 x chondrites). The heavy REE have about 10-20x chondrites abundances.

5.5 Cycle I Metavolcanic Rocks of Felsic Composition

5.5.1 Major and Trace Element Abundances

Cycle I felsic metavolcanic rocks as a group have more Na relative to K (Fig. 5-11) falling in the trondhjemite field (Fig. 5-12). They have been subdivided, for purpose of discussion, on the basis of volatile free SiO₂ content into dacites (62-67 percent) and rhyolites (67-80 percent). The rhyolites are further grouped (after Fryer and Jenner, 1978) into these with a volatile free silica content of 70 to 75 percent and these with a silica content
S-11 a, b, c K₂O vs Na₂O for felsic volcanic rocks; a is cycle I, b is cycle II, c is cycle III.
5-12 Normative feldspar composition—An is anorthite, Ab is albite, Or is K-feldspar, fields after Streckeisen (1976). a) Cycle I and II, b) Cycle III.
Figure 5-12: Normative feldspar composition of felsic volcanic rocks
greater than 75 percent.

The group with high silica content are depleted in Ti, Al, Fe, Ca, Na, P, and Sr relative to the group with low silica content. Indicators of fractionation such as Zr, Y, Nb, and Ti (Frey et al., 1974) suggest that the low Si group is related to the high Si group by fractionation of plagioclase, a mafic phase, and apatite. The small number of samples does not permit testing of this hypothesis. The high Cr and Ni content of the rhyolites relative to the andesites suggests there is no simple genetic link between these two rock types.

5.5.2 Abundances of Rare Earth Elements

REE patterns of the Cycle I rhyolites, in particular 77-401, because of depletion in heavy REE, are those of more fractionated rocks than are the patterns of the andesites of Cycle I. The REE pattern of sample 77-401 is similar to that observed in the Prince Albert group (Fryer and Jenner, 1978) except for greater abundances of the light REE, a function of light REE enrichment during a possible alteration event (Condie et al., 1978; Hellman and Henderson, 1977) of which this feature is the only evidence. The pattern for sample 77-422 is relatively flat, slightly depleted in heavy REE with a negative europium anomaly which may be a function of fractional crystallization of clinopyroxene.

5.6 Cycle II Metavolcanic Rocks of Mafic Composition
5.6.1 Major and Trace Element Abundances

Cycle II mafic metavolcanic rocks are quartz-normative tholeiitic basalts which have, at a silica content of basaltic andesite, a character transitional to calc-alkalinity on both the AFM- (Fig. 5-7) plot and on Al₂O₃-FeO⁺+TiO₂-MgO (cation percent) plot (Fig. 5-8). Formation E was sampled on the west limb of the synclinorium in the Narrow Lake area and formation F sampled from the upper two minor cycles (Anhaeusser, 1971) beneath the HST chert. On the basis of all available analyses, the formation can be sub-divided into three cycles similar to those described in Cycle I in which the Fe and Ti increase and Ni, and Cr decrease upward in the section (Fig. 5-9). The Fe increase is accompanied by more V, Sc, Zr, and Y and less Al, Ca, Sr, and Mg. These abundances are similar to those observed in Cycle I and are believed to be caused by fractionation of plagioclase and olivine.

At the base of each Fe enrichment cycle, basalts contain 8 to 10 percent MgO at TiO₂ and P₂O₅ abundances of 0.72 and 0.09 percent respectively. As fractionation proceeds to a TiO₂ content of 1.96 percent, P₂O₅ content of 0.14 percent, FeO⁺ increases from 11.1 percent to 15.8 percent and MgO decreases to 3.6 percent (Table E-2). Y and Zr abundances (Frey et al., 1974) increase by factors of 2 to 3 and Cr and Ni decrease a minimum of 10 fold through
each Fe enrichment cycle. These patterns indicate 50 to 60 percent fractionation. Increased V and Sc toward the end of each Fe enrichment cycle correlates with the appearance of 5 to 10 mm amphibole pseudomorphs and is thought to be caused by clinopyroxene accumulation (Frey et al. 1974). Relatively constant Ti/Nd suggest no oxide phase fractionation. Formation E on the east limb was analyzed for major elements only. Based upon this, the same general trends are present.

5.6.2 Abundances of Rare Earth Elements

The REE patterns of Cycle I basalts in formation E are relatively flat like those of the Cycle I tholeiites (Fig. 5-13). Sample 77-405, midway through formation E at the high Fe end of an Fe enrichment cycle is the most fractionated sample, with the largest REE content and is enriched in the intermediate REE, Nd to Gd, possibly a result of cumulate clinopyroxene, present as amphibole pseudomorphs.

5.7 Cycle II Metavolcanic Rocks of Intermediate Composition

5.7.1 Major and Trace Element Abundances

The intermediate metavolcanic rocks of Cycle II range from basaltic andesite to andesite in composition. Andesites occur intercalated with the formation E in the area of Narrow Lake and basaltic andesite in the minor cycles of formation F. Andesites of formation E appear to be of at least two distinct types based upon REE.
5-13 REE patterns Cycle II, vertical axis chondrite normalized values. a = Cycle II basalts, b = Cycle II andesites, c = Cycle II minor cycle basaltic andesites. Sample numbers from the 77 series.
Figure 5-13
5.7.2 Abundances of Rare Earth Elements

One type is represented by samples 77-408 and 77-407 which have flat REE patterns (Fig. 5-13) similar to the tholeiitic basalts and low abundances of K, Zr and P, but higher abundances of Si and lower Fe, Mg, Co and Al than the basalts. This suggests that they may be related to the basalts and the lack of enrichment in LIL elements is not readily explicable. A second type is represented by sample 77-403 which has greater K, P and LIL element contents and a strongly fractionated REE pattern (Fig. 5-13). These characteristics are similar to those of the minor cycle samples. As in Cycle I, the Cycle II andesites have a relatively large Ni and Cr content which precludes an origin by fractional crystallization from more mafic magmas.

The minor cycle basaltic andesites are of three different types, one type is represented by sample 77-442, the only rock containing significant Cr and Ni. It has a REE pattern similar to sample 77-407 (Fig. 5-13) which is basalt from formation E with a low Zr content of 48 ppm. Sample 77-448 represents another type with concave downward patterns and abundances near that of andesite such as sample 77-403 from formation E. Samples 77-437 and 77-438 represent the third type which has greater REE abundances and concave upward REE patterns with heavy REE abundances 3 times the other types.
This variability within basaltic andesites suggests the presence of genetically different rock types with similar major element compositions. No simple relationship to formation F is possible given this diversity and the fractionated patterns.

5.8 Cycle II Metavolcanic Rocks of Felsic Composition

5.8.1 Major and Trace Element Abundances

Felsic metavolcanic rocks of Cycle II on both limbs of the regional synclinorium and of the minor-cycles are also divided into groups with high and low Si content. The high Si group has lesser Al, Fe, Ti, Ca and P and greater Na and K relative to the low Si group. This pattern may be a function of fractionation of plagioclase, an oxide phase, apatite (Glikson, 1971) and quartz (Fig. 5-14).

The dacites and low Si rhyolites of formation F in the east limb overlying the minor-cycle basaltic andesites have 50-60 ppm Cr in the low Si group but abundances are 10 to 20 ppm in the high Si group. Ni decreases more rapidly than Cr, Al decreases as Si increases. Ba is irregularly scattered; Sr has an inconsistent decrease. Zr is generally low with greater abundance correlating with greater Y abundance. Based on the low content of incompatible elements, these samples are the depleted siliceous volcanic rocks (DSV) of Condie (1976).

The Zr content relative to basalts from this area suggest that a continuing crystal fractionation process
Figure 5-14

5-14 Log Rb vs. Log Ba Cycle II felsic and intermediate volcanics. Squares are dacites and low Si rhyolites, triangles are high Si rhyolites.
with a basaltic or andesitic parent liquid was not the operative process. The remaining possibilities are volatile transport of incompatible elements (Collerson and Fryer, 1978) or liquid immiscibility (Watson, 1976; Gelinas et al. 1976) or magma mixing.

The rhyolites with a high silica content on the west limb of the regional synclinorium include two samples with large Na\textsubscript{2}O/K\textsubscript{2}O, samples 77-446 and 77-444 have minor Zr and Y contents and more Ti relative to other rocks in the high Si group and have recrystallized chert admixed with the fine tuffaceous material at the top of individual beds producing anomalously large Si content and a Ti content of a lower silica volcanic rock.

The large K content and large K\textsubscript{2}O/Na\textsubscript{2}O and lesser P content of samples 77-414 and 77-415 relative to other rhyolites of Cycle II may be caused by leaching in a weathering environment (Fryer, 1977), as the rocks are very welded and have been deposited subaerially (Savory, 1976; Thurston, 1979). However addition of K and Si are reported to take place during devitrification and formation of spherulites (Lofgren, 1971). Removal of Na during cooling and devitrification of ignimbritic ash flows is described by Lipman (1967) and Scott (1977).

Samples 77-407, 77-410 and 77-413 have from 62.0 to 63.8 percent SiO\textsubscript{2}, and are therefore compositionally (Fig. 5-19b) between basaltic andesites and dacite of the
minor-cycle. The apparent compositional gap in the minor-cycle (Table E-2) may therefore be a function of sampling, or it may be a function of sorting during pyroclastic activity in that the minor cycle rocks are relatively distal, a complete section may not be present. Basaltic andesites tend to form flows and dacites tend to form coarse pyroclastic rocks. Andesitic ash size material makes up the matrix of formation H (Sopuck, 1977). The matrix andesite of formation H fills the gap between the rhyolites of formation H with abundant K on the west limb and the Na-rich rhyolites of formation F (Table E-2). Vanadium in andesite of formation E is greater than in the intermediate to felsic rocks of formation H on the east limb, also suggesting the lack of any compositional gap.

5.8.2 Abundances of Rare Earth Elements

There are two distinctive groups of samples in formation F based on REE abundances (Fig. 5-15a). Samples 77-444, 77-445, and 77-440, dacites and low Si rhyolites, have low heavy REE abundances and strongly fractionated patterns. Samples 77-435 and 77-441, high Si rhyolites, on the other hand have higher REE abundances, high heavy REE abundances and a pronounced negative Eu anomaly. There are no differences in major element abundances between the two groups of felsic volcanic rocks. The group with less heavy REE has much less Y and Zr. Some difference in major
5-15 REE pattern Cycle II felsic volcanics
   a is minor cycle rhyolites
   b is felsic top of east limb
   c is intermediate volcanic rocks west limb
   d is felsic volcanic rocks west limb
Figure 5.15
Figure 5-15
element abundance in samples 77-444 and 77-440 could be obscured by chert admixed with the fine grained tuffaceous tops of individual beds producing anomalously large Si contents. This is also suggested by their high Na₂O/K₂O. The felsic rocks are not related by fractionation to the basaltic andesites in that the felsic rocks have more Cr and Ni than the latter.

Dacites of formation H on the east limb of the regional synclinorium are depleted in heavy REE as in samples 77-464, 77-465 and enriched in heavy REE as in sample 77-467 (Fig. 5-15b). The former are similar to dacites and low Si rhyolites of the minor-cycle and are probably genetically related. Sample 77-467 is similar to the high Si rhyolites with high heavy REE abundances in the minor-cycle. It does not however have as much SiO₂ as those of the minor-cycle and appears to be distinctly less fractionated on the basis of more FeO* and Ti and less Zr and Nb.

All the intermediate and felsic volcanic rocks on the west limb of the regional synclinorium except 77-409 have REE patterns with similar slopes (Fig. 5-15c, d) implying that they may be related to one another. Sample 77-411 has less total REE than the others along with similar depletions in other LIL elements. The lesser total REE could be caused by incorporation of sedimentary chert into the tuff, verified by Si and Ti contents. The west limb
samples of formation H include samples with varying proportions of pumice to shards and both varying SiO₂ and compatible FeO*, TiO₂, CaO, MgO, vis a vis Sr contents, it is not possible to state unequivocally that they are related by differences in fractionation in high-level magma chambers in spite of the currency of this concept (Hildreth, 1979). Sample 77-409 has a REE pattern similar to the Cycle I andesites and less Zr and more Nb than comparable Cycle II andesites of the west limb of the regional synclinorium.

5.9 Cycle III Metavolcanic Rocks of Mafic Composition

5.9.1 Major and Trace Element Abundances

The flows of formation K are basalts to andesites on the basis of volatile-free SiO₂ contents (Table E-3). They are separated for purposes of description into those above and those below the variolithic flows.

Basalts below the variolithic flows are quartz normative tholeiitic basalts (Fig. 5-7) (Table E-3) with greater Ti content at equivalent Cr and Ni contents relative to Cycle I and II basalts (Fig. 5-9). Basalts below the variolithic flows have decreasing Cr and Ni with increasing Ti, Fe, Zr, and Y contents up section. These rocks differentiate upward into basaltic andesites which are discussed below. Cr and Ni are less than 50 ppm at 51 percent SiO₂ and 2.18 percent TiO₂ in Cycle II versus 53.7 percent SiO₂ and 1.8 percent TiO₂ in Cycle III. The rocks of Cycle III are
therefore more fractionated, yet they have high Cr contents, for example 1.53 percent TiO$_2$ and 222 ppm Cr, whereas in Cycle II at 1.57 percent TiO$_2$ there is typically 15 ppm Cr. This higher degree of fractionation is particularly apparent on a plot of Cr vs TiO$_2$ (Fig. 5-9), and Zr vs SiO$_2$ (Fig. 5-5). The Fe enrichment trend for rocks below the variolitic flows is marked by an 8 fold increase in Zr and a minimum of four-fold increase in Y, and is an indication of the degree of fractionation. The lesser increase in Y, where correlated with anomalously small increases in P$_2$O$_5$, with fractionation measured independently by Zr or Ti suggests apatite crystallization as the mechanism for removal of Y from the liquid (Zielinski, 1975). Concentrations of Y and Sc increase with fractionation, suggesting the late appearance of clinopyroxene on the liquidus (Frey et al. 1974).

Above the variolitic flows the basalts are olivine to quartz normative tholeiites, in the tholeiitic field on an AFM plot or the Al$_2$O$_3$-FeO$^+$TiO$_2$-MgO plot (Jensen, 1976) (Fig. 5-7, 5-8). They are by criteria of N. Green (1975) and Irvine and Baragar (1971) high-alumina tholeiites. The same Fe, Ti enrichment trends noted in other cycles are present here, with three enrichment cycles above the variolitic flows. Although there is a general cyclicity of Ti vs Cr (Fig. 5-9) and Ti vs Ni abundances there is a considerable range of high Ti contents over which
relatively constant Cr and Ni are present. There is relatively constant Al, P, variable Mg and Ca and a quite minor K content. This pattern is probably a function of fractionation of some plagioclase and olivine in an open system (O'Hara, 1977).

Above the variolitic flows, the usual measures of fractionation, Zr and Y abundances, (Frey et al. 1974) increase within each Fe enrichment cycle from 31 to 49 ppm for Zr with the exception of an extremely fractionated sample 77-460 with 199 ppm Zr. V and Sc increase through each Fe enrichment cycle from 200 to 400 ppm and from 25 to 40 ppm respectively in the more Fe-bearing samples. This pattern suggests about 25 percent fractional crystallization involving olivine and plagioclase with the appearance late in each Fe enrichment cycle of clinopyroxene on the liquidus.

Sample 460 is interpreted as an extremely fractionated basalt. There is a decrease in V and Sc, and Al, Ca, and Sr are all low relative to the less fractionated basaltic rocks. In fact in terms of SiO₂ content (55 percent) the sample is andesitic in composition. This sample is likely related to the underlying basaltic rocks by fractionation of clinopyroxene and plagioclase.

5.9.2 Abundance of Rare Earth Elements

Basalts below the variolitic flows have fractionated REE patterns with slight enrichment of light REE, La/Sm
E.F.R. = 1.5 avg., La/Yb of 0.6 (Fig. 5-16a).

Fractionation increases with stratigraphic height and causes an increase in the light REE and depletion of the heavy REE, provided a mafic mineral is involved.

REE patterns of the basalts above the variolitic flows are generally relatively flat (Fig. 5-16b).

Sample 77-430 has a fractionated pattern with a positive Eu anomaly indicative of clinopyroxene fractionation and plagioclase accumulation (Zielinski, 1975). Sample 77-460 has greater abundances indicative of a more evolved nature with REE abundances of 80 to 60 times chondrites at the light REE end. The sample represents continued fractionation of olivine and plagioclase.

5.10 Cycle III Variolitic Flows

A massive variolitic flow unit (Geliñas et al. 1976) has many of the petrographic and field criteria of liquid immiscibility (ibid). Matrix-variole pairs from the Bobbo Point outcrop on Confederation Lake were analysed. Sample 77-449 (matrix) and 77-450 (varioles) constitute one pair and sample 77-451 (matrix) and 77-452 (varioles) the other. Given the close proximity of the samples, the large Si content of 77-449 relative to 77-451 suggests that the sample was contaminated with variole material.

The mafic matrix pair are andesitic in composition with abundant Al, P, K, Fe, Mg and the LIL elements Zr, Nb, Y and Ba. Unlike most intermediate rocks of the
5-16 REE patterns Cycle III basalts, vertical axis chondrite normalized values.
   a) below variolitic flows
   b) above variolitic flows, samples 430 and 460 represent extremely fractionated basalts, with higher REE abundances than normal in this unit.
   c) variolitic flows and intermediate volcanics
      sample 449 matrix
      " 450 variole
      " 451 Matrix
      " 452 variole.
CYCLE III BASALTS: below variolitic flows

10
20
30
40
50
60
70
80

455
457
456

CYCLE III BASALTS: above variolitic flows

10
20
30
40
50
60
70
80

460
430

Average of 5
[TiO2 = 0.72 - 0.90%]

CYCLE III INTERMEDIATE-VOLCANIC ROCKS

100
200

451
449
430
452

Figure 5-16
Confederation Lakes area they are essentially devoid of Cr and Ni as compared to 77-453 and 77-428 from Cycle III or any of the Cycle II intermediate metavolcanic rocks.

The varioles are felsic and similar to one another. They are low in Al relative to the mafic matrix, and other felsic metavolcanic rocks of Cycles I and II. They are very rich in Zr and Y but lower than the mafic fraction. These patterns are those predicted for liquid immiscibility in the basaltic system (Watson, 1976). Composition of the felsic varioles is identical to that of the rhyolites stratigraphically higher in Cycle III.

The REE pattern of the variolitic flows is somewhat fractionated with negative Eu anomalies (Fig. 5-16c). The REE patterns of the matrix-variole pairs are remarkably unfractionated but considerably enriched in all REE with respect to chondritic meteorites and are strikingly similar to those of the strongly fractionated basalts found immediately below them as in samples 77-457 and 77-455 in Figure 5-16a. This suggests a genetic link between the fractionated basalts and the variolitic horizon as will be discussed below with the rhyolites.

5.11 Cycle III Metavolcanic Rocks of Felsic Composition
5.11.1 Major and Trace Element Abundances

The felsic metavolcanic rocks of Cycle III are rhyolitic and relatively K-poor, plotting in the trondhjemite field on a normative feldspar plot (Fig.
5-12). They have a tholeiitic trend on AFM and Al2O3 - FeO* + TiO2-MgO diagrams (Jensen, 1976) (Fig. 5-7, 5-8). The rhyolites range in silica content from 71 to 82 percent and are characterized by relatively low and constant Al contents relative to the Marda complex (Hallberg et al. 1976). Relative to most other Archean rhyolites these rocks have greater Ti which decreases with increasing Si. The trace elements are characterized by high Zr, Y and Nb. As might be expected, plots of log Rb vs log Ba and log Sr (McCarthy and Robb, 1977) have a trend indicating that the high Si rhyolites are derived from the low Si rhyolites by fractional crystallization of plagioclase and quartz (Fig. 5-17a, b).

5.11.2 Abundances of Rare Earth Elements

In keeping with the large abundances of LIL elements, the REE abundance of Cycle III rhyolites is unusual (Fig. 5-18). For rhyolitic compositions, the patterns are flat, with very great abundances from 120 to 240 times chondrites at the light REE end and 53 to 100 times chondrites at the heavy end (Fig. 5-18). La, Sm, E.F. averages 1.43 and La, Yb, E.F. = 2.16. The origin of these patterns will be discussed in chapter 6 but it should be noted that they are unlike those of the previous cycles with a few exceptions and are most similar to the variolitic flows of the Cycle III basalts.

5.12 Granodiorites
5-17 a) Log Ba vs Log Rb Cycle III felsic volcanics and granodiorite.
b) Log Rb vs Log Sr Cycle III felsic volcanic and Granodiorite.
- open triangles low silica rhyolites
- open squares granophytic granodiorite
- closed squares varioles in basalts of formation
- circles high silica rhyolites
5-18 REE pattern Cycle III felsic volcanics and granodiorite chondrite normalized values on vertical axis
Figure 5-18
The granodiorites have the same range of Si abundances as the rhyolitic rocks of Cycle III and the same abundances of Zr, Y, and REE. Hence they are considered to be associated with Cycle III magmatism and are not hypabyssal rocks associated with cycles I or II, neither are they associated with later granitic rocks (Appendix I).

5.13 Cyclical Volcanism

5.13.1 General Statement

In the Abitibi belt Gelinás et al. (1977), Jensen, (1978, 1978a, 1976) and Pyke (1978, 1978a) described a continuum of compositions from a komatiitic basalt through tholeiitic basalts and tholeiitic rhyolitic rocks or, from tholeiitic basalt through calc-alkaline felsic rocks (Jensen, 1976). Hallberg et al. (1976) describe a continuum from an andesitic base through rhyolite with no apparent compositional gaps in the Manda complex.

Histograms of silica content of each cycle (Figs. 5-19a, b, c) tend to indicate these continua do not exist in this area. In Cycle I using 66 samples, a maximum occurs at 48.25 percent (s.dev. - 3.56), and a poorly defined maximum in the andesite to dacite range followed by a decrease to the 78 to 80 percent SiO₂ class. In Cycle II, utilizing 106 samples, a minimum occurs at 56 to 76 percent SiO₂. In Cycle III a pronounced minimum in the silica histogram occurs between 56 and 66 percent SiO₂ in 133 samples. Distinct minima occur in the SiO₂ histograms in
5-19 Histograms of volatile free SiO₂ content (weight percent).

a) Cycle I  n = 66
b) Cycle II  n = 106
c) Cycle III  n = 133
Cycle I  $n = 66$

Cycle II  $n = 106$

Cycle III  $n = 133$

Figure 5-19
the andesitic range, a so-called "Daly gap" (Daly, 1925). Even with Si continuity there are distinct discontinuities in the behaviour of Zr, Y (Fig. 5-5) (Fig. 5-20a, b, c).

There appears to be a continuum from basaltic andesite, SiO\textsubscript{2} ~ 50 to 55 percent, to andesite 55 to 62 percent SiO\textsubscript{2} in Cycle II at least. However the andesites of Cycle II on the west limb of the regional synclinorium are derived by extreme fractionation of basalts with high Si, Zr, Y etc. derived from the underlying basalts rather than from the basaltic andesites of the minor-cycle. There are two distinct trends on Fig. 5-5 and Fig. 5-21b. These anomalous discontinuous trends suggest that Cycle II magmatism at least is not a simple pattern involving fractional crystallization of andesite from a basaltic parent magma. Are several liquids involved? The following consideration is intended to examine some of the possible alternatives.

5.13.2 Cycle I

Cycle I can be described as primitive or not evolved. Higher Cr concentrations are found in Cycle I basalts at low Ti concentrations than in basalts of Cycles II and III with similar Ti concentrations. In addition, a Zr-SiO\textsubscript{2} plot (Fig. 5-5) has Zr abundances increasing more slowly with increasing Si in Cycle I than in Cycles II and III. The basalts through andesites define a linear array with an abrupt discontinuity at about 60 percent SiO\textsubscript{2} and about 180
5-20 Y vs SiO₂
a) Cycle I
b) Cycle II
c) Cycle III
5-21. Y vs Zr

a) Cycle I
b) Cycle II
diamonds are minor cycle samples.
open squares are west limb
circles are minor cycle
square are east limb
c) Cycle III
squares are above variolite unit
triangles are below variolite unit
circles are variolite related
ppm Zr with a new array beginning at 68 percent SiO₂ and 100 ppm Zr, extending to 80 percent SiO₂ and about 200 ppm Zr. In Y vs Zr, Y does not vary sympathetically with Zr (Fig. 5-21); Y remains at about 20 ppm and Zr increases to 170 ppm. There are few samples with Zr contents between 50 ppm and 110 ppm also suggesting a hiatus in any fractional crystallization trend.

5.13.3 Cycle II

In analyses of the most mafic part of minor-cycle II (Fig. 5-21) Y and Zr increase sympathetically; until Y ceases to increase at about 25 ppm and stays relatively constant with increasing Zr. Basalts and andesites of the mafic lower part of the cycle maintain a continuous sympathetic relationship between Y and Zr, defining a trend with a slope of about +1. Andesites below formation H of Cycle II (open squares on fig. 5-21) on the west limb of the regional synclinorium have a relatively horizontal trend. The felsic rocks of the west limb appear on both the horizontal and the more steeply sloping trend, but they show a distinct gap between 250 and 235 ppm Zr and 38-55 ppm Y. Figure 5-20 a plot of Y vs SiO₂ also has two trends.

High Cr and Ni content is a feature of relatively unfractionated basaltic magmas (Jolly, 1975; Hallberg et al. 1976). However in this instance Fig. 5-22, a Cr vs SiO₂ diagram reveals high Cr content of basaltic through
andesitic rocks. Fig. 5-5 a Zr vs SiO₂ diagram has two poorly defined trends: 1) at the mafic end of the spectrum where Zr increases with SiO₂ with a slope of about 1/3 and 2) as 65 percent SiO₂ is approached Zr abundances decrease to below 100 ppm before increasing to about 250 ppm at 78 percent SiO₂. In a system involving only crystal fractionation only one trend should be apparent.

5.13.4 Cycle III

In Cycle III a paucity of intermediate Si abundances is readily apparent (Fig. 5-19c). Y vs Zr has only a trend of Y increasing with Zr except for two intermediate samples (Fig. 5-21c). A plot of Zr vs SiO₂ (Fig. 5-20) again demonstrates a paucity of intermediate rocks, however, the trend of points for the siliceous metavolcanic rocks is similar to that for the mafic to intermediate metavolcanic rocks. It should be noted that in a plot of Cr vs SiO₂ there is no longer high Cr contents in the 60 percent SiO₂ range (Fig. 5-22b).
5-22 Cr vs. SiO₂ for mafic flows of Cycle II and III.
CHAPTER 6

Petrogenesis

6.1 General Statement

This chapter examines the probable chemical and mineralogic character of parent magma at its time of origin, the extent of partial melting required to produce this parent magma, the pressure and temperature regime during partial melting, the nature of residual phases and, the rock record of daughter magmas derived by crystal fractionation, magma mixing or liquid immiscibility. The consensus is that the source of basalt in general is the mantle and that it may be derived from two groups of materials (cf. Yoder, 1976): 1) material of basaltic composition, that is basalt, gabbro, amphibolite, hornblende and eclogite and 2) plagioclase peridotites, spinel peridotites, and garnet peridotites. However, generation of a basaltic magma in situ from group 1 material would be difficult because of crystal settling, fractionation and so forth. The most likely mantle material based on phase relationships at depth would be garnet peridotite (Kushiro and Yoder, 1966; Yoder, 1976).

6.2 Basalt Genesis

6.2.1 Basaltic Primary Magmas

The following criteria have been used to identify primary magmas:

1) Frey et al. (1978) indicate that the least refractory
upper mantle peridotite has 100Mg/Mg+Fe**2** where Mg is 88 to 89. Basaltic magmas from sources such as this have Mg in the range of 68 to 75 if the percent melted is >30 percent using Kd Fe/Mg 01/Liq=0.3 (Roeder and Emslie, 1970).

2) Compatible trace elements such as Co, Cr, Ni and Sc have mineral-liquid partition coefficients exceeding 1 for upper mantle minerals such as garnet, clinopyroxene or olivine. Therefore, their abundance in basaltic liquids is a function of the degree of partial melting of the parental mantle. One to 20 percent partial melting of a hserzolite source will yield basaltic liquid with Ni 90 to 670 ppm, Co 27-80 ppm, and Sc 15-28 ppm (Frey et al., 1978).

3) Chondritic values of the ratios Ti/Zr, Zr/Nb, Zr/Y can be used as an indication of a relatively large degree of partial melting that is greater than 20 percent.

6.2.2 Conditions of Melting

Frey et al. (1978) has used the K2O and P2O5 content of basalts to estimate the degree of melting of pyrolite source. Alkali metasomatism of Confederation Lake basalts has been demonstrated, in Chapter 5, Fig. 5-3a, b, and c, therefore P2O5 content is used as the minor element measure of the percent melting of the source, assuming, that Kd is sufficiently low to approximate percent melting by the relation C1/C0 = 1/P.

C1 = concentration of incompatible element in the
liquid

\[ C_m = \text{concentration of incompatible element in mantle source} \]

\[ F = \text{amount of fractionation} \]

Condie (1976) reviews the compositions of Archean greenstone belts, and proposed two major types of tholeiitic basalts based primarily upon trace element and REE abundances: 1) depleted Archean tholeiite (DAT) characterized by flat REE patterns and low abundances of large-ion lithophile (LIL) elements and 2) enriched Archean tholeiites (EAT) characterized by slight enrichment in light REE and LIL elements (Table 6-1, Fig. 6-1). Condie suggests that EAT increased in abundance at higher stratigraphic levels in greenstone successions. He points out a similarity between DAT and modern rise and island arc tholeiites and EAT and modern calc-alkaline and oceanic island tholeiites.

D. Green (1971) developed a petrogenetic grid using the pyrolite mantle which relates depth of melting, percent melting and depth of a pyrolite composition containing 0.1 percent water to the type of basalt produced (Fig. 6-2). Accepting this as a valid picture of the Archean mantle, one can obtain an estimate of the percent melting involved in the origin of the Confederation basalts.

6.2.3 Liquid Immiscibility

Field studies (Gelinas et al., 1976) and experimental
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<th>Archean EAT</th>
<th>Modern rise</th>
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6-1 Chondrite normalized REE patterns for Archean tholeiite; Rise-arc, oceanic rise and island arc tholeiites; EAT is enriched Archean tholeiite; calc-isl is calc-alkaline and island arc tholeiites.
6-2 Petrogenetic grid for mantle-derived basaltic rocks.
(after Green, 1971)
work (Visser and van Groos, 1979; 1976) suggest that basalts may originate by liquid immiscibility. Chemical criteria which are unique to this petrogenetic process are enumerated here. With liquid immiscibility P is partitioned into the mafic fraction (Gélinas et al. 1976). Experimental studies of element partitioning during liquid immiscibility by Watson (1976) indicate that Zr, Y, Nb, Ba, Sr, and the REE are partitioned into the mafic liquid. Cs is partitioned into the felsic liquid, the opposite of that anticipated in fractional crystallization given the small Kd for this element with respect to most minerals. Ryerson and Hess (1978) explain this phenomenon in terms of cations with high charge density such as the REE etc. preferring the basic melt which is relatively de-polymerized due to its low Si/O ratio relative to felsic melts. The concept of charge density of cations and state of polymerization of melts has been applied by Eby (1979) to alkalic rocks. Similar trace element behaviour was noted by Vogel and Wilband (1978) in a composite dike composed of mafic and felsic portions which is considered on the basis of textures such as lack of chilled margins between mafic and felsic portions and trace element chemistry to have most likely formed by the process of liquid immiscibility.

6.3 Andesite Genesis
6.3.1 General Statement

Andesites have 52 to 63 percent silica, and an alkali
content lower than mugearite, and trachyandesite (Kuno, 1968). The essentially chemical definition of Chayes (1968) is used here.

Trace element abundances for andesites are summarized by Taylor (1968) as follows:

1) the large cations (Cs, Ba, Rb, K, Pb) are variable but generally low in abundance, similar to average basaltic concentrations, K/Rb ratios are high and Rb/Sr ratios are low.

2) the rare earths have low total abundances. The rare earth relative abundance patterns vary from those sub-parallel to the chondritic pattern to those close to the sedimentary pattern, i.e. fractionated.

3) the highly charged cations (Th, U, Zr, Hf, Sn, and Nb) have concentrations similar to average basaltic levels.

4) Nickel and cobalt content is minor and Ni/Co-ratios are low, about 1. The chromium content is minor and variable, but vanadium and scandium are present. Distribution of these elements in andesites resembles that in high Al basalts.

6.3.2 Archean Andesites

Andesites are commonly reported in Archean supracrustal sequences (Baragar and Goodwin, 1968; Condie, 1976; Hallberg et al. 1976). They are from 18.4 to 30.4 percent (mean 23.0 percent) of the volcanic belts reported by Baragar and Goodwin (1968). The available chemical data
(Hallberg et al. 1976; Baragar and Goodwin, 1968) suggests that Archean andesites have more Fe, Na, Ti, Ba, Ni, Sc, V, Cr, and less K than Taylor's (1966) average andesite. (See Table 6-2).

6.3.3 Petrogenesis of Andesites

6.3.3.1 Fractional Crystallization From a Basaltic Parent Magma

a) Amphibole controlled fractionation (cf. Ringwood, 1974).

Basaltic magmas crystallizing under high PH2O crystallize amphibole (Yoder and Tilley, 1962; T.H. Green and Ringwood, 1968).

Fractionation of amphibole does not alter the Na/K ratio of the residual liquid or the partial melt and does not strongly fractionate the REE. As amphibole transforms into garnet plus pyroxene plus H2O, with increasing pressure (D. Green and Ringwood, 1967; Lambert and Wyllie, 1968) the amphibole-controlled fractionation cannot occur at depth greater than 90-100 km (Ringwood, 1974).

Amphibole fractionation does produce a calc-alkaline trend on an AFM diagram.

b) Eclogite-controlled fractionation

In eclogite-controlled fractionation melting occurs at 20-40 kb (D. Green and Ringwood, 1968) to produce andesitic liquids which follow a calc-alkaline trend, contain Na but little K, decreasing Na/K, and are strongly depleted in heavy REE because of the presence of garnet in
the residuum (Ringwood, 1974).

6.3.3.2 Mixing Hypothesis

As andesites are chemically mid-way between basalt and rhyolite in the volcanic spectrum with respect to the major elements, andesite could be the result of a 50:50 mixture of basalt and granite or a 40:60 mixture of basalt and granodiorite. Mixing of unusual crustal rock types with basalts are usually ruled out by trace element constraints.

Taylor (1968a) examined the proposition of mixing 60 percent average granodiorite with 40 percent average continental basalt, or 50 percent granite and 50 percent basalt and encountered difficulties reconciling trace element abundances.

Taylor (1968a) considers the problem of production of modern andesites by mixing of basaltic magma with material from the lower crust. He dismisses this idea on the basis that the lower crust in orogenic areas would be depleted in elements which are found in high abundance in andesites. Crustal thickness is also quite variable in orogenic areas, (Gorshkov, 1962).

Pyroxene and glass inclusions with compositions of basaltic origin in rhyolitic rocks and quartz, sodic plagioclase and rhyolitic glass inclusions in olivine bearing rocks of basaltic affinity with the inclusions ranging in size from microscopic to several metres in size led to the conclusion that large scale mixing has gone into
Zr, Nb, Y, and REE; low Rb/Sr and high K/Rb, Na/K and Ba/Rb. The presence of garnet, with high Kd for the heavy REE means that in melting of eclogite, if garnet is left in the residue, a highly fractionated REE pattern will be produced. The large cations listed above will behave incompatibly, readily entering the melt, producing the same characteristics of relatively low abundances of these elements if the felsic liquids are produced by 20 to 30 percent partial melting, rather than low degrees of partial melting (Fig. 6-4).

6.4.2 Origin by Fractional Crystallization of Basalt

Production of dacitic to rhyolitic rocks by fractional crystallization of a basaltic parent will concentrate incompatible elements such as U, Th, Zr, Y, Nb, Rb, Ba and the REE. Fractionation will serve to lower the K/Rb ratio (Beswick, 1976). The distinctive marks of this process when compared to felsic rocks of other origins is a lower content of Ca, Al and Sr and a negative Eu anomaly in felsic rocks derived by this process. Assuming that the felsic rock is derived by fractional crystallization of plagioclase, olivine and minor clinopyroxene, a relatively flat REE pattern with a negative Eu anomaly results (Fig. 6-5).

6.4.3 Origin by Partial Melting of Amphibolite

Glikson (1976) has modelled the effects of various degrees of partial melting of quartz eclogite vs
production of intermediate volcanic rocks (Eichelberger 1975, 1978). Basaltic magma and basaltic xenoliths have mineral compositions indicating origin in the upper mantle, whereas rhyolitic magmas are too siliceous to be derived by partial melting of ultramafic mantle (Stern and Wyllie, 1973) based upon experimental data; rather they have been produced by a maximum of 20 percent partial melting of a basaltic lower crust (Helz, 1976). Rhyolitic melts are, in Eichelberger's (1978) view caused by the heat supplied by ascent of basaltic magma. In his view, continental crust and compressional tectonics result in production of a lot of rhyolite and extensive mixing; continental crust and extensional tectonics result in much rhyolite and little mixing; oceanic crust and extensional tectonics results in little rhyolite or mixing; oceanic crust and compressional tectonics produce little rhyolite and much mixing.

Magma mixing has been suggested to be a possible means of triggering felsic pyroclastic eruptions in Iceland (Sparks et al. 1977) and in Guatemala (Koch and McLean, 1976). Sparks et al. (1977) described plinian pumice fall deposits from Askja (Iceland) and Santorini (Greece) which contain tephra of two compositions occurring as discrete fragments and interbanded within single fragments. They ascribe this intermixing of fragments to magma mixing; as well, they suggest the mixing event is a trigger for pyroclastic eruptions. Their model is paraphrased as
follows:

A felsic magma occupying a crustal magma chamber is intruded by basic magma. Evidence from net-vein complexes (Blake et al. 1956) and composite dikes (Vogel and Wilband, 1978) suggests that a mafic fraction separates into pillow-like masses which lose heat in a matter of hours or days, superheating the felsic magma at the base of the magma chamber. Superheating sets up vigorous, turbulent convection stirring the whole magma chamber in a matter of days, or weeks. Magma at the base of the chamber, saturated with volatiles, becomes supersaturated as it rises to the top. As well, the increase of temperature of the felsic magma caused by intrusion of mafic magma, decreases the solubility of gases in the felsic magma, a second source of supersaturation. Intrusion of the mafic magma into the chamber serves to quench the mafic magma releasing some of its volatiles to the chamber. The supersaturation in volatiles is deemed sufficient to trigger the pyroclastic eruptions in some cases. Heating of the felsic magma reduces its viscosity, permitting more rapid ascent through fractures and increasing the velocity of convection. Rapid convection caused by magma mixing results in entrainment of mafic fragments in a dominantly felsic eruption throughout the eruption.

6.3.3.3 Andesitic Primary Magmas

Taylor (1968a) rejected an origin of primary andesitic
magma by mantle melting. Trace element analyses showed low concentrations of large cations, low REE abundances, low concentrations of highly charged cations, and low Ni and Co abundances. These features are difficult to reconcile with mantle partial melts, therefore T. Green and Ringwood's (1968) multi-stage process in which andesitic magmas are derived from subducted slabs of quartz eclogite or amphibolite was favoured by Taylor (1968a).

On the basis of experimental work by Nicholls and Ringwood (1972, 1973) Ringwood (1974) stated that andesitic and dacitic magmas can be produced by direct partial melting of pyrolite at depths of less than 40 km only under anhydrous conditions. Olivine tholeiite and saturated tholeiite can be produced by melting pyrolite under H2O-saturated conditions at depths of 70>100 km. Upon rising, the latter liquid differentiates from basaltic andesite to andesite within 30 km of surface by crystallization of olivine. This liquid follows a tholeiitic trend, will have low abundances of incompatible elements, unfractionated REE patterns and will have low abundances of Ni, Mg and Cr relative to MORB and are analogous to the island arc tholeiites.

6.3.4 Origin of Archean Andesites

Condie (1976) classifies Archean andesites into three categories:

1) depleted Archean andesite (DAA), which has flat REE
patterns, negative Eu anomalies, low LIL element contents.
2) low-alkali Archean andesite (LAA) with minor light REE enrichment and low LIL element contents.
3) high-alkali Archean andesite (HAA) with light REE enrichment and high LIL element contents (see Table 6-2, Fig. 6-3).

LAA is suggested to be more abundant than HAA in most greenstone belts with HAA increasing in abundance at upper stratigraphic levels. DAA has only been reported for the Abitibi belt associated with DAT (Condie and Baragar, 1974). DAA has a flat REE pattern like modern arc andesites but higher abundances.

Based primarily upon trace element abundances, Condie (1976) discards fractional crystallization of basalt as an origin for Archean andesites. He prefers a 10 to 20 percent melting of plagioclase peridotite or a 10 to 30 percent melting of eclogite.

6.4 Genesis of Felsic Volcanic Rocks

The possible origins of felsic volcanic rocks are numerous, ranging from 1) partial melting of eclogite, 2) fractional crystallization of basalt, 3) partial melting of amphibolite, greywacke, peridotitic mantle, granitic rocks and granulite (Arth and Hanson, 1975; Hanson, 1978).

6.4.1 Origin by Partiial Melting of Eclogitic Rocks

Quartz eclogite is essentially of basaltic composition, therefore it has minor abundances of K, Rb, Cs, Ba, U, Th,
6.3 Chondrite normalized REE patterns Archean andesites, after Condie (1976). HAA is high alkali Archean andesite; LAA is low alkali Archean andesite; DAA is depleted Archean andesite. Dashed andesite field is for Phanerozoic andesites.
REE pattern for melting of eclogite (after Arth and Hanson, 1975).

a) Eclogite melting compared to a parent tholeiite. Shaded area represents REE patterns of Saganaga Tonalite and dacite produced by partial melting of eclogite. Solid lines show modelling results for 5, 20, and 35 percent partial melting.

b) Lined area is REE pattern of tholeiitic basalts, dotted area is field of Saganaga tonalite and dacite with patterns for various dacites and rhyodacites.
amphibolite. Presence of garnet in the eclogite will produce more severely fractionated patterns in the REE. Additionally, melting of the amphibolite will enrich the melt in Rb quite dramatically and produce lower K/Rb ratios than melting of the eclogite (see Table 6-3, after Glikson, 1976 and Fig. 6-5).

6.4.4 Origin by Partial Melting of Greywackes

Partial melting of pre-existing sedimentary rocks is marked by production of relatively K-rich melts near the ternary minimum in the granite system (Qtz-Plag.-orthoclase, Winkler, 1974) with melts having low K/Rb, high Rb/Sr, low Sr/Ba and high K, Rb, and Sr contents. These are not consistent with a basaltic or eclogitic parentage. Hanson (1978) demonstrates that either 97 percent fractional crystallization or less than 3 percent partial melting of the typical Archean tholeiites is required to produce approximate K, Rb, and Sr contents. Similar problems exist with andesitic or dacitic protoliths. Greywacke-argillite couplets have appropriate composition at least in part. The coarse wacke fraction is mostly volcanic debris of basaltic and dacitic composition which is not appropriate. However, the argillite fraction is enriched in K and Rb and has a lower K/Rb ratio than the source volcanic rocks. Modelling of the origin of REE patterns of the Giants Range quartz monzonites (Arth and Hanson, 1975) by 10 to 50 percent partial melting of
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(after Glikson, 1976)
greywackes indicates this to be a viable model of origin (see Fig. 6-6 and 6-5). The pattern is distinguished from partial melting of tholeiite by higher abundances of light REE.

6.4.5 Trace Element Signature of Various Fractionating Phases

McCarthy and Robb (1977) have modelled the behaviour of Rb, Sr, and Ba upon crystallization of plagioclase, quartz, potash feldspar and biotite as shown in Fig. 6-7.

6.5 Origin of Volcanic Rocks in the Confederation Lake Area
6.5.1 Basalts

Cycle I Basalts

Given the existence of Mg metasomatism (Fig. 5-2a) it is difficult to assign primary magma status to individual samples based upon Mg abundances after the method of Frey et al. (1978). This has been attempted however and samples 77-420, 77-421 are the least evolved on this basis. Using the incompatible nature of P2O5, the degree of partial melting of a mantle source (after Nesbitt and Sun, 1976) varies between 16 and 22 percent. Close to chondritic values for Ti/Zr and Zr/Y (Nesbitt and Sun, 1976) also suggest that these two samples represent relatively complete melting of an Archean mantle.

The basalts of Cycle I plot near the plane of silica saturation in the basalt tetrahedron of Yoder and Tilley (1962) and therefore have been produced (D.H. Green and
REE patterns for felsic volcanic rocks produced by several petrogenetic processes, after Hanson (1978).

- Circles: Archean quartz monzomite derived by partial melting of amphibolite or eclogite.
- Squares: Archean quartz monzonite derived by partial melting of metasediments.
- Diamonds: Dacite from Saipan, derived by fractional recrystallization of a plagioclase and clinopyroxene from a basalt.
- Triangles: Trachyte from Ross Island, Antarctica derived by fractional crystallization of olivine, spinel, clinopyroxene, amphibole, plagioclase, apatite, and anorthoclase from a light REE enriched alkali basalt.
6-6 REE patterns for felsic volcanic rocks produced by melting greywackes (after Arth and Hanson, 1975). Large circles: Greywacke
Stippled pattern: Quartz monzonite
Solid lines: Modelling of 10-50 percent melting
a) Biotite bearing metasediment
b) Hornblende bearing assemblage
Residue is rare-earth distribution of high grade assemblage after 30 percent melting.
The effect of fractional crystallization upon Sr, Rb and Ba (after McCarthy and Robb, 1977).

The effect of fractional crystallization on Sr and Rb(a) and Ba and Rb(b) contents of a granitic melt. Initial melt is at A. From this melt, 47% plagioclase, 49% quartz and 4% biotite are fractionally removed, causing the liquid to move towards B. The composition of the solid phase lies along DE. At B, which represents 55% crystallization of melt A, the liquidus mineralogy changes to 32% plagioclase, 28% quartz, 30% K-feldspar, and 10% biotite. The liquid composition now changes towards C, and the fractionally separated solid compositions lie along FG. HI represents the compositions of biotite in equilibrium with melts along AB, and IJ biotites in equilibrium with melts along BC. K is the composition of a 50-50 mix of E and B; L a 5% addition of biotite I to K, and M a 10% addition of Biotite I to K.
Ringwood, 1967; D.H. Green, 1970; 1973) by 10 to 30 percent melting and separation from residual phases at relatively low pressure such as less than 10 kbars leaving a residue of olivine and orthopyroxene. They have (Fig. 6-8) REE patterns typical of Archean tholeiitic basalts derived by modelling studies of 10 to 20 percent melting of this type of mantle. Using results of Arth and Hanson's (1975) modelling, the basalts of Cycle I appear to be products of 15 to 25 percent melting of a mantle with similar REE abundances. The degree of $P_2O_5$ enrichment over Nesbitt and Sun's (1976) Archean mantle suggests 16 to 23 percent partial melting of the mantle.

6.5.1.2 Cycle II Basalts - Formation E

The basalts of Formation E are variably quartz and olivine normative, therefore have a slightly shallower depth of separation from residual phases than for basalts of Cycle I, that is, pressures less than 10 kbars (D.H. Green, 1971, 1970, 1973; Green and Ringwood, 1967; Fig. 6-1). The basalts of formation E have relatively flat REE patterns typical of DAT and similar to Cycle I again indicating 10 to 25 percent partial melting of Archean mantle. MgO content (3.96 percent), Ti/Zr ratios and abundance of $P_2O_5$ (0.11 percent), (sample 77-405) suggest similar amounts of partial melting of a peridotitic mantle (Frey et al. 1978). Residual phases in the mantle are suggested to be olivine and clinopyroxene (Nesbitt and Sun,
REE patterns for production of tholeiitic liquids by varying degrees of partial melting of the mantle (Modelling by Arth and Hanson, 1975).
6.5.1.3 Cycle II Basalts - Formation F

The basalts of formation F, that is, basaltic andesite are generally quartz normative tholeiites indicative of a shallow (less than 20 km) depth of separation from residual phases and generally lower degrees of partial melting of a mantle source than for Cycle II basalts of formation E (D.H. Green, 1971). P205 abundances (0.08 to 0.11 percent) suggest a maximum of 22 to 30 percent melting. The REE abundances have a flat pattern falling within the 10 to 25 percent limits (Arth and Hanson, 1975) though toward the low margin, assuming the Archean mantle to be similar to the modern mantle. Residual phases are olivine and clinopyroxene.

6.5.1.4 Cycle III Basalts

Within Cycle III the lower part of the basaltic section below the variolitic flows consists of relatively evolved rocks which are discussed later. The most primitive basalts, based upon abundances of Mg, Zr, Y, etc. are above the variolitic flows. Based upon Mg values, samples 77-458 and 77-461 most closely approach a primary magma composition. Calculation of percent melting in the source based upon P205 suggest 100 percent melting of a mantle or pyrolite source, much too high for tholeiitic basalts (Gast, 1968). This suggests apatite fractionation may be involved. Residual phases are possibly phlogopite, olivine
and possibly clinopyroxene based on nonchondritic Ti/Y and Zr/Y ratios (Table E-3) (Nesbitt and Sun, 1976).

However, the REE plots for Cycle III basalts indicate that most samples are within the 10 to 25 percent melting window of Arth and Hanson (1975). Depth of generation of high alumina tholeiites is on the order of 30-40 km, equivalent to about 10 kb (D.H. Green, 1971).

6.5.2 Andesites

Flows and pyroclastic rocks of andesitic composition are within all three cycles in the Confederation Lake area.

6.5.2.1 Cycle I

Sample 77-419 (Table E-1) is the sole representative of the group. Compared to Taylor's (1968) average andesite, the sample is low in Al, Na, and high in Fe, Mg and Ti and low in Sr and high in Cr and Ni. As the cycle I andesites do not have much less Cr and Ni than the basalts and, have only 3 times greater Zr they cannot be products of fractional crystallization of the basalts. The light REE enriched pattern does not suggest fractionation of clinopyroxene and olivine; instead they most closely resemble the low alkali andesite of Condie (1976). As well two parts tholeiitic basalts mixed with one part grey gneiss (Collerson et al., 1976) will satisfactorily produce the LAA of Cycle I (Thurston and Fryer, 1980).

Older sialic material is mixed with Cycle I rhyolites based upon the presence of older xenocrystic high U cores.
in zircons from these rocks (Nunes and Thurston, 1979) indicating clearly the existence of magma mixing.

6.5.2.2 Cycle II

Andesites with flat REE patterns intercalated with the basalts could be derived by a mixture of 50 percent DSV (Condie, 1976) and 50 percent tholeiitic basalt such as sample 77-416. The variable Eu anomaly could be caused by alteration (Sun and Nesbitt, 1978) or varying fO2 causing Eu to partition into +1 and +3 states.

Production of cycle II flat REE pattern andesites by fractionation of a cycle II basaltic parent magma is ruled out as the amount of fractionation required by the major element data is not compatible with the small increase observed in REE concentrations (Fig. 5-13-a, b).

Sample 77-403 in general resembles Condie's (1976) HAA high alkaline andesite which can be produced by 10 to 20 percent melting.

Above the andesites associated with the basalts are the basaltic andesites forming the base of each of the minor cycles in formation F. On the REE plots (Fig. 5-13b, c) 3 different types of basaltic andesite are found: 1) the flat pattern of sample 77-439, 2) the heavy REE enriched pattern of samples 77-437 and 77-435, and 3) the depleted heavy REE pattern of samples 77-448 and 77-442. The concave downward fractionated heavy REE depleted pattern of samples 77-448 and 77-442 is similar to sample 77-403 of Cycle II and
represents 10 to 30 percent partial melting of an eclogite source (Condie, 1976). The relatively flat pattern of sample 77-439 suggests an origin similar to that for the andesites (77-404 and 77-408) of formation E by mixing of tholeiitic basalt and depleted siliceous volcanic rock (Condie, 1976).

The heavy REE enriched patterns of samples 77-437 and 77-438 can be interpreted in several ways: 1) transport of heavy REE by CO₂ rich fluids in the fashion suggested by Collerson and Fryer (1978); 2) fractional crystallization of olivine, clinopyroxene, plagioclase, K-feldspar, and apatite from a heavy REE depleted andesite such as is found beneath the Cycle II rhyolites will yield a heavy REE enriched felsic liquid; 3) fractionation of amphibole from a basaltic andesite parent liquid. (Fountain, 1979; Mysen and Boettcher, 1975). A final possibility is that of a mixture of half tholeiitic basalt and half trondhjemite similar to that described for the Cycle I andesites.

6.5.2.3 Cycle III

The heavy REE depleted patterns of the andesites of Cycle III (Fig. 5-16c) are similar to those of the other cycles and are considered to be caused by partial melting of an eclogitic source.

6.5.3 Felsic Volcanic Rocks

6.5.3.1 Cycle I

The Cycle I felsic metavolcanic rocks have very
fractionated REE patterns, with depleted heavy REE, relatively high K/Rb, low Rb/Sr and high Sr/Ba, therefore they appear to represent partial melting of an eclogitic source (Condie, 1976) (Fig. 6-4). The higher degrees of partial melting are preferred as the Yb concentrations are about 3 times chondrites.

6.5.3.2 Cycle II Formation F

The heavy REE depleted group generally has a small negative Eu anomaly and is extremely depleted in heavy REE. Like Cycle I, they are also interpreted as partial melts of an eclogite source with plagioclase and garnet as residual minerals. This is based upon the low heavy REE abundances and the presence of the negative Eu anomaly (Hanson, 1978). This interpretation is also borne out by the high Sr/Ba and low Ba/Sr ratios.

6.5.3.3 Cycle II East Limb of Regional Synclinorium

Intermediate volcanic rocks have extremely fractionated heavy REE depleted patterns (Fig. 5-15b). Sample 77-467 is stratigraphically above 77-464 and 77-465 and based upon the REE patterns is more closely related to the heavy REE enriched basaltic andesites of the minor cycle (77-437 and 77-488) by about 50 percent fractionation of plagioclase and clinopyroxene, based upon the relative abundances of Zr, Nb, and Y in the two rocks. Alternatively 77-467 could represent mixing of tholeiitic and felsic liquid such as 77-464 a high silica rhyolite. Sample 77-466, a high Si-
rhyolite, has a REE pattern with a slight negative Eu anomaly which may be indicative of fractional crystallization from a heavy REE enriched parent such as sample 77-439.

6.5.3.4 Cycle II, West Limb of Regional Synclinorium

The REE patterns of west limb felsic metavolcanic rocks appear to have similar slope (except specimen 77-409) suggesting that they are related to each other by fractionation. They are, however, not related to the east limb rocks in that the west limb samples, at equivalent SiO2 contents have 4 times greater REE abundances. The pattern suggests origin by partial melting of an eclogite parent material followed by fractionation of clinopyroxene, plagioclase, and quartz.

6.5.3.5 Rocks of Intermediate Composition

There are two types of intermediate metavolcanic rocks in Cycle III: 1) variolitic basalt with a silica content in the intermediate range and 2) pyroclastic rocks stratigraphically above the basalt. They are described here because of the similarity in trace elements to felsic volcanic rocks.

Data from samples 77-449 and 77-451 of matrix and 77-450 and 77-452 of varioles indicate:

1) The mafic fraction is enriched in P2O5 relative to the felsic fraction (Table E-3).

2) The mafic fraction is enriched in Zn, Ba, Sr, Rb, Zr.
Nb, Y and the REE relative to the felsic fraction (Table E-3).

The magnitude of the error associated with the rare earth determinations does not permit an unequivocal statement that the REE are concentrated in the mafic fraction. However, when examined in the light of the Zr and Y data, the rare earth data are believed to be reliable.

On the basis of the above, liquid immiscibility is the preferred petrogenetic theory for the variolitic basalts of Cycle III. Although the variolitic unit is intermediate in composition, its stratigraphic position and the relationship of the trace element data to the underlying fractionated basalts suggest that the variolitic unit is related to the former by fractional crystallization.

The intermediate flows in formation K (samples 77-453, 77-460) represent magma mixing of tholeiitic basalt and a felsic liquid or melting of amphibolite.

6.5.3.6 Cycle III Felsic Metavolcanic Rocks

The felsic metavolcanic rocks of Cycle III have very unusual flat REE patterns and large abundances of incompatible elements. Possible petrogenetic mechanisms for these rocks are:

1) Fractional crystallization of a heavy REE enriched parent.

2) Volatile transport of heavy REE (Collerson and Fryer, 1978).
Evidence of the existence of volatile phase consists of:

1) Cycle III basalts have epidote concentrated at pillow margins (Thurston, 1978).


3) A Cu-Zn-Ag massive sulphide orebody at South Bay Mines associated with the endogenous dome of quartz-feldspar porphyry and consanguinous rhyolitic pyroclastic rocks (Pollock et al., 1972) derived by magmatic explosive activity.

Collerson and Fryer (1978) have reviewed the problem of LIL element mobility, pointing out that carbonate, sulfur and halogen rich volatile phases are possibly generated under granulite facies metamorphic condition enriching partial melts in LIL elements. Fryer and Edgar (1977) suggest that Y and heavy REE abundances in peralkaline undersaturated rocks are greatly increased by volatile phase complexing. The REE patterns for Cycle III rhyolites are similar to those of the Nora Karr and Magnet Cove alkaline bodies but with lower abundances however (Fig. 5-18).

6.6 The Role of Fractional Crystallization in Cyclical Volcanism

Classically, fractional crystallization has been regarded as the main means of producing basalt through andesite to rhyolite in volcanic rock sequences (Bowen,
1928). This process has been considered dominant in genesis of Archean volcanic sequences (Goodwin, 1967; Hallberg et al., 1976). However, rocks of the Confederation Lake Area do not fit this simple model.

The basalts of each cycle consist of two or more Fe enrichment cycles.

In general andesites and basalt i.e. andesites of all three cycles are not relatable to underlying primitive basalts in each cycle by processes of fractional crystallization. In many instances, although the andesites have relatively flat REE patterns, the overall REE abundances are less than the abundances present in the basalts — thus precluding derivation of the andesites by fractional crystallization from the basalts. Fractional crystallization from a basaltic parent magma by crystallization of olivine, plagioclase and minor clinopyroxene would produce a REE pattern with greater abundances than in the basalt, a negative Eu anomaly and a slight increase in the light REE. Individual andesitic rocks such as 77-460 are thought to have been derived from underlying basalts by fractional crystallization. These rocks are marked by relatively large abundances of the indices of fractionation such as Zr.

The felsic metavolcanic rocks of each cycle such as dacite and rhyolite, are genetically related in that the dacite can give rise to the rhyolite by fractional
crystallization of plagioclase, magnetite, apatite, and a mafic phase which is probably biotite. However, trace and major element data do not permit derivation of the felsic metavolcanic rocks from andesitic parent magmas.

6.7 Role of Magma Mixing - Confederation Lake Area

Evidence for the process of magma mixing as a petrogenetic process in the Confederation andesites intercalated with basalts in cycle II consists of a flat REE pattern. Derivation of these andesites from near by basalts by an open system crystal fractionation model (O'Hara, 1977) is successful only with geologically unreasonable assemblages of cumulate phases such as 60 percent clinopyroxene, 3.5 percent apatite, and 30 percent olivine, therefore the composition of the andesite cannot be derived from the basalt by any reasonable model of fractionation. The large Cr, Ni content and low Zr, Y, and Nb content point to a relatively primitive origin as do the REE patterns. Therefore magma mixing of trondhjemite and tholeiitic basalt is preferred (Thurston and Fryer, 1980).

Intermediate to felsic volcanic rocks of Cycle II are best explained by the interaction of the processes of magma mixing and the generation of felsic melt by partial melting of tholeiite (Helz, 1976). When the felsic metavolcanic rocks of the east limb of Cycle II are in stratigraphic order from bottom to top (77-465, 77-464, 77-466, 77-467) the REE patterns suggest that 77-464, and 77-465 were
derived by partial melting of amphibolite (cf. Arth and Hanson, 1975). Using the premise that a felsic liquid can be produced by partial melting of a tholeiite (Hélz, 1976) the liquid for samples 77-464 and 77-465 could be produced by about 20 percent partial melting of tholeiite. Magma mixing occurred subsequently producing violent Plinian activity (Sparks et al. 1977) exemplified by samples 77-466 and 77-467 both pumiceous pyroclastic rocks.

In the subaqueous ash-flows of Cycle II on both limbs of the regional synclinorium, several types of fragments with appreciable differences in Si content are observed as well as differences in composition between ash size fragments and larger fragments (Sopuck, 1977). The presence of Plinian ash flows with mafic essential clasts in one stratigraphic unit (chapter 3) supports the magma mixing hypothesis of Sparks et al. (1977), as the preferred mode of origin of the Cycle II ash flows.

In the intermediate pyroclastic rocks of Cycle III violent Plinian activity is evident, but fragments of contrasting composition are not as commonly observed. However the trace element pattern in Cycle III permits origin of the intermediate pyroclastic and flow rocks by magma mixing (samples 77-428 and 77-453).

6.7.1 Genesis of Andesites

Magma mixing is the favoured petrogenetic process for the genesis of andesite and dacite in several recent works
(Eichelberger, 1975, 1978; Fountain, 1979). The detailed chemical criteria necessary to demonstrate that the process has been active in forming a suit of rocks are given by Anderson (1976). They involve disequilibrium assemblages of minerals and glasses. However the criteria are not applicable to metavoanic rocks as metamorphism obscures such features as fragment boundaries and glass inclusions in phenocrysts.

6.8 The Role of Liquid Immiscibility

6.8.1 Preamble

Liquid immiscibility as a petrogenetic process has a chequered past. As first proposed by Rosenbusch in 1887, the process consists of splitting of magmatic liquids into a felsic and mafic fraction during differentiation as a means of producing a felsic liquid. Liquid immiscibility is suggested by Colinas et al. (1976) to explain the occurrence of siliceous varioles in high Fe tholeiitic basalts. The variety of modes of occurrence of the varioles concentrated in pillow centers, or pillow rims, in fractured hyaloclastic fragments, and as massive flows has been taken as evidence that the varioles are a pre-eruption phenomenon. Siliceous and Fe rich glasses described from the matrix of lunar basalts are attributed to liquid immiscibility (Roedder and Weiblen, 1970).

Bowen (1928) listed the following textural criteria necessary to prove liquid immiscibility: 1) two glasses of
contrasting composition in the same rock, 2) occurrence of identical crystals in both glasses, and 3) coalescence of globules to form distinct layers, such as in the massive xenolithic flows. Greig (1928) and Bowen (1928) suggested from experimental work that liquid immiscibility occurred at very high temperatures, however Roedder (1951) documented stable liquid immiscibility at lower temperatures in the system $K_2O-FeO-Al_2O_3-SiO_2$. Liquid immiscibility has been described metastably Visser and Koster van Groos (1976), and stably (ibid, 1977, 1979) in a part of the system of importance in basalt genesis.

Watson (1976) suggested, based upon experimental data, that in liquid immiscibility the mafic melt is enriched in P, the REE, Ta, Ca, Cr, Ti, Mn, Mg, Sr, and Ba, and only Cs is enriched in the felsic fraction. Vogel and Wilband (1978) examined major and trace element abundances of a composite dike of mafic and felsic parts and found higher concentrations of light REE in the mafic fraction suggesting that Watson's (1976) prediction based upon experimental data is correct. Ryerson and Hess (1978) suggest that this partitioning is a function of the felsic melt being more highly polymerized with Al substituting more extensively for Si in tetrahedral co-ordination; alkalies fill unsatisfied charges permitting enrichment of felsic melts only in elements of low charge density such as Cs whereas the less highly polymerized mafic melt is
enriched in elements of high charge density such as the REE.

The largely experimental work of Watson (1976) and theoretical explanation by Ryerson and Hess (1978) is supplemented by the observations on the variolitic basalts described by Gelinás et al., (1976) in which they point out the partitioning of P into the mafic melt in contrast to its concentration in felsic melts where processes of fractional crystallization are followed (Anderson and Gottfried, 1971; Philpotts, 1977). Liquid immiscibility has a different chemical signature than fractional crystallization.

6.8.2 Application to the Confederation Lake Area

Textures in the variolitic basalt of Cycle III suggest that it represents a massive variolitic flow of Blake River type which Gelinás et al., (1976) suggest on the basis of preserved quench textures, flow differentiation studies and major element chemical trends to have been produced by rapid cooling of a two liquid magma. In the variolitic basalts of Cycle III of the Confederation Lake area there is concentration of $P_2O_5$ in the mafic fraction as described by Gelinás et al., (1976) in Table E-3 in which samples 77-449 and 77-451 of the matrix and 77-450 and 77-452 represent the variolite.

Greig (1927) devised a ternary diagram with end members $SiO_2$-$CaO+MgO+FeO^+$-$TiO_2$-$K_2O+Na_2O+Al_2O_3$ upon which a region
of liquid immiscibility was postulated to occur between SiO₂ and CaO+MgO+Fe0*+TiO₂. Basalt and andesite of Cycles II and III plotted on Greig's (1972) diagram (Fig. 6-9) indicate that these rocks are in part within the area of liquid immiscibility. Limited data suggest that P and TiO₂ may increase the width of the immiscibility solvus (Freestone, 1978) and that pressure has the same effect up to 5 kb (Watson and Naslund, 1977) although CO₂ has the opposite effect.

Following the prediction by Watson (1976) based upon experimental work, REE data on variole-matrix pairs in Cycle III basalts (Fig. 5-16c) have enrichment of REE in the matrix of proposed immiscible pairs. The pattern of LIL element enrichment in the mafic pair is also evident in the data for Zr, Y, Nb, Ba and Sr (Table E-3).

Textural, major element, and trace element data all suggest that the variolitic basalts of Cycle's II and III originated by processes of liquid immiscibility.

The major and trace element abundances of the varioles in basalt of Cycle III is similar to that of overlying rhyolite of Cycle III in that it has low Al₂O₃, high TiO₂, and FeO* as well as REE, Zr, Nb, and Y abundances (Table E-3, Fig. 5-16c and 5-18). Cycle III rhyolites have unfractionated REE patterns, with large abundances of the heavy REE (Fig. 5-18).

Fractionation of virtually any mafic mineral (Hanson,
Figure 6-10: $\text{SiO}_2 \cdot \text{CaO} \cdot \text{MgO} \cdot \text{FeO} \cdot \text{TiO}_2 \cdot \text{Na}_2\text{O} \cdot \text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3$ after Creig (1928)

6-9 $\text{SiO}_2 - \text{CaO} + \text{MgO} + \text{FeO}^* + \text{TiO}_2 - \text{K}_2\text{O} + \text{Na}_2\text{O} + \text{Al}_2\text{O}_3$ diagram. (after Greig, 1927) "Liquid immiscibility" occurs in the dashed area.

a) Cycle I
b) Cycle II
c) Cycle III

The lines join analyzed matrix-variole pairs from Cycle III. Single points represent analyzed variolitic basalts, shaded areas represent analyzed non-variolitic basalts.
1978) will cause depletion in heavy REE in any magma derived from a more mafic parent magma. Rhyolites derived by partial melting of sedimentary rocks, granulites, eclogite, amphibolite or granitic rocks will produce a REE pattern varying from somewhat fractionated to extremely fractionated (Arth and Hanson, 1975; Glikson, 1976a).

The data with respect to Rb, Sr, Ba and the general indicates of fractionation (Frey et al. 1974) suggest that the rhyolites of Cycle III are related to the underlying dacites of Cycle III by fractionation of plagioclase, K-feldspar, quartz and biotite and an oxide mineral (McCarthy and Robb, 1977). Therefore the unfractionated REE pattern of the rhyolites is explained as follows:

Liquid immiscibility is enhanced by high $f_{O_2}$ (Naslund 1976) and high pressure but somewhat depressed by CO$_2$ (Watson and Naslund, 1977). Irvine (1976) indicates that the role of H$_2$O may be significant. Volatiles may also play a role in enrichment of the rhyolitic rocks in LIL elements. Collerson and Fryer, 1978) have reviewed the problem of LIL element mobility, pointing out that carbonate, sulfur, and halogen rich volatile phases are possibly active under granulite facies metamorphism in enriching partial melts in LIL elements.

U is transported by CO$_2$ rich fluids (Naumov, 1959); Th by chlorides and sulphate rich sea water (Rogers and Adams, 1969); Rb, Cs, K and Pb by halogen rich fluids (Wedepohl,
1969). U content of cycle III rhyolites is uniformly below 1 ppm (Table E-3), hence, the volatile phase appears to have been a halogen rich brine, although U could have been removed during metamorphism.

The fluid phase may play an important role in the basaltic magmatism of Cycle III. Sample 77-460, the most fractionated mafic metavolcanic rock, based upon TiO$_2$ and Zr content, also has a greater content of both CO$_2$ and H$_2$O$^+$, although the high volatile content may be a function of extreme fractionation as much as 80 to 90 percent.

In summary, the most likely petrogenetic process for cycle III rhyolites is large scale liquid immiscibility.
CHAPTER 7

Tectonic Reconstruction

7.1 General Statement

Attempts to make tectonic reconstructions of Archean terrains are fraught with peril. In order to develop an adequate scheme, one must take into account rock types and their distribution in time and space, and chemical composition of the volcanic rocks and, structure. Tectonic models are separable into two broad classes, first "fixist" models involving processes acting in place, and second, models involving some sort of plate tectonic process.

7.1.1 Fixist Concepts

Fixist tectonic concepts for the Archean low grade volcano-sedimentary superbelts are considered (Young, 1978) here only if published since the acceptance of plate tectonics, that is in the last 15 years.

Representative schemes (Anhaeusser et al. 1969); McGlynn and Henderson, 1970; Windley and Bridgewater, 1971; Viljoen and Viljoen, 1971; Young, 1978; Kroner, 1977) all involve rifting of pre-volcanism basement along fundamental fractures followed by development of laterally extensive ultramafic to mafic plates surmounted by areally restricted felsic volcanic centers.

The adjacent high grade sedimentary superbelts (Young, 1978) such as the English River subprovince represent synvolcanic in-filling of a basin above an older sialic
basement complex (Harris and Goodwin, 1976) although McGlynn and Hehderson (1970) suggest the metasediments are largely post volcanic in parts of the Slave Province. The boundary between the volcanic-superbelts and the paragneiss superbelts is generally faulted (Thurston and Breaks, 1978) and gravity evidence (Barlow et al., 1976) suggests that the depth extent of the metasediments is considerable south of the Sydney Lake Cataclastic Zone, the faulted south boundary of the Uchi subprovince.

Subsidence of the volcanic-granitic superbelts is probably a gravity driven mechanism as suggested by Gorman et al. (1978) with thrusting developing at the margins of the subsiding volcanic belt transporting material toward the center of the central synclorium.

Study of large scale relationships in Precambrian terrains has resulted in two contrasting theories of shield genesis; onion skin tectonics is one in which a central ancient sialic nucleus develops successively younger orogenic belts on the periphery of the nucleus (Goodwin, 1968; Engel and Kelm, 1977) and the cratonization theory of Clifford (1968, 1970) in which an old sialic nucleus or plate is transected by younger mobile belts which rework the older material structurally and perhaps add intrusive rocks (Williams, 1977). In review of the African shield Kroner (1977) has shown, based upon geochronologic and field data, that, for example the Rhodesia and Kaapvaal
cratons, each in excess of 3.5 b.y. old, are separated by the Limpopo mobile belt, built by a re-working at about 2.7 b.y. of the >3 b.y. old material. This represents a picture then of cratonization and later re-working of mobile belts, which persisted, in the African shield, through to Pan African event (Bertrand and Lasserre, 1976) in the Hoggar region. The re-working in the Hoggar region did not simply involve addition of granitic material in the mobile belt as is the case in the Limpopo belt (Kroner, 1977) but rifting of basement and deposition of volcanics, sediments, and emplacement of plutonic rocks, followed by an orogenic cycle.

7.1.2 Plate Tectonic Concepts

Plate tectonics has been applied to the Archean in a general sense by Talbot (1973), with more detail added by Goodywin and West (1974) who proposed the possibility of:
a) simple convergent plate system with volcanism on pre-existing mafic crust adjacent to a down-going slab of oceanic crust with sediments accumulating on both sides of the volcanic pile, or
b) a convergent plate model with a migrating subduction zone resulting in the generation of successively younger volcanic piles with intervening metasedimentary areas or
c) full convection system with a central spreading center with two island arc systems developing adjacent to areas of older sialic crust.
Langford and Morin (1976) and Burke et al. (1976) have applied the concept of a migrating subduction zone to north-western Ontario and the Superior Province generally on the basis of scanty geological, geochemical, and geophysical evidence.

Tarney et al. (1976) propose that the marginal or back-arc basin is the closest Phanerozoic analogue to the Archean greenstone belt - gneiss belt couple. They compare the "Rocas Verdes" complex of southern Chile with typical Archean greenstone belts and point out the following similarities:

1) Ophiolites abut and overlap upon pre-existing deformed Paleozoic basement and are cut by younger calc-alkaline plutons and associated felsic to intermediate volcanics.
2) The marginal basin is similar in size, structure, and rock types to a greenstone belt and distribution of metamorphic grade is similar.
3) The pattern and style of deformation of the marginal basin is similar.
4) The dominant rock type of the Rocas Verdes basin is greywacke with abundant volcanic detritus similar to Archean sedimentary superbelts.
5) Tarney et al. compare the composition of the Rocas Verdes complex volcanics mainly tholeiitic basalt, to Archean volcanic rocks.
6) Andesites and more felsic volcanic rock types are absent.
in the Rocas Verdes complex, but are found in other marginal basin environments such as Japan (Sugimura and Uyeda, 1973).

7) The batholith cutting the Rocas Verdes complex is similar in structural behaviour and chemistry to Archean post-tectonic batholiths.

7.1.2.1 Chemical Studies

Numerous chemical studies have postulated an island arc environment for Archean calc-alkaline volcanic rocks (Gelinas et al., 1977; Hallberg et al., 1976; Dykes, 1979; Pearce et al., 1977). Volcanic rocks of the calc-alkaline suite are found in two tectonic environments, the active continental margin and the oceanic island arc. The two environments contain rock suites which differ little mineralogically. The chemical differences between the two environments summarized by Dykes (1979) are shown in Table 7-1. Significant features of this compilation are the lower content of Ba, Rb, Sr, and Zr in the island arc environment and the similar Co and V content of both environments. From this compilation, Dykes devised a variation diagram employing Ba+Rb+Sr on the ordinate and Co+V in the abscissa which effectively separates rock suites from the two environments.

Tarney et al. (1976) have compiled data on the trace element chemistry of Archean basalts vs marginal basin basalts (Table 7-2) which suggests the marginal basin
Table 7-1  Trace element compositions of Island Arc and Active Continental Margin calc-alkaline volcanics

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<th>ACTIVE CONTINENTAL MARGIN</th>
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<td></td>
<td>Range</td>
<td>Average</td>
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<tr>
<td>Ba</td>
<td>1400 - 300</td>
<td>700</td>
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<tr>
<td>Rb</td>
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<tr>
<td>Sr</td>
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<td>650</td>
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<tr>
<td>Co</td>
<td>40 - 12</td>
<td>20</td>
</tr>
<tr>
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<td>120</td>
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<tr>
<td>Cr</td>
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<tr>
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<td>7</td>
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<tr>
<td>Sc</td>
<td>60 - 12</td>
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After Dykes (1979)
Table 7-2  Typical values of selected elements in Archean greenstone basalts compared with suggested values for fresh ocean ridge basalts, island arc tholeiites and preliminary data for marginal basin basalts.

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<td>407</td>
<td>150</td>
<td>3</td>
<td>97</td>
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<td>-</td>
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<td>Australia</td>
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<td>106</td>
<td>10</td>
<td>102</td>
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<tr>
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<td>-</td>
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<td>85</td>
<td>-</td>
<td>124</td>
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<tr>
<td>Vermilion</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td>150</td>
<td>-</td>
<td>70</td>
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<tr>
<td>Mean</td>
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<td>120</td>
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<td>80</td>
<td>5</td>
<td>150</td>
<td>27</td>
<td>.90</td>
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After Tanney et al (1976)
analogy may be valid.

7.2 Tectonic Reconstruction of the Confederation Lake Area

7.2.1 General Statement

Any reconstruction of tectonic environment and processes from the Confederation Lake area must take into account the form and volcanic style of greenstone belts, the relationship with high grade metasedimentary belts and older basement and the structural behaviour, age relations and composition of the granitic plutons.

Blackburn (1979) makes the interesting observation that although Schwerdtner et al., (1979) can account for the crustal shortening in the Wabigoon subprovince by diapirism of the surrounding batholiths this sort of vertical tectonics cannot account for the many thrust faults he has observed in the Wabigoon subprovince. Therefore he observes that "the only mechanism that allows both for uplift and thrusting is collision tectonics and crustal shortening, a necessary adjunct of plate tectonic theory".

7.2.2 Chemical Aspects

However as described in Chapter 6, certain trace elements such as Co, V, Ti, Zr, Y, Nb, Ce are only moderately mobile (Frey et al., 1968; Herrmann et al., 1974; Ferrara, 1976). Therefore an attempt will be made, using the diagrams of Pearce and Cann (1973) and Dykes (1979) to postulate environments for the metavolcanic rocks of the Confederation Lake area. It should be recalled in
the course of using these diagrams that the principal causes of chemical signatures of various paleoenvironments are variables such as P, T, fO2, and extent of crustal contamination. However it should be borne in mind that the effects of contamination, mixing etc. can completely swamp the effects of crystal fractionation etc. as demonstrated by Dupuy et al. (1979) for two adjacent strata-volcanoes nominally within the same tectonic environment in Sardinia.

Figure 7-1 shows that the rocks of Cycles I, II, and III in the Confederation Lake area are of island arc affinity. Pearce and Cann (1973) plots employing Y, Sr, and Ti demonstrate that the basaltic rocks of Cycle I are of oceanic and low K tholeiite affinity and those of Cycle II and III are similar. Given their potential inapplicability to Archean terrains they are not presented here.

7.2.3 Reconstruction

Taking Blackburn's (1979) observation to be valid, one must attempt to reconcile the apparently rift related distribution of the metavolcanic rocks of the Confederation Lake area and the probable presence of both vertical and horizontal tectonics which is most readily accomplished by postulating the existence of a form of plate tectonics in Archean time.

The simple convergent plate system with volcanism taking place on pre-existing crust adjacent to a subduction
zone (Goodwin and West, 1974) does not provide a mechanism for the development of the extensive accumulation of sediment in the English River subprovince, nor does it explain the cyclical nature of the volcanism. Goodwin and West's (1974) migrating subduction zone model which results in successively younger volcanic piles with intervening sedimentary belts does not explain the cyclicity of volcanism in the Uchi subprovince (Nunes and Thurston, 1977) or the existence of 2 cycles of volcanics in the Wabigoon subprovince to the south (Blackburn et al. 1978). Goodwin and West's (1974) third alternative of a full double convecting system with simultaneous development of two island arc systems does not fit with the existing geochronologic data for the Wabigoon subprovince (Davis et al. 1979) or the Uchi subprovince (Nunes and Thurston, 1979). Neither does this system explain the existence of an intervening strip of older basement (Krogh et al. 1976) in the southern English River subprovince; or the asymmetry of the large sedimentary superbelts (Quetico and English River subprovinces).

The back arc basin models of Tarney et al. (1976) does account for:

1) the extensive English River metasediments represent the filling of the back arc basin;
2) the older sialic basement described by Krogh et al. (1976)
3) the late granitic rocks and their mode of intrusion (believed to be similar to that described by Schwerdtner et al., 1979 in the Wabigoon subprovince);
4) the general synformal nature and size of the Uchi-Confederation belt;
5) distribution of metamorphic grade and intensity of deformation;
6) the types of metasedimentary rocks in the volcanic and sedimentary "superbelts" (Young, 1978);
7) the chemical similarities previously described.

However, Hyde (1975) and Ericsson (1979), through development of facies models in the Abitibi subprovince and the Kaapvaal craton respectively, have shown that transitions between fluvial and alluvial fan to abyssal environments are abrupt in Archean terrain. As well, Gupta (pers. comm. V.K. Gupta, 1979) has shown that the vertical extent of the English River metasediments is on the order of 10 km south of the Sydney Lake Cataclastic Zone whereas the depth extent of the volcanics in the Uchi subprovince does not exceed 5 km. On the basis of sedimentologic evidence, Ericsson (1979) has suggested that the abrupt transition from the subaerial-shallow marine model to a deep water facies is marked by a fault scarp which effectively removes the shelf environment present in many Phanerozoic environments. An interesting corollary of this is the fact that shelf sediments such as carbonates and
Figure 7-2

A - Cycle I volcanism
B - Cycle II volcanism
C - Cycle III volcanism before foundering of the sector graben
D - Foundering of the sector graben

E - Post-foundering volcanism
Figure 7-2
TECTONIC RECONSTRUCTION

- Mafic volcanics
- Subvolcanic intrusion
- Granitic rocks
- Sialic basement
- Felsic volcanics
- Sediments
mature clastic sediments are scarce in the Archean (Armstrong, 1960).

These facies models of Archean sediments reviewed above can be incorporated into the back arc basin model of Tarney et al. (1976) as shown in Figure 7-2 particularly if the extensional phases of the scheme persists through volcanism. One of the major difficulties with cyclical volcanism over a long time span in the Confederation Lake area is the seemingly fortuitous recurrence at scattered time intervals of volcanism in the same area. Similar volcanism over long time intervals is known in Japan. The apparent restriction of the three cycles of volcanism to a small area reflect the existence of some sort of a fundamental fracture or rift which controlled the location of volcanism.

The detailed evolution of the Uchi-Confederation area is proposed as follows:
1) extension of a pre-volcanism sialic basement, producing a marginal basin;
2) development of Cycle I mafic and subsequent felsic volcanism from a shield volcano in relatively shallow water; with simultaneous clastic sedimentation of the marginal basin; Fig. 7-2a.
3) sedimentation of carbonate sediments and possible cessation of subduction;
4) the commencement of basin extension, further development
of trap door basin morphology (cf. Hoffman and McGlynn, 1977), commencement of Cycle II mafic volcanism presumably by renewal of subduction, build up of a stratovolcano with violent plinian eruptions eventually resulting in subaerial deposition of the upper part of Cycle II on the west limb of the regional synclinorium. (Fig. 7-2b).

5) Deposition in the marginal basin of clastic sediments during volcanic quiescence caused by cessation of subduction;

6) Development, during renewed subduction, of Cycle III volcanism involving construction of a stratovolcano. The edifice founded due to withdrawal of magma and extension of the basin, followed by resurgent felsic volcanism in a sector graben, followed by a terminal hydrothermal stage resulting in deposition of the South Bay Mine Cu, Zn, Ag orebody (Fig. 7-2c, d, e).

7) Termination of subduction followed by movement of the island arc toward the crystalline basement closing and deforming the marginal basin.

Trace element evidence for the polarity of the plate tectonic process in the form of the trace element data on the granitic rocks of this area vs the area to the south or trace element data on the scattered metavolcanic rocks to the south (Breaks and Bond, 1975) do not exist. Convincing evidence of the existence of horizontal tectonics such as occurrence of ophiolites do not exist because of the lack
of shallow shelf areas onto which ophiolites are obducted (Church, 1972).

Because of the high geothermal gradient postulated for the Confederation Lakes area (Thurston and Breaks, 1978) the thinner crust would have been more ductile than Phanerozoic crust as evidenced by the horizontal tectonics and extensive deformation in Archean gneissic areas (Sheraton et al., 1973). Back arc extension in the Archean would result in crustal thinning and extrusion of basaltic lavas in shallow seas. Archean sea depths were probably shallower than present (Hargraves, 1976). Less rifting in Archean back arc basins, coupled with an abundant rate of magma supply would tend to make sheeted dike complexes thinner or non-existent (DeWitt and Stern, 1978).

The only potential evidence for polarity of subduction is in the northward transport direction of allochthonous metavolcanic rocks at Springpole Lake to the north (Thurston, 1978) and the sequence of gneiss domes south of the anticlinal allochthonous Red Lake metavolcanic belt.
CHAPTER 8
Summary and Conclusions

8.1 Summary

The rocks of the Confederation Lake area are 3 mafic to felsic volcanic cycles. Each cycle begins with pillowed subaqueous basalt to andesite and grades upward into dacite to rhyolite which are predominantly pyroclastic. The Confederation Lake area has proximal facies volcanic rocks, whereas the coeval dominantly sedimentary accumulations with minor volcanic rocks of the English River subprovince are a distal facies. The large scale structure of the Confederation Lakes area is interpreted as a medial synclinorium with an anticlinorium on the east side of the belt. The anticlinorium has been produced by thrusting.

Cycle I is 2500 m of pillowd mafic subaqueous flows and about 2700 m of intermediate ignimbrites, debris flows and minor air fall tuff succeeded upward by about 300 m of felsic ignimbrites.

Cycle II is a basal 2300 m of amygdaloidal pillowd basalt to andesite of subaqueous origin on the west limb of the fold. Correlative with this on the east limb there are four 150-200 m thick minor cycles ranging from subaqueous pillowed basaltic andesite to air fall rhyolite tuff. Overlying these rocks on both limbs of the fold there are several subaqueous intermediate ignimbrites and minor
intercalated flows grading upward from pumice conglomerates to fine tuffs interbedded with subaqueous debris flows. Two subaerial ignimbritic flow units of tuff, lapilli and tuff breccia are succeeded by 60 m of shallow water marble. About 200 m of correlative felsic pumiceous subaqueous ignimbrite outcrops on the east limb.

Cycle III has a base of 3400 to 5500 m of pillow subaqueous basalt to andesite flows with 2 variolitic horizons on the west limb, this is somewhat thinner on the east limb and is overlain by 2000 m of intermediate to felsic ash flows. It is broken by the sector graben which contains 1500 m of felsic flows and 450 m of ash flow with minor intercalated air fall material, all of Cycle III. This is succeeded by 200 m of debris flows and 60 m thick mafic flow. A complex of felsic flows, pyrolastic rocks, and the endogenous dome, at the South Bay Mine are at the top of the sequence.

The basalts of all three cycles are tholeiitic, whereas the upper intermediate to felsic part of each cycle have a calc-alkaline trend. The basalts are olivine normative in Cycle I and variably olivine and quartz normative in Cycles II and III. Alteration involving additions of Mg, Ca and Na is described for some basalts in each cycle.

Ti as an index of fractionation suggests basalts of all cycles have enrichment of Fe, V, Sc, Co, Zr and Y and a decrease of Ca, Al, Sr and Mg which represent
crystallization of olivine, plagioclase and, late in the Fe enrichment cycle, clinopyroxene.

The basaltic liquids evolve in composition from olivine normative tholeiites in Cycle I to variably quartz and olivine normative tholeiites to high-alumina tholeiites in Cycle III. This evolution is also marked by successively higher Y and Zr contents. The basaltic liquid of Cycle III entered a region of liquid immiscibility.

Basaltic andesite and andesite intercalated with the basalts of Cycles I and II are of two types: those with flat REE patterns and those with fractionated REE patterns. Basaltic andesites and andesites associated with the minor cycles are of three types:
1) flat REE patterns
2) heavy REE enriched
3) heavy REE depleted concave downward REE pattern.

Felsic rocks of each cycle are dacite to rhyolite and are in two groups: a heavy REE depleted group and heavy REE enriched group. Inter-relations of abundances of Ca, Al, Cr, Ni, Zr, Y, Nb, K etc. suggest that in most instances felsic volcanic rocks within any one cycle are related by fractionation of plagioclase, K-feldspar, quartz, and biotite.

Felsic volcanic rock types in Cycle I evolve to more siliceous differentiates resulting in a slow rise of Y and Zr values. Cycle II felsic volcanic rocks have the Cycle I
low Y, Zr trend and a trend involving higher contents of Y and Zr. Cycle III felsic volcanic rocks have only the high Y and Zr trend.

Fractional crystallization is responsible for differentiation within the basaltic sequences and has brought about the dacite to rhyolite transition in most instances, but the process is not responsible for the basalt to rhyolite trend within each cycle. Other petrogenetic mechanisms have also been active.

The heavy REE enriched andesites were produced by mixing of tholeiitic basalt and trondhjemite and the flat REE pattern andesites were produced by mixing of tholeiite and Condie's (1976) DSV. Cycle II felsic magmatism is viewed as initial production of heavy REE depleted rhyolite by partial melting of amphibolite followed by magma mixing producing violent plinian activity (cf. Sparks et al., 1977) which resulted in the overlying felsic volcanics with flat to heavy enriched patterns.

Liquid immiscibility produced the variolitic basalts of Cycles II and III, minor amounts of felsic volcanic rocks in Cycle II and the dacites and rhyolites of Cycle III.

8.2 Conclusions
1) Cyclical volcanism in the Confederation Lakes area consists of three basalt to rhyolite cycles, corresponding to the major cycle and minor and mini cycle scales of Anhaeusser (1971).
2) Cycle I represents eruption in a shallow water environment from a shield volcanic of mafic flows followed by Plinian eruption of felsic ignimbrites. In Cycle II, the Narrow Lake area on the west limb of the fold represents a relatively proximal environment for both basalt and andesite flows and the overlying pyroclastic rocks.

The intermediate pyroclastic sequence above the basaltic flows commenced as a mixture of proximal subaqueous ignimbrites and debris flows, with minor flows capped by two ignimbrite flow units which form a single cooling unit. The minor cycles of formation F represent another volcanic source based upon chemistry and facies analysis. Cycle II activity commenced with quiet effusion of nonviscous basalts and andesites, later pyroclastic rocks are the result of Plinian eruptions into relatively gentle volcanic slopes. In a large scale sense this pattern represents formation of Krakatoan caldera which did not progress to the resurgent stage.

Cycle III volcanism commenced with quiet extrusion of basalt flows, followed by Plinian eruptions of felsic ash flows and flows, development of a sector graben filled with later flows, ignimbrites and debris flows.

3) The style of volcanism evolves from cycle to cycle, with Cycle I marked by construction of a shield volcano, Cycle II by construction of a shield volcano which evolved to a
stage II of the Smith and Bailey (1969) caldera cycle, whereas volcanism in Cycle III, involving a similar edifice, proceeded through a full caldera cycle involving resurgence and later hydrothermal activity.

4) There are Fe enrichment cycles in the basalts caused by fractional crystallization of olivine, plagioclase and minor clinopyroxene. Si enrichment in dacites and rhyolites is caused by fractional crystallization of plagioclase, quartz, K feldspar and biotite.

Each cycle of basalt to rhyolite appears to have involved several magmatic liquids. Initial tholeiitic basalts produced by 30 percent partial melting of mantle, intercalated andesites with flat REE patterns are produced by mixing of tholeiite and rhyolitic liquid and intercalated andesites with fractionated REE patterns are produced by melting of amphibolite.

The basalts of Cycle I are considered to have originated as a partial melt of mantle material. The andesites of Cycle I are considered to have originated by melting of eclogite or mixing of theoleiitic basalt and trondhjemite basement. The rhyolites originated by partial melting of eclogite.

Basalts at the base of Cycle II originated by partial melting of mantle, the intercalated andesites by mixing of DSV (Condie, 1976) and tholeiitic melt. The andesites of formation E with a flat REE pattern originated by magma
mixing and the heavy REE depleted andesites originated by partial melting of eclogite. The overlying basaltic andesites of formation F include the flat and heavy REE depleted types with origins similar to the two types described above and a heavy REE enriched, basaltic andesite which originated by mixing of tholeiite and DSV or partial melting of eclogite. The felsic volcanic rocks of formation F comprise a heavy REE depleted suite and a heavy REE enriched suite; probable origins are partial melting of amphibolite for the former and possible amphibole fractionation from basaltic andesite or liquid immiscibility for the latter. The felsic volcanic rocks of formation H represent both partial melting of eclogite followed by magma mixing.

The high alumina tholeiites of Cycle III have originated by partial melting of mantle. Differentiation of Cycle III basalts proceeded by fractional crystallization of olivine, plagioclase and clinopyroxene until the liquid became immiscible, producing variolitic basalts. The two liquids formed the high Fe basaltic matrix and low K rhyolite variolites. The unique trace element signature of liquid immiscibility is the partitioning into the mafic portion of the system of \( P_2O_5 \) and the LIL elements. The variolites have a unique heavy REE enriched character which is also present in the Cycle III felsic volcanic rocks suggesting they are the felsic
portion of a two liquid system, derived from liquid immiscibility during basaltic magmatism.

5) The variety of petrogenetic processes involved and their inter-relationships suggest that cyclical volcanism is a complex interplay of fractional crystallization of an original mantle-derived liquid followed by various types of magma mixing, re-melting of basaltic rocks and liquid immiscibility.

6) Cyclical volcanism in the Confederation Lakes took place over an appreciable span of time as Cycle I rhyolites are 2958.6 ± 1.7 m.y. old, Cycle II rhyolites are 2794 ± 6 m.y. old, and Cycle III rhyolites are 2739 ± 31 m.y. old.

7) The preferred tectonic model for this Archean volcanic sequence is a back arc basin similar to that of Tarney et al., (1976).
THE VOLCANOLOGY AND TRACE ELEMENT GEOCHEMISTRY OF CYCLICAL VOLCANISM IN THE ARCHEAN CONFEDERATION LAKE AREA, NORTHWESTERN ONTARIO
APPENDICES

by

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Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Faculty of Graduate Studies
The University of Western Ontario
London, Ontario
March 1980

VOLUME II

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# TABLE OF CONTENTS

## VOLUME II APPENDICES

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOMENCLATURE AND CLASSIFICATION</td>
<td>293</td>
</tr>
<tr>
<td>APPENDIX B – U/Pb GEÖCHRONOLOGY</td>
<td>297</td>
</tr>
<tr>
<td>APPENDIX C – O ISOTOPIC DETERMINATIONS</td>
<td>349</td>
</tr>
<tr>
<td>APPENDIX D – ANALYTICAL METHODS, PRECISION &amp; ACCURACY</td>
<td>353</td>
</tr>
<tr>
<td>APPENDIX E – ANALYTICAL RESULTS</td>
<td>355</td>
</tr>
<tr>
<td>APPENDIX F – SAMPLE DESCRIPTIONS AND LOCATIONS</td>
<td>385</td>
</tr>
<tr>
<td>APPENDIX G – SUPPLEMENTARY STRUCTURAL DATA</td>
<td>398</td>
</tr>
<tr>
<td>APPENDIX H – DISCUSSION OF TRACE ELEMENT MOBILITY</td>
<td>404</td>
</tr>
<tr>
<td>APPENDIX I – PUBLICATIONS</td>
<td>410</td>
</tr>
<tr>
<td>a. Thurstonand Breaks (1978)</td>
<td>411</td>
</tr>
<tr>
<td>b. Thurston (1980)</td>
<td>425</td>
</tr>
<tr>
<td>c. Gupta, Thurston and Dusanowskj</td>
<td>448</td>
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<tr>
<td>d. Thurston et al. (1978)</td>
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<td>517</td>
</tr>
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<td>VITA</td>
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</tr>
</tbody>
</table>
APPENDICES
APPENDIX A

Nomenclature and Classifications

Rocks are classified in the field and introductory chapters by modal color index (Ayres, 1969), the sum of mafic minerals in the rock (chlorite, amphiboles, biotite, and minor clinopyroxenes). The color index system is an approximate measure of chemical composition as the dark minerals contain most of the Fe and Mg in metavolcanic rocks and Fe and Mg decrease with increasing SiO₂.

<table>
<thead>
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<th>Compositional group</th>
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<tr>
<td>mafic</td>
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<tr>
<td>intermediate</td>
<td>15 to 35</td>
</tr>
<tr>
<td>felsic</td>
<td>less than 15</td>
</tr>
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</table>

Ayres (1969) correlated these groups with a limited suite of chemical analyses and established the boundaries in the andesite and dacite fields. Reliable determination of modal colour index in the Confederation Lakes area is hampered by the fine grain size.

In Chapter 5 and subsequent parts of this work, chemical classification of the metavolcanic rocks is based on the volatile free silica content using elements of the schemes presented by Goodwin (1967), Irvine and Baragar, (1971), Kuno (1968) and Fryer and Jenner (1978).
Rock name  $\% \text{SiO}_2$

basalt  
basalt andesite  52-56  
andesite  52-63  
dacite  62-67  
rhyolite  67-75  
high Si rhyolite  75+


1) "Authoclastic volcanic breccias are those formed in fragmentation of semi-solid or solid lava by explosive disruption by the gases contained within the lava or by movement of the lava (Wright and Bowes, 1963)."

2) Alloclastic volcanic breccias are formed by "the fragmentation of any pre-existing rock by sub-surface volcanic processes (Wright and Bowes, 1963 quoted by Parson, 1969).

3) Hyaloclastic breccias are formed by thermal strain of volcanic rocks, principally flows in a subaqueous environment (Macdonald, 1972; Dimroth, 1977).

4) Pyroclastic rocks are produced by vesiculation of magma and gas-driven violent discharge from the vent (Sparks,
1978). The various types of eruptions and their effects upon fragmentation of the magma and area of dispersal are described in terms of Walker's (1973) model in Chapter 7 for primary pyroclastic rocks which have not moved from the original site of emplacement prior to lithification, whereas secondary pyroclastic rocks have been moved short distances by fluvial, mass movement, and atmospheric processes prior to lithification but during eruptive activity.

Pyroclastic fragments are classified by Macdonald (1972, p. 123) as: 1) essential directly derived from the source magma, they may be magmatic or fragments of solidified magma; 2) accessory fragments are also volcanic fragments derived from previous eruptions. They are termed lithic fragments and may be partially or wholly crystalline or may have features such as bedding; 3) Accidental fragments are formed of non-volcanic rock types or volcanic rock types relatable to eruption of a previous volcano. The grain size conventions used in this work are those of Fisher (1966) with ash <2 mm, lapilli 2-64 mm and >64 mm termed blocks and bombs.

Smedes and Prostka (1972) and Parsons (1969) have described volcanic environment in terms of "vent or cone complex facies" close to the eruptive site and "alluvial or epiclastic facies" which interfingers with the former. The vent facies consists of flows, high level intrusions
and pyroclastic rocks with andesite flows and rhyolite flows generally restricted to the vent facies (Dimroth and Rocheleau, 1979). The epiclastic or alluvial facies consists of aprons of epiclastic volcanic rocks, airfall tuff, pyroclastic flows and lahars. Section thickness and clast size decreases away from the vent and sorting and rounded of clasts increase (Smedes and Prostka, 1972). In this work, the vent facies is simply termed proximal and the alluvial facies distal.

The nomenclature for metasedimentary rocks in the work is that devised by Young (1967) from the schemes of Gilbert (1954), McBride (1963) and Dott (1964).
APPENDIX B

U/Pb GEOCHRONOLOGY

This appendix consists of the text of Nunes and Thurston (1979).
Two-hundred twenty million years of Archean evolution --
a Zircon U-Pb age stratigraphic study of the Uchi-Confederation
Lakes greenstone belt, North-western Ontario.*

by

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*Publication approved by the Director, Ontario Geological
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Accepted by Can. Jour. Earth Sci.
Abstract

Three metavolcanic units in the Uchi-Confederation Lakes greenstone belt have been dated by the zircon U-Pb method. Ages obtained reveal a time interval of $221 \pm 3.6$ m.y. separating the cycle I crystal tuff ($2958.6 \pm 1.7$ m.y.) from the cycle III rhyolite ($2738 \pm 5$ m.y.). A cycle II rhyolite about 2787 m.y. old lies between the other two units. Uranium-rich xenocrystic cores occur in the cycle I zircons and are indirect evidence of pre-existing siliceous material.

A metamorphosed granodiorite, intrusive into the cycle III rhyolite, is about the same age as the rhyolite. A post-metamorphic quartz monzonite pluton is dated at $2729.6 \pm 1.3$ m.y. A period of dynamothermal metamorphism in this portion of the Superior Province ("Kencran Orogeny") is indirectly dated at $2734 \pm 9$ m.y.
INTRODUCTION

Greenstone belts separated from each other by extensive relatively more siliceous gneissic and plutonic terrains are known in Shield areas the world over. Detailed mapping of greenstone belts in the Superior Province of the Canadian Shield has revealed extensive stratigraphic records of Archean crustal development. Prominent mineral deposits, commonly restricted to one or a very few volcanic horizon(s) within a given region (e.g. Goodwin, 1961), provide economic incentive to document as accurately as possible their geologic evolution.

Attempts by other workers to decipher Archean greenstone belt histories using the Rb-Sr technique (e.g. Jahn and Murthy, 1975; Jahn and Condie, 1976; Hawkesworth et al, 1975) have been of limited success owing to large age measurement errors. Such errors are either a consequence of open-system behaviour of the Rb-Sr whole-rock system or sampling uncertainties whereby rocks of different age and initial $^{87}\text{Sr}/^{86}\text{Sr}$ values are improperly lumped together, or both. Perhaps the most comprehensive study illustrating open-system behaviour of the Rb-Sr whole-rock system in contrast to stratigraphically consistent zircon U-Pb ages of metamorphosed volcanic and granitic rocks was reported by Page (1978). He found for metamorphosed older pro-
terozoic rocks in the Mount Isa region of Australia that Rb-Sr whole-rock ages were 10% to 15% too low relative to U-Pb zircon ages.

The present detailed U-Pb zircon study of the Uchi-Confederation Lakes greenstone belt was undertaken in order to: (1) clarify our understanding of greenstone belt evolution; (2) test zircon age precision using detailed geologic mapping as a relative age control; (3) further demonstrate the potential of U-Pb zircon dating as a time-stratigraphic correlation tool; and (4) to document, in this and future studies, non-random relationships, if present, between ore deposits and the age of their host rocks at various regional scales.

GEOLOGICAL RELATIONSHIPS

Stratigraphy

The Uchi-Confederation greenstone belt is a sequence of metavolcanic and minor metasedimentary rocks within the Uchi sub-province of the Superior Province of the Canadian Shield (Ayres et al., 1971) (Fig. 1). The belt trends north for 84 km, is 32 km wide, and has an estimated total stratigraphic thickness of 8500 to 11,240 m. folded about a central syncline.
and a marginal anticline on the eastern margin of the belt (Fig. 2). The belt is bounded to the south by the predominantly metasedimentary English River sub-province, a gneissic belt (Breaks et al., 1978; Thurston and Breaks, 1978) and to the east, west, and north by granitic rocks.

Two cycles of mafic to felsic volcanism recognized by Goodwin (1967) are herein termed cycles II and III. Pryslak (1971) recognized cycle I, the lowest stratigraphic unit. On the west limb of the central syncline, the rocks form a vertically dipping, east-facing sequence (Fig. 2). The felsic metavolcanic rocks of cycle III lie mainly within a graben defined by a) northeast to north trending border faults and b) northeast striking units folded about shallow, plunging axes in contrast to the northerly striking units with steeply plunging structures outside the graben (Thurston, 1978). Relations on the east limb of the central syncline are complicated by complex fold patterns (Thurston et al., 1974).

Cycle I on the west limb consists of (1) a basal, dominantly pillow basaltic unit (Thurston and Fryer,
1979) 2200 m thick, overlain by a 1500 m thick wedge of mixed felsic pyroclastic and metasedimentary rocks; (2) a second basaltic to intermediate flow unit followed by coarse intermediate submarine pyroclastic breccias of probable ash flow origin (Thurston, 1978) and (3) a small area of rhyolitic vitrocrystal tuff and lapilli tuff ~480 m thick. The latter was sampled for dating cycle I. The metavolcanic rocks of cycle I are conformably overlain in the western part of the area by a maximum thickness of 90 m of marble and/or sulphide facies iron formation. Total thickness of cycle I is about 5300 m.

Cycle II consists of a basal amygdaloidal pillow-ed basaltic unit 2300 m thick apparently conformably overlying the cycle I marble. On the west limb of the fold a 40-60 m thick unit of oxide facies iron formation occurs mid-way through the basalts. Approximately correlative with these rocks on the eastern limb of the central syncline are four basalt to rhyolite "minor cycles" (Annhaeusser, 1971) herein designated "mini-cycles" each about 200 m thick. The basalts on the west limb and the mini-cycles of the east limb are overlain by submarine pumice-rich pyroclastic units
150-300 m thick of intermediate composition which form several normally graded subaqueous ash flows (Yamada, 1973) rhyolitic flows, and intensely welded subaerially-deposited lapilli tuff and tuff (Savory, 1976; Thurston, 1974). Conformably overlying the welded felsic tuff is about 60 m of stromatolitic carbonate. This cycle has a maximum total thickness of about 6500 m. The felsic flows forming the upper-portion of the cycle were sampled.

Cycle III basalts conformably overlie the cycle II marble. Cycle III (total thickness 43950 m) consists of about 1500 m of pillowed basaltic flows conformably followed by intermediate and felsic pyroclastic rocks totalling 2400 m in thickness. A quartz and feldspar phric endogenous dome (Pollock et al., 1972) within the graben in the upper portion of cycle III was radiometrically dated by Krogh and Davis, (1971). For this program a quartz phric felsic flow outside the graben was dated.

The South Bay Mine, a zinc-copper-silver deposit, is the only massive sulphide deposit of economic significance found so far in this region (Pollock et al., 1972; Thurston et al., 1978). This deposit occurs in siliceous cycle III volcanic rocks associated with the quartz-feldspar por-
phry dome.

Rocks of cycle III are intruded by granodioritic to trondhjemitic synvolcanic rocks forming major sills and stocks mainly within cycle III (Pryslak, 1970). These units have bulk and trace element chemistry similar to the felsic metavolcanic rocks of cycle III and have been linked to cycle III magmatism by Thurston and Fryer (1979) on chemical grounds.

The belt is cut by several syn to post kinematic granitic bodies of quartz monzonite to trondhjemite. Representative of these is the Okanse Lake pluton which was selected for dating.

Mineralogy, petrology and chemistry

The Uchi-Confederation greenstone belt metavolcanic rocks contain assemblages indicative of low grade Abukuma type metamorphism (Thurston and Breaks, 1978). Mineralogy is almost entirely secondary. Basaltic rocks contain saussuritized plagioclase laths in a matrix of tremolite-actinolite and/or chlorite with minor epidote, opaque phases, carbonate and sphene; amygdules and veinlets contain quartz, carbonate, biotite, stilpnomelane. Occasional primary pyroxene is observed in coarse flows.
Intermediate and felsic rocks contain relict glass as shards, or plates, devitrified to very fine grained saussuritized plagioclase, epidote, chlorite, and pumiceous or lithic fragments composed of saussuritized plagioclase, tremolite-actinolite, white mica, chlorite, biotite, and quartz. Accessory minerals include sphene, zircon, stilpnomelane, and an oxide phase with secondary carbonate, quartz, and epidote.

A study of major, trace and rare-earth element chemistry of the metavolcanic rocks (Thurston and Fryer, 1979) has revealed: 1) Mobility of the alkalic elements has been documented in most samples. 2) Mg and/or Ca metasomatism is present in some basaltic rocks. 3) Most of the "immobile" trace elements (Winchester and Floyd, 1977; e.g. Ti, Zr, Y, Nb, Ce, Ga, Sc) have been relatively unaffected by alteration processes.

The dated samples (see appendix c) contain green-schist and amphibolite facies assemblages.

ZIRCON U–PB DATA

General Observations
Twenty-three zircon analyses from five volcanic samples, one granodiorite and one quartz monzonite, have U concentrations which range from 87 ppm to 1818 ppm (Table 1). The data range from concordant (i.e. within analytical error of concordia) to about 30% discordant (Fig. 3). To a first approximation an increase in discordance for zircon splits from a given sample parallels an increase in U content, magnetic susceptibility, and a decrease in grain size -- a relationship observed by Silver and Deutsch (1963). Some exceptions to this rule of thumb, however, are present.

In the three cases where 2-stage zircons are well defined (i.e. data falls within analytical error of a discordia line), lower concordia intercept ages of ≤160 m.y. (cycle I tuff), ≤30 m.y. (cycle III rhyolite), and 136±82 m.y. (cycle II rhyolite) are obtained. This indicates a very recent episodic loss of Pb or, less likely, U gain for these samples (Wetherill, 1956). Probably the best explanation for recent episodic Pb loss from these zircons is the dilatancy model of Goldich and Mudrey (1969). In the two cases where 2-stage zircons are approximately defined (i.e. data almost falls within analytical error of a discordia line), somewhat older concordia intercept ages of =400 m.y. are inferred.
from "best fit" discordia lines (quartz monzonite and granodiorite). The slopes of these lines are slightly higher than that obtained with a continuous diffusion Pb loss model (Tilton, 1960, Wasserburg, 1963). The lower concordia intercept age of ≈400 m.y. has no obvious geological significance. Thus, if the process of continuous diffusion of Pb was significant, we suspect that it was confined to U enriched zones which were later mixed in the laboratory digestion procedure with low U areas in the zircons to produce mixing lines (Steiger and Wasserburg, 1969). Multiple episodic loss of Pb or combined recent episodic and continuous diffusion Pb loss events (e.g. Allegre et al., 1974) can reasonably explain the data patterns. The concordant to slightly discordant nature of the data in Table 1 and the consistency of the upper concordia intercept ages with relative rock ages deduced from field work indicate that these ages are not significantly dependent on the exact mechanism whereby Pb was lost (or U gained) from the zircons.

In all but four analyses (N76-9-3, N76-11-1, N77-8-1, and N77-8-2) common Pb in the zircon exceeds
the blank by more than two times indicating that common Pb (i.e. non-radiogenic Pb) is a quantitatively known constituent for the remaining analyses. Generally, but not exactly, for a given rock the common Pb content of the zircons increases with the degree of discordance. Individual error estimates (Table 1, Appendix B) were conservatively evaluated in detail.

Three Younger Rocks and the Kamloops Orogeny

Three zircon samples obtained from the post metamorphic and post-folding Okanagan Lake pluton were analysed (Fig. 3). One is concordant within analytical error, and yields an age of $2729.6 \pm 1.3$ m.y. This age is interpreted as representing the time of formation of this pluton.

Four analyses of cycle III rhyolite zircons lie within analytical error of a 0 m.y. Pb loss line which yields an upper concordia intercept age of $2739 \pm 31$ m.y. (95% confidence limits, see Appendix B). When the least precise analysis is excluded, an upper concordia intercept age of $2737 \pm 20$ m.y. (95% confidence limits) is obtained. An age and error estimate of $2738 \pm 5$ m.y. includes the range of the $^{207}\text{Pb}/^{205}\text{Pb}$ ages and is a reasonable estimate for the time of formation of these rocks.
Three analyses of the metamorphosed granodiorite which intrudes the cycle III rhyolite do not, within analytical error, define a discordia line. They approximate a discordia line with upper and lower concordia intercept ages of 2744 m.y. and 321 m.y. respectively. The scatter in the data means that these ages are subject to geological error impossible to treat statistically. The most concordant analysis has a $^{207}\text{Pb}/^{206}\text{Pb}$ age of $2735 \pm 3$ m.y. and is interpreted as a minimum age for this rock. Since the granodiorite intrudes the $2738 \pm 5$ m.y. old cycle III rhyolite, we infer it is younger than 2743 m.y. old. Hence, an age of $2737 \pm 5$ m.y. represents the time of intrusion of the granodiorite. The lack of discernable age difference between the granodiorite and the cycle III rhyolite supports the genetic link for these units inferred from their bulk and trace element chemistry (Thurston and Fryer, 1979).

A distinct time interval of $8 \pm 6$ m.y. separates the metamorphosed 2738 m.y. old cycle III rhyolite and the post-metamorphic 2730 m.y. old quartz monzonite. Because the metamorphism in this region occurred after extrusion of the cycle III rhyolite and prior to the
intrusion of the quartz monzonite, it is indirectly
dated at $2734 \pm 9$ m.y. This period of metamorphism
and igneous intrusion =2734 m.y. ago, in this portion
of the Superior Province, appears to represent the
Kenoran orogeny as defined geologically by Stockwell
(1973) as the last period of important folding, meta-
morphism, and intrusion in the Superior Province.
This $2734 \pm 9$ m.y. age is the same within the uncer-
tainties, as the zircon age Krogh et al. (1974) obtained
for a diapiric pluton in the Berens River block just
north of the Uchi Subprovince. Not far to the South,
in the English River Gneiss belt, zircon ages from
paragneiss leucosome material associated with meta-
morphism and post-orogenic granites (Krogh et al. 1976)
yield ages which are in the 2700-2640 m.y. range for the
Kenoran orogeny. Still further south and =900 km east
in the Abitibi greenstone belt, zircon "Kenoran" ages of
= 2650 m.y. have been determined for the Preissac-
Lacorne batholith and a quartz-monzonite south of Lake
Timagami, Ontario (Steiger and Wasserburg, 1969). Hence,
late metamorphic to post-metamorphic ages appear to be
older in the northern part of the Superior Province as
first pointed out by Krogh et al. (1975). In particular,
limited data currently available suggest the "Kenoran orogeny" peaked at 2734 m.y. ago north of the Uchi-English River Subprovince boundary and at 2650 m.y. south of this boundary.

The 2738 m.y. age for the cycle III felsic volcanic rocks compares with an age based on three zircon analyses of 2760 m.y. (Krogh and Davis, 1971) for the South Bay Mine porphyry (also cycle III material). The reason for the discrepancy between these two age determinations is not clear. It is noteworthy, however, that the two most concordant analyses of Krogh and Davis (1971) approximately lie on a 0 m.y. Pb loss trajectory (analogous to the volcanic zircon data presented here) which intercepts concordia at 2740 m.y. -- an age analytically indistinguishable from the 2738 m.y. age reported in this paper. Possibly, the most discordant analysis obtained for the mine porphyry was more readily disturbed by one or more Pb loss events between 2740 m.y. and 0 m.y. ago which did not affect the two relatively more concordant zircon populations from the same rock. If this explanation is correct, the discordia line reported by Krogh and Davis (1971) is a mixing line of 2-stage and 3-stage U-Pb systems. Such a mixing line would yield an erroneous upper concordia intercept age older than the true age. Alternatively, if the 2760 m.y. age is correct, the data in this paper may reflect zircons which were disturbed by later events such as the
Kenoran orogeny resulting in too young $^{207}\text{Pb}/^{206}\text{Pb}$ ages. We believe the 2738 m.y. age reported here is correct because: 1) if the cycle III data reflect Pb loss at a younger time (e.g. the Kenoran orogeny), the agreement of the four $^{207}\text{Pb}/^{206}\text{Pb}$ ages must be explained by coincidence -- thought by us to be unlikely; and 2) evidence that relatively discordant zircons were more affected by the Kenoran orogeny than relatively concordant zircons from the same rock is documented later in this paper for cycle II and cycle I zircons. Yet another, less likely, explanation for the ~20 m.y. age discrepancy between the cycle III mineral porphyry (Krogh and Davis, 1971) and the cycle III rhyolite reported here is that they are, indeed, different in age -- a possible consequence of cycle III material forming over an extended period of time, rather than exactly contemporaneously.

Two Older Rocks -- Early Volcanism in the Superior Province

Zircons were obtained from three samples of cycle II volcanics. Sample N76-8 which was sledged from a highly sheared outcrop, displays by far the most evidence of fluid alteration (e.g. complete sericitization of the plagioclase, -- see Appendix C). Sample N76-12 is a rhyolite collected ~25 m from N76-6. It was blasted from a more coherent outcrop and is petrographically less altered.
The least altered sample is a welded tuff collected about 12 km south of the rhyolites (Fig. 2). It is relatively impervious to fluids. Three zircon analyses from the most altered sample (N76-8; Table 1) define an area on Figure 7 which illustrates that the two analyses with the youngest $^{207}\text{Pb}/^{206}\text{Pb}$ ages (2780 m.y. and 2694 m.y.) have suffered at least two periods of U-Pb disturbance (i.e. they reflect a $\geq$3-stage U-Pb evolution history). The least disturbed N76-8 analysis with the highest $^{207}\text{Pb}/^{206}\text{Pb}$ age (2788 ± 1 m.y.), together with three analyses of zircons from the less altered cycle II rocks, define within analytical error a discordia line (Fig. 4) with upper and lower concordia intercept ages of 2794 ± 6 m.y. and 136 ± 82 m.y. (95% confidence limits). The 2794 ± 6 m.y. age is interpreted as representing the time of extrusion of the cycle II rhyolite. Thus, four of the six cycle II zircon analyses apparently represent two-stage U-Pb systems which lost Pb (or gained U) very recently (about 135 m.y. ago). Had we only obtained analyses N76-8-3 (a $\geq$3-stage system), N76-8-1 and N78-1-1 (two-stage systems), we would have obtained a mixing line of 2-stage and $\geq$3-stage U-Pb systems with too old an upper concordia intercept age of about
2830 m.y. and a meaningless lower intercept age of 
=630 m.y. This observation stresses that more than 
two zircon analyses are required for an accurate age 
determination. These patterns also suggest that 
many of the zircon discordia lines with lower concordia 
intercepts significantly >0 in the literature obtained 
by analysing larger samples could reflect mixing lines 
of >3-stage discordant zircons and relatively less dis-
cordant material representing 1- or 2-stage systems.
The accuracy of upper concordia intercept zircon ages 
inferrred from such data heavily depends on how mean-
ingful is the lower concordia intercept age, exactly 
how concordant are the most discordant data, and how 
consistent the upper intercept age is with known geo-
logical relationships and other U-Pb age data.

Polished grain mounts of cycle II N75-8 rhyolite 
zircon populations were etched with 48% HF for =15 
sec. in the manner reported by Krogh and Davis (1974).
Alteration zones concentrated along growth zones, are far more prominent among the most magnetic zircons as is the common Pb content (see raw $^{206}$Pb/$^{204}$Pb values, Table 1). Thus, more prominent alteration zones, and higher common Pb contents appear to be characteristic of the more complex (i.e. $>3$-stage) U-Pb systems.

Seven U-Pb analyses of zircon from a cycle I crystal tuff reveal two distinct populations: one which is less magnetic, much more concordant, and without cores; and one which is slightly more magnetic, grossly discordant, and contains xenocrystic cores. Three analyses of the less magnetic material (Fig. 4) define, once again, a Pb loss trajectory which passes within the uncertainties through 0 m.y. One of these analyses is concordant and yields an age of 2958.6 ± 1.7 m.y. This age is interpreted as representing the age of extrusion of the tuff.
and is, with one exception (Nunes and Wood, 1979), the oldest metavolcanic rock known in the Superior Province.

The slightly more magnetic cycle I zircon populations are grossly discordant, and define an area, rather than a line, on Fig. 1. Ten second etches of polished grain mounts with 48% HF reveal cores which were readily attacked. This indicates that the U concentrations of up to ≈1800 ppm for the more magnetic splits (in contrast to ≈190 ppm for the less magnetic zircons) result from U-rich cores (Table 1, plates 1 and 2). The cores and overgrowths also have distinctly different Th/U values.
as inferred from measured $^{208}\text{Pb}/^{206}\text{Pb}$ values (Table 1.)
The U concentration, $^{208}\text{Pb}/^{206}\text{Pb}$ values, and etching experiments indicate that older xenocrystic zircon from a different source were overgrown with 2959 m.y. old zircon -- the age most likely representing eruption of the cycle I crystal tuff. The most magnetic zircon analysis of the cycle I tuff lies within analytical uncertainty of the Pb loss trajectory defined by the $\sim 2736$ m.y. old quartz monzonite. This strongly suggests that the two most recent disturbances of the older most discordant zircon systems occurred $\sim 2730$ m.y. ago during the "Kenoran orogeny" and within the last 400 m.y. The data (Figs. 3 & 4) suggest that no geological events of any significance have affected the zircons in these rocks since $\sim 2730$ m.y. ago, other than recent uplift and associated leaching. The more magnetic zircon analyses for the cycle I tuff are, in part, mixtures of overgrowths and older cores. Hence, they represent at least 4 stages of U-Pb evolution: (1) formation of cores, $>2959$ m.y. ago (2) formation of overgrowths and new grains, $2958.6 \pm 1.7$ m.y.
ago (3) disturbance at \( \approx 2730 \) m.y. ago, and (4) disturbance \( \leq 400 \) m.y. ago. Additional periods of Pb loss or U gain cannot be ruled out. This complicated history and the discordant nature of the data do not allow an age of any credibility to be inferred for the core material, other than a minimum age of 2959 m.y. -- the inferred age of the overgrowths and eruption of the tuff.

DISCUSSION

The data just presented illustrate that the upper felsic rocks of cycles I and II and cycles II and III are separated in time by about 165 m.y. and about 56 m.y. respectively. It is further evident that an overall time interval of 221 \( \pm \frac{3}{7} \) m.y. separates the cycle I and cycle III metavolcanic rocks dated. This 221 m.y. interval is a minimum estimate of the evolution of the Uchi-Confederation Lakes greenstone belt since still older, mafic, metavolcanics stratigraphically underlie the cycle I tuff dated. Time intervals within a single cycle of volcanism, however, may not be very great as evidenced by the \( \leq 15 \) m.y. interval inferred from preliminary zircon data
for a single cycle of mafic to felsic volcanism near Kirkland Lake (Nunes, et al., 1978). The carbonate horizons (chemical metasediments) which lie on top of the cycle I and II felsic units dated may mark paraconformities in the stratigraphic sequence.

Such a long period of evolution for the Uchi-Confederation Lake greenstone belt contrasts markedly with a much shorter period of \( < 45 \) m.y. inferred from zircon ages of volcanics and coeval intrusives in the Abitibi belt of \( \approx 2740 \) to \( 2685 \) m.y. (Krogh and Davis, 1971; Nunes, et al., 1978; Wanless, oral communication, 1978). The absolute ages and time intervals in the Abitibi belt are very similar to those inferred from U-Pb Sphene (Tilton and Grunenfelder, 1968) and U-Pb Zircon data (Hart and Davis, 1969) for metasediments, metavolcanics and Laurentian igneous rocks near Rainy Lake, Ontario.

The presence of both rather old (2958.6 \( \pm \) 1.7 m.y.) and relatively young (2738 \( \pm \) 2 m.y.) volcanic rocks in
the Uchi-Confederation Lake area complicates previous suggestions that a progressive younging of volcanism existed in the Superior Province from north to south (Goodwin, 1966; Krogh and Davis, 1971). Such a pattern may still hold, however, for the oldest rocks in each belt since no volcanic rocks clearly older than about 2750 m.y. have yet been found to the south and east of the Uchi area greenstone belts. Alternatively, major crustal discontinuities such as the Sydney Lake cataclastic zone forming the southern boundary of the Uchi sub-province may mark abrupt changes in the age of volcanism. Clearly, additional data similar to that reported here is needed before any accurate reconstruction of the evolution of the Superior Province can be made.

The high-U xenocrystic cores of the zircons from the cycle I tuff are indirect evidence of a pre-existing sialic crust in the Uchi region since they likely formed in a siliceous rock prior to their incorporation in the cycle I magma. This observation supports, but does not prove, the conclusion drawn by Baragar and McGlynn
(1976) that granitic rocks existed prior to the formation of the greenstone belts in the Canadian Shield.

SUMMARY

We emphasize the following conclusions:

1. In favorable cases, Archean zircon ages may be precise to \(< 1\) m.y.

2. Zircon populations may be mixtures of one-stage, two-stage, and multi-stage U-Pb systems. Typically, the more complex the U-Pb history of a given zircon, the more discordant it will be. Unless concordant (one-stage U-Pb system) data are obtained, caution must be exercised in interpreting the upper concordia intercept ages obtained by extrapolating linear discordia trajectories back to concordia — particularly when the lower concordia intercept ages are geologically meaningless and significantly >0. Such colinear data could result from analysing a mixture of zircons which have suffered a different number of U-Pb evolution stages, just as easily as from analysing material which has all experienced a two-stage U-Pb evolution history. If the mixing explanation is more common
than previously thought, many of the upper concordia intercept ages in the literature could be incorrect. The degree of age accuracy increases with increasing concordance of the data. For much of the Archean zircon data from the Canadian Shield, reported upper concordia intercept ages are probably accurate within about 20 m.y., owing to the only slightly discordant nature of the data.

(3) Excellent agreement of zircon ages and relative ages based on detailed geological mapping demonstrate the utility of zircon age dating as a time stratigraphic tool in the Precambrian. Time intervals of about 165 m.y. and 56 m.y. separate the upper felsic rocks of volcanic cycles I and II and cycles II and III respectively. The overall development of this volcanic section took at least $221 \pm 3$ m.y.

(4) One of the oldest volcanic rocks known in the Superior Province is dated at $2959 \pm 2$ m.y. Zircons from this tuff contain high-U cores of still older material which is indirect evidence for the existence of pre-existing sialic material in this part of the Superior
Province.

(5) A major period of metamorphism in the Uchi-
Confederation Lakes area is bracketed by pre- and post-
metamorphic rock ages and thus indirectly dated at
2734 ± 9 m.y..

APPENDIX A. ANALYTICAL PROCEDURE
Sample Preparation

Approximately 100-pound samples were blasted and/
or sledged from relatively unweathered outcrop. They were crushed in
jaw crusher and pulverized in either a hammer mill or
disc mill. Standard density and magnetic separation
techniques were used prior to hand-picking zircon con-
centrates of >99.9% purity. Concentrates were given a
warm acid wash in 7 NHNO₃ for =20 min. and rinsed with
clean water and clean acetone prior to digestion.

Zircon Chemistry

Zircon digestion procedures were those of Krogh
(1973). Samples were totally spiked with a mixed $^{205}$Pb-
$^{235}$U spike with a Pb isotopic composition of: 205/206 =
24.67 ± 0.2, 206/207 = 250 ± 107, 206/208 = 200 ± 128,
205/204 ≥80,000. No $^{204}$Pb correction was necessary when
subtracting the spike Pb from the sample Pb. The $^{205}$Pb
was a portion of the solution prepared by Krogh and Davis (1975). For most samples, Pb was isolated on a 0.012 cc. resin column (Dowex 1 x 8) with a miniaturized version of a single-column HBr technique (Nunes, 1975) which evolved from previous HBr Pb isolation descriptions (e.g. Oversby, 1970; Tilton, 1973). U passed through the HBr column and was isolated with HCl on a 0.4 cc. column (Krogh, 1973). Total chemistry Pb blanks ranged from 2.5 ng (first data) to 0.13 ng (most recent data). Lead blanks ranged from 7 to 11 pg (9 loading blanks) 21 to 26 pg (2 HBr column blanks); and 44 to 300 pg (15 teflon bomb digestion blanks). Radiogenic lead memory of reused digestion bombs was detected at levels of =0 to 220 pg. Care was taken to insure negligible cross contamination of samples. Relatively high bomb blanks are probably a consequence of impure teflon.

Hydrogen Bromide was cleaned with an ion exchange column. All other reagents were cleaned with Mattinson's (1972) two-bottle technique.

All isotopic composition measurements were obtained with a Micromass mass spectrometer with a 30 cm radius of curvature for the flight tube. Automatic peak switching capability was achieved with digital control of the
magnetic field via interfacing to a Hewlett Packard 9830A desktop computer. Data was acquired with a modified version of the BASIC program described by Stacey and Hope (1975). Lead was run with a modified version of Cameron Smith and Walker's (1969) silica gel technique, much like that described by Tatsumoto et al. (1972). Uranium was run with the tantalum pentoxide technique (Krogh, 1973).

Most of the $^{207}\text{Pb}/^{206}\text{Pb}$ values and about half the uranium ratios were obtained with a Faraday cup Cary vibrating reed electrometer detector system. The other lead and uranium ratios were obtained with a Daly knob-photomultiplier detector in the analogue mode.

APPENDIX B. ERRORS

Three $^{235}\text{U}/^{205}\text{Pb}$ values for the mixed spike were obtained from two calibrations using ground portions of the NBS =50 ppm standard glass water (Barnes et al., 1973) and from two additional uranium and lead shelf calibrations. The average $^{238}\text{U}/^{205}\text{Pb}$ value was 109.4 with a total range of 1.9%. This ratio is thought to presently be accurate to about $\pm$ 1.0%. Because the spike was diluted during these determinations, absolute concentrations are slightly less accurate and estimated at $\pm$ 1.5%.

All age errors in this paper are precision error
estimates. Where data within error of concordia were obtained, the age error was estimated from the precision error of this analysis since the purpose of generating discordia lines is, after all, to extrapolate back to concordia. When data within analytical error defined a discordia line, ages and their uncertainties (95% confidence limits) were obtained with a program (K. Ludwig written communication, Dec., 1978) utilizing York's (1969) least squares correlated error treatment. Where the best fit line passed within error, but to the right of the origin of the concordia diagram, the \(^{207}\text{Pb}/^{206}\text{Pb} \) age of the centroid was used to infer a minimum age (i.e. one cannot have future Pb loss).

Accuracy age errors may be estimated by adding 3 m.y. to the precision errors in this paper -- a consequence of the U half life uncertainty of about \(\pm 0.1\% \) (Jaffey et al., 1971).

Uncertainties in the Pb isotopic composition of the \(^{205}\text{Pb} \) spike are of negligible consequence.

Uncertainties in Table I were obtained by error propagation: Final error \(\delta F = \sqrt{\sum (\frac{\delta F}{\delta X_i} \Delta X_i)^2} \)

where \(\Delta X_i = \) The error in the \(i^{th}\) variable. An error
propagation program was used which enabled us to let the computer perform the partial differentiation for each variable. If \( x = F(x_1, x_2, \ldots, x_n) \), \( \frac{\partial F}{\partial x_1} \Delta x_1 = F(x_1 + \Delta x_1, x_2, \ldots, x_n) - F(x_1, x_2, \ldots, x_n) \). The computer program calculates the right hand side of this equation for each variable and quadratically sums all these values according to the previous equation.

Individual variables and errors propagated in this manner are:

1. Sample and spike weighing errors. Weights obtained with the Sartorius semi-micro and Cahn micro balances were estimated to be correct to \( \pm 0.05 \) mg and 0.005 mg respectively.

2. Uranium fractionation values and uncertainties at the 2\( \sigma \) level were determined to be \( -0.06 \pm 0.09\% \) per atomic mass unit (measured heavy/light isotope ratios were too high) for the Faraday collector system and \( 0.09 \pm 0.14\% \) per atomic mass unit for the Daly knob-photomultiplier detector. These correction factors are based on seven and nine standard runs of NBS SRM U500 for the Cary and Daly detector systems, respectively.

3. Lead fractionation values and uncertainties at the 2\( \sigma \) level are \( 0.11 \pm 0.04\% \) per atomic mass unit (measured heavy/light isotope ratios were too low) for the Faraday cup detector and \( 0.26 \pm 0.14\% \) per atomic mass unit for the Daly knob detector. These numbers are based on eight standard
runs on each detector of SRM 981 — the NBS common lead standard (Catanzaro, et al., 1968). Load was run at 1280 to 1330°C (Cary) and 1180 to 1250°C (Daly). A conservative Pb fractionation error of ± 0.1% per atomic mass unit was used for data obtained with the Faraday cup prior to purchase of our optical pyrometer.

(4) Measurement errors of isotopic ratios used are twice the standard error of the mean: 

\[ \sigma_m = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2} \]

where \( \bar{x} \) is the mean of \( N \) values and \( x_i \) = the \( i \)th value.

Typically, six to ten blocks of data were taken with each block consisting of at least 6 peak switching cycles of the isotopes being measured.

(5) All Pb and U blank uncertainties were estimated at ± 50%. Total lead blanks were run alongside each set of five samples. Two total chemistry uranium blanks were 0.1 and 0.2 ng. All samples were corrected for a U blank of 0.15 ng.

Common lead subtracted from the data was assumed to have an isotopic composition defined by Stacey and Kramer's (1975) 2-stage evolution model. Possible errors associated with departures from this assumption were not evaluated.

APPENDIX C. SAMPLE DESCRIPTION AND LOCATION

N76-9 Cycle I Crystal Lithic Tuff

Bedded felsic lapilli tuff with 5-10 mm lithic
fragments and broken crystals in a fine-grained matrix. Mineral assemblage—very fine grained plagioclase (albitic) with phenocrysts of quartz and plagioclase, minor porphyroblasts of biotite, white mica and carbonate. Accessories — apatite and sphene. Lat. 51°12'; Long. 92°51'.

N76-8 Cycle II Amygdular Felsic Flow

Quartz and minor sericitized plagioclase phenocrysts in a very fine grained matrix of heavily saussuritized plagioclase and sericite + quartz. Occasional sphene phenocrysts. Secondary carbonate in patches. Lat. 51°12'; Long. 92°51'.

N76-12 Cycle II Felsic Flow

Quartz and minor plagioclase phenocrysts in a matrix of very fine grained quartz, albite, sericite, and chlorite with minor secondary carbonate grains. Relict pyroxene phenocrysts replaced by chlorite and stilpnomelane. Lat. 51°12'; Long. 92°51'.

N76-7 Cycle III Felsic Porphyritic Flow

Quartz and feldspar (albitic) phenocrysts in a very fine grained, massive matrix of plagioclase (albitic) + quartz + epidote + biotite + sericite + carbonate with traces of opaque iron oxides and sphene. Lat. 51°03'; Long. 92°40'.

N76-11 Granodiorite

Laths of slightly sericitized plagioclase (An5) in a matrix of quartz and chlorite with occasional grains of heavily sericitized orthoclase — quartz symplectic inter-
growths. Minor fine grained opaque iron oxides, white mica and sphene. Lat. 51°07'; Long. 92°42'.

N77-8 Okanse Lake Quartz Monzonite

Plagioclase (An5) phenocrysts in a matrix of hypidiomorphic granular quartz and quartz-microcline symplectite with anhedral grains of chlorite and brown biotite, trace of opaque iron oxides. Lat. 51°09'; Long. 92°36'.

N78-1 Welded Felsic Lithic Tuff, Cycle II

Lithic and pumiceous fragments and devitrified glass displaying eutaxitic texture. Now comprised of very fine grained anhedral albite plagioclase, quartz and oriented secondary potash feldspar. Minor epidote, sericite and carbonate. Pumice fragments replaced by quartz. Lat. 51°08'; Long. 92°45'.

Acknowledgments.

Dr. T.E. Krogh designed the column used for the Pb chemistry, made $^{205}$Pb spike available for this work, and provided enthusiastic and constructive discussions throughout the period of this study. We benefited from discussions with Dr. M. Tatsumoto, Dr. A.C. Nunes, and D.M. Unruh.

We thank B. Podstawskyj for mass spectrometer maintenance support and J.M. Hodgson for careful mineral separation and other laboratory assistance. Dr. K.D. Card furnished geological insight and enthusiasm necessary for the initia-
tion of this project. We thank J. Grant for help with manuscript preparation.

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Onikobe caldera, Miyagi Prefecture, Japan; Journal 
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<th>Analysis</th>
<th>Magnetic susceptibility</th>
<th>Mesh size (mm)</th>
<th>Sample weight (mg)</th>
<th>Concentrations blank corrected (ppm)</th>
<th>Atomic ratios corrected for blank (ppm)</th>
<th>Pb atomic abundance relative to $^{206}$Pb = 1000</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total U</td>
<td>Total Pb</td>
<td>$^{206}$Pb/$^{207}$Pb</td>
</tr>
<tr>
<td>1*</td>
<td>NMo*</td>
<td>+200</td>
<td>1.053</td>
<td>86.6</td>
<td>52.5</td>
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<td>2*</td>
<td>NMo*</td>
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<td>92.4</td>
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<td>5*</td>
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</tr>
<tr>
<td>6*</td>
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<td>7*</td>
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</table>

Notes: All Pb data have been corrected for 61% SmS-14Sm fractionation (Cary data) and 6.6% SmU (Daly data). All analyses were totally spiked with a combined $^{206}$Pb-207Pb enriched spike. NM = non-magnetic; M = magnetic; A = amperes. Number following N and NM refers to degree of tilt on the Schmidt goniometer separation.

Following digestion in HF-HNO3, fluors were diluted with 5% H2O2, dried down and picked up directly with 1 1/2 ml of HBr for Pb column isolation. All other analyses were treated with HCl (Krieh 1973) prior to column chemistry.

1* Clear grain.
2* Cloudy grain.
Figure and Plate Captions

Fig. 1. Map of Ontario illustrating location of the Uchi Confederation Lakes area.

Fig. 2. Geological Map of Uchi-Confederation Lakes area with sample localities. Geology after Thurston (1978).

Fig. 3. Concordia diagram with zircon data for cycle III rhyolite (N76-7), Granodiorite (N76-11) and Quartz Monzonite (N77-8). Error envelopes are analytical precision error estimates (see Appendix B). Discordia lines illustrating Pb loss or U gain for samples N77-8 and N76-7 (cycle I volcanic rocks) are illustrated (see text). Constants used are: \( \Lambda 238 = 0.155125 \times 10^{-9} \text{yr}^{-1} \), \( \Lambda 235 = 0.98485 \times 10^{-9} \text{yr}^{-1} \) (Jaffey et al., 1971) and \( \frac{238}{235} = 137.880 \).

Fig. 4. Concordia diagram with zircon data for cycle I crystal tuff (N76-9) cycle II rhyolite (N76-8, N76-12 and N78-1) and Quartz Monzonite (N77-8). Error envelopes are analytical precision error estimates (see Appendix B). Possible discordia lines for cycle I least magnetic zircons, cycle II least disturbed zircons and Okanese Lake Pluton are illustrated (see text).

Plate 1. N76-9 zircons NMO°, 100-200 mesh. Polished and etched 10 seconds with 48% HF vapor. Note uniform nature of grains which strongly resisted HF vapor attack.

Plate 2. N76-9 zircon M3°, NM4° and 200 mesh. Polished and etched 10 seconds with 48% HF vapor. Note core of readily attacked (high-U) material surrounded by more resistant (low-U) rim material strongly resembling the NMO° zircons in Plate 1.
APPENDIX C

Isotopic Determinations on the Hill-Sloan-Tivey Chert

The evidence cited in Chapter 3.8 suggests that the HST is a primary chemical precipitate (Table 6-1) (Thurston, 1978). Knauth and Lowe (1978) show a secular variation in $\delta^{18}O$ ranging from 22 permil at 3.8 b.y to 34 permil at the present time. The HST is approximately 2794 to 2739 m.y. old as it lies between two units dated by the U-Pb method on zircons (Nunes and Thurston, 1979). At 2.8 b.y., Knauth and Lowe's secular trend indicates a range from 18 to 23 permil for $\delta^{18}O$ is to be expected for cherts. If the ocean were constant in temperature through time, the Archean ocean at 2.8 b.y has, a value of $\delta^{18}O = 12$ to -14 permil. It is more reasonable to assume however that the isotopic composition of sea water has been constant at -0.92 permil which assumes that the low $\delta^{18}O$ polar ice caps were melted and returned to the ocean (Shackleton, 1967). Therefore the 2.8 b.y. ocean had an approximate temperature of 65°C. The HST chert should therefore fall in the range of $\delta^{18}O$ of 17 to 23 permil. The possible reasons for falling below the range given the good control upon the geologic age and its identification as chert are: 1) it could have been at 18 permil and subject to long-term exchange with low $\delta^{18}O$ groundwater. Knauth and Lowe (1978) demonstrate however that this process if operative
on Onverwacht Group cherts resulted in a shift of δ\(^{18}\)O of -0.7 permil.

2) A theoretical possibility of exchange with metamorphic fluids of +5 to +12 permil exists. However, Knauth and Lowe (1978) investigated this possibility for Onverwacht Group cherts and found little change in δ\(^{18}\)O.

3) Decrease of δ\(^{18}\)O in the near-shore or subaerial environment brought about by contact with lower δ\(^{18}\)O meteoric water runoff. Although the upper part of cycle II on the west limb of the synclinorium has been demonstrated to be subaerial (Thurston (1979), that section is well above HST which is in contact with pillowed basalts and hyaloclastites indicative of a submarine environment.

4) Low δ\(^{18}\)O values are reported for silicified volcanioclastic detritus, silicified tuffs and cherts of a problematical origin (Knauth and Lowe, 1978), reflecting low δ\(^{18}\)O impurities such as feldspar, muscovite or volcanic glass. As these impurities are not abundant in the portion of the HST examined (see Table C-1) it must be suggested that:

Low δ\(^{18}\)O values are a function of contact with hot ocean bottom waters.

Using the δ\(^{18}\)O fractionation equation of Clayton et al. (1972)

\[ \Delta_{\text{qtz-H}_2\text{O}} = -2.73 + 9.75 \times 10^6 T^{-2} \]
and that of Knauth and Epstein (1976)

2) $\Delta_{\text{qtz-H}_2\text{O}} = -3.29 + 3.09 \cdot 10^6 T^{-2}$

the estimated temperature of the sea bottom where the HST chert was deposited ranges from 178 to 220°C. Using the Clausius-Clapeyron equation (Castellan, 1964, p. 77)

3) $\ln p = \frac{Q_{\text{vap}}}{RT} + \ln p$

where $p =$ vapor pressure, $Q_{\text{vap}} =$ heat of vaporization

$R =$ gas constant, $T =$ temperature and $p =$ constant,

$p = 3.14 \text{ atm}$ for a temperature of 220°C which corresponds to a minimum depth for the sea of approximately 325 m.
TABLE C-1 Chemical Composition of the HST Chert

<table>
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<tr>
<th>Element</th>
<th>Concentration</th>
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<tbody>
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<td>SiO₂</td>
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<tr>
<td>TiO₂</td>
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<tr>
<td>Al₂O₃</td>
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<tr>
<td>Fe₂O₃</td>
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<td>MnO</td>
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<td>δ¹⁸O</td>
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Majors by XRF excepting Na and Mn. As, Sb, W, Rb, Sr, Y, Zr, Nb, Ba by XRF, all remainder by AA.

* probably contamination from Bleuler.

major elements in wt. %
trace elements in ppm.
APPENDIX D

Analytical Techniques

Si, Al, Fe, Mg, Ca, Na, K, Ti, P and Mn were determined by x-ray fluorescence on discs produced by fusion with Li tetraborate and La oxide after the method of Norrish and Hutton (1967). The precision of the method is in most instances about ± 10 percent Ba, Co, Cr, Cu, Ni, Pb, Sr and Zn were determined by atomic absorption on a Perkin Elmer mod. 603 instrument. Detection limits for all elements are approximately 10 ppm with precision and accuracy exceeding 10 percent. U was determined by ultra-violet fluorescence after fusion with K₂CO₃, Na₂CO₃, NaF flux. The detection limit is 1 ppm.

Th was determined by x-ray fluorescence on a pressed pellet. Fe₂O₃ was determined volumetrically against KMnO₄. V was determined by emission spectroscopy on a Jarrel-Ash 3.4 m instrument with an estimated precision of ± 20 percent. The above work was done in the laboratories of the Ontario Geological Survey under the direction of C. Riddle and A. Pitts.

Y, Zr, Nb and Rb were determined by x-ray fluorescence on pressed pellets with a precision of ± 10 percent on a PW 1450 Philips spectrometer at the University of Western Ontario.
Precision and accuracy of analyses for these elements calculated from at least two determinations on each AGV, GSP, W1, BCR, BR, and Ga are ± 10 percent. Detection limits are approximately 5 ppm for Y, Zr, Nb, and 3 ppm for Rb.

REE were analysed by thin-film x-ray fluorescence using the technique of Fryer (1977). About half the samples were done at the University of Western Ontario and half at the Memorial University of Newfoundland. Precision and accuracy are ± 15 percent.
APPENDIX E

ANALYTICAL RESULTS

Results are listed by cycle with Cycle I followed by Cycles II and III. Samples for which trace elements have been determined are listed first in order of increasing silica content, followed by supplemental analyses of basaltic rocks to document the Fe enrichment trends. Additional analyses used to produce the AFM and cation plots are listed in Thurston (1978). Table E-1 lists results for Cycle I, E-2 results for Cycle II and E-3 results for Cycle III.
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APPENDIX F. SAMPLE LOCATION AND DESCRIPTION

Samples numbered 401 to 475 inclusive are the 1977 series referred to in the text as 77—which have been analyzed for trace elements. They are listed in the order Cycle I through Cycle III as in Appendix E. Samples from other years of field work follow, listed in order of mention in the text. All other samples chemically analyzed in this work are described and located in Thurston (1978).
SAMPLE NUMBER

CYCLE I

511  Pillow Nafic Flow
Radiating tremolite-actinolite grains in matrix of anhedral albite plagioclase (epidotized). Tracys: opaques epidote porphyroblasts

536  Pillow Nafic Flow
Subhedral granular tremolite-actinolite with laths of albite plagioclase. Tracys: chlorite and/or penninite.

146  Gabbro Dike
Coarse, granular with tremolite-actinolite subhedral with clinopyroxene cores in a matrix of saussuritized albite plagioclase (epidote very fine grained) and traces of Sphene and myrmekitic plagioclase-quartz intergrowths.

522  Massive Nafic Flow
Well foliated with feathery plates of tremolite and minor chlorite with interstitial saussuritized albite plagioclase. Tracys: epidote.

473  Massive nafic flow
Radiating sheaves of tremolite-actinolite with anhedral saussuritized plagioclase and traces of epidote and opaques.

418  Pillow nafic flow
Hypidiomorphic granular with rounded grains of hornblende, with minor chlorite and oligoclase. Fractures filled with quartz plus oligoclase plus epidote plus biotite.

419  Pillow nafic flow
Radiating tremolite-actinolite with anhedral saussuritized plagioclase. Tracys: opaques.

474  Intermediate lithic tepolill tuff
Anhedral mosaic of saussuritized albite plagioclase, quartz, chlorite and secondary carbonate with traces of opaques and sericite.
Intermediate Pumiceous tuff breccia (essential fragment)
Quartz and albite plagioclase aggregates (subhedral) with secondary chlorite, sericite, and carbonate grains. Traces: epidote, opaques, sphene.

Felsic crystal tuff
Finely bedded with 6 mm crystal fragments of saussuritized subhedral plagioclase and quartz in a matrix of biotite plagioclase and quartz tracess: sphene and zircon.

Welded felsic crystal vitric lapilli tuff occasional small lichic fragments, plagioclase and quartz fragments in a matrix of subhedral quartz and untwinned plagioclase anhedral grains with wispy interstitial biotite and muscovite. Traces: epidote and opaques

CYCLE II

Flooded Mafic Flow
Subhedral rounded plagioclase laths in a matrix of chlorite and carbonate.

Coarse massive mafic flow interior
Subophitic texture with fine grained epidote and albite plagioclase in laths with tremolite-actinolite and minor chlorite in matrix. Traces: sphene.

Massive mafic flow
Foliated hypidiomorphic granular with porphyroblasts of albite plagioclase in a matrix of chlorite albite plagioclase, carbonate and traces of opaque iron oxides.

Variolitic Mafic flow
Matrix: laths of tremolite-actinolite in a matrix of finer plagioclase with irregular patches of chlorite altering to tremolite. Traces: epidote, sphene. Varioles: up to 2 - 3 cm, composed of an ophitic textured margin and dendritic center with laths of tremolite-actinolite in a matrix of albite plagioclase succeeded inwards by dendritic fine granular epidote after plagioclase, carbonate, albite plagioclase and larger epidote needles.
Pillowed intermediate flow
Pilotaxitic texture with phenocrysts of albitic plagioclase, quench plagioclase needles in a matrix of chlorite, epidote, and minor carbonate. Traces: sphen.

Pillowed intermediate flow, amygdular
Pilotaxitic texture with quench plagioclase needles in a matrix of chlorite and epidote. Fractures filled with carbonate, quartz, epidote, and sphen. Amygdules filled with quartz and carbonate.

Pillowed intermediate flow
Pilotaxitic texture with acicular albitic plagioclase in a matrix of epidote, chlorite, tremolite-actinolite, biotite, and carbonate.

Pillowed intermediate flow
Quench textured albitic plagioclase needles with fine grained epidote granules within in a matrix of tremolite-actinolite, epidote grains, and carbonate.

Intermediate flow (massive
Isogranular texture-coarse hornblende needles and subhedral albitic saussuritized plagioclase in a matrix of epidote, anhedral albite plagioclase and accessory sphen, subhedralapatite and minor quartz

Intermediate flow
Ophitic texture - albitic plagioclase laths in a matrix of chlorite, epidote and carbonate with accessory sphen and opaque iron oxides.

Pillowed intermediate flow
Intergranular texture with needles of relic albitic plagioclase in a matrix of tremolite-actinolite anhedral chlorite, quartz and abundant accessory sphen.

Intermediate amygdular flow
Pseudomorph granular texture with rounded irregular saussuritized albitic plagioclase with fine epidote granules, irregular plates of chlorite and biotite and anhedral of quartz and epidote.
442 Gabbroic flow center
Ophitic texture with saussuritized albite a
  circular plagioclase and sheaves of tremolite
  actinolite with accessory epidote and sphe.

444 Intermediate pumiceous lapillistone
Bioite phenocrysts in a very fine grained anhedral
  disorganized matrix of white mica, biotite, chlorite,
  albite plagioclase and quartz.

445 Intermediate Flow
Granular texture with irregular aligned chlorite
  grains and anhedral rounded grains of albite
  plagioclase epidote, quartz and minor carbonate
  and opaque iron oxides.

446 Intermediate crystal tuff-bedded
Oscillatory zoned plagioclase phenocrysts in a fine
  grained anhedral groundmass of albite plagioclase,
  chlorite quartz and epidote.

445 Intermediate pumiceous lapillistone
Dewitrified pumice consisting of lenticular
  saussuritized plagioclase with a matrix of quartz,
  wispy sericite and porphyroblasts of biotite and
  chlorite.

447 Feisic Pumiceous lapillistone
Lapilli 1 x 5 cm consisting of "fingernail" like
  swirls of very fine grained epidote plus chlorite
  plus albite plagioclase and quartz in a matrix of
dewitrified shads now chlorite, epidote, albite
  plagioclase, and quartz

444 Feisic vitric tuff
Anhedral grains of albite plagioclase and quartz
  in a matrix of chlorite, wisps and finely granular
  epidote

435 Feisic crystal tuff
Anhedral albite plagioclase and quartz with
  intergranular epidote and sericite with minor chlorite
  phenocrysts and secondary carbonate.

441 Feisic vitric tuff
Plagioclase and quartz anheda with fine granules
  of epidote, sericite, chlorite.

446 Feisic crystal tuff
Feldspar crystals in a matrix of fine grained anhedral
  albite plagioclase and quartz with minor epidote and
  sericite with secondary carbonate.
Felsic pumiceous lapilli tuff
Pumiceous essential fragments with subhedral saussuritized albitic plagioclase phenocrysts in a groundmass of plagioclase, quartz, epidote and traces of sericite.

Pillow intermediate flow
Ophitic texture with laths of saussuritized albitic plagioclase in a matrix of chlorite, sericite and quartz. Accessory - orthoclase and opaque iron oxides.

Intermediate lithic hyaloclastite
Subophitic texture with fine albic plagioclase laths in a matrix of quartz, plagioclase and chlorite. Fractured filled with carbonate, epidote albic plagioclase and quartz.

Felsic-pumiceous crystal lapilli tuff
Pumiceous fragments; biotite, sparker, albite plagioclase, and opaque iron oxides. Matrix: devitrification texture composed of albite plagioclase, orthoclase, biotite, sericite, epidote and quartz. Trocho - sillimanite.

Massive intermediate flow
Trachytic texture composed of laths of albite plagioclase, occasional stumpy albite phenocrysts in a matrix of chlorite, epidote granules and grains and occasional chlorite and carbonate porphyroblasts.

Felsic lapilli tuff
Eutaxitic texture with felsic lithic fragments, flattened pumice fragments and relict shard matrix. Fine grained albite, orthoclase, quartz with accessory epidote and sericite.

Felsic lapilli tuff
Eutaxitic texture with deformed shard replaced by quartz and albite plagioclase draped over felsic lithic fragments with a groundmass of recrystallized quartz and albite and epidote.

Felsic vitrophyre
Elongate corroded quartz and anhedral albitic plagioclase phenocrysts in a matrix of very fine grained albite, quartz orthoclase epidote and sericite. Fractures contain quartz and zircons.

Felsic crystal tuff
Eutaxitic texture with quartz phenocrysts in a matrix of corroded anhedral orthoclase, albite and quartz with secondary carbonate, sericite and epidote.
CYCLE III

456. Pillowed Mafic flow
Ophitic texture with laths of albite plagioclase
in a matrix of chlorite, carbonate epidote and
opaque iron oxides.

457. Mafic Flow
Porphyroblasts of tremolite-actinolite in a matrix
of fine grained anhedral chlorite, albite plagioclase
and epidote. Traces - sphene

458. Mafic flow
Coarse ophitic texture with, epidote and albite
plagioclase after plagioclase phenocrysts in a
matrix of chlorite, minor biotite, albite epidote
and quartz.

459. Pillowed mafic flow
Radiating sheaves of tremolite-actinolite in an
aggregate of very fine grained granular epidote,
albite plagioclase and opaque iron oxides.

460. Pillowed mafic flow
Amygdular, with ophitic texture albite plagioclase
needles in a matrix of chlorite, epidote and carbonate.

461. Pillowed mafic flow
Ophitic to trachytic with feldspar needles and
interstitial subhedral to anhedral tremolite-
actinolite, chlorite and epidote. Traces - sphene.

462. Pillowed mafic flow
Ophitic with saussuritized plagioclase, tremolite-
actinolite and accessory sphene.

463. Basaltic hyaloclastite
Very fine grained quenched plagioclase in a matrix
of chlorite and epidote with a matrix of chlorite,
epidote with a matrix of chlorite, epidote biotite
and carbonate with relict pelagonitic texture.

464. Pillowed mafic flow
Relict ophitic texture - tremolite-actinolite,
epidote, carbonate, and chlorite.

465. Mafic flow
Plagioclase phyric basalt with interstitial
tremolite epidote and carbonate. Some mafic grains
are a clinopyroxene core surrounded by chlorite and
tremolite - actinolite.
Mafic flow
Chlorite plates after pyroxene, phenocrysts in a matrix of plagioclase plus chlorite, carbonate, biotite and quartz.

Intermediate flow
Ophitic texture with plagioclase needles in a matrix of anhedral tremolite-actinolite, epidote, albite and quartz.

Intermediate puniceous lapillistone
Crystal fragments: albite plagioclase and sericite. Lithic fragments and sherd matrix - chlorite, epidote, albite plagioclase and sericite.

Variolitic flow - matrix
A circular, radiating tremolite and anhedral patches of chlorite in a matrix of anhedral albic plagioclase epidote and quartz.

Variolitic flow - coalesced varioles
Lenticular anhedral quartz and chlorite grains in a matrix of very fine grained albite plagioclase, biotite and epidote.

Variolitic flow - matrix
Radiating subhedral tremolite-actinolite, chlorite plates in a matrix of albic plagioclase, biotite and epidote. Traces - quartz.

Variolitic flow - coalesced varioles
Lenticules of polysutured quartz in a matrix of very fine grained albic plagioclase, chlorite and biotite with traces of sericite.

Felsic tuff breccia
Partly welded texture with relict shards of quartz, albic plagioclase, epidote and chlorite and occasional relict puniceous lapilli with similar mineral assemblages.

Felsic crystal vitric tuff
Occasional strained quartz and sericitised albic plagioclase phenocrysts in a matrix of glass with spherulitic plagioclase, epidote and quartz with inter spherulite chlorite plus plagioclase.

Felsic crystal vitric tuff
Quartz and albic plagioclase phenocrysts in a matrix of relict spherulitic glossy material now comprised of chloritic area minor biotite between spherulitic textured albite, epidote, chlorite and quartz.
Felsoic vitric lapilli tuff
Relict vitric spherulitic matrix composed of
albitic plagioclase, epidote, and quartz in a
matrix of plagioclase, epidote, chlorite and carbonate
with pumiceous clasts of similar mineralogy with
quartz phenocrysts.

Felsoic flow - spherulitic
Spherulites of albitic plagioclase epidote quartz
carbonate, muscovite, in a matrix of brown finely
granular biotite, plagioclase, epidote, quartz, and
traces of opaque iron oxides.

Felsoic flow - spherulitic
Spherulites of albitic plagioclase, epidote and
traces of sericite in a matrix of albitic plagioclase,
epidote, chlorite, sericite and biotite.

Felsoic flow - porphyritic
Quartz and lesser albitic plagioclase phenocrysts in
a fine grained matrix of devitrified glass composed
of anhedral quartz, albite, epidote, sericite
carbonate and biotite.

Felsoic lithic lapilli tuff
Lithic and pumiceous lapilli in a spherulitic glossy
matrix, now composed of quartz phenocrysts in a
matrix of saussuritized plagioclase anhedral and
fine grained anhedral quartz and secondary inter-
granular biotite and porphyroblasts of subhedral,
epidote.

Felsoic crystal vitric tuff
Quartz and minor albitic plagioclase phenocrysts in a
matrix of plagioclase and fine grained epidote
anhedra with quartz, sericite and carbonate.

Quartz feldspar porphyry
Subhedral albite plagioclase phenocrysts, subordinate
corroded quartz phenocrysts in a matrix of fine
grained anhedral quartz, plagioclase, sericite,
chlorite, epidote and opaque iron oxides.

Felsoic flow - porphyritic
Quartz phenocrysts in a very fine grained anhedral
matrix of albitic plagioclase, epidote, chlorite and
sericite.

Chloritic Granodiorite
Phenocrysts of antiperthite feldspar in a ground-
mass of albitic plagioclase, quartz, chlorite
sericite, epidote and carbonate, hypabyssal texture.
**Biotite-sericite Granodiorite**

Hypidiomorphic granular texture with perlitic potash feldspar phenocrysts in a groundmass of albitic plagioclase, epidote, biotite, quartz and opaque iron oxides.

**Granodiorite**

Plagioclase phenocrysts in a hypidiomorphic granular groundmass of epidote quartz and white mica with accessory opaque iron oxides and carbonate.

### SAMPLES MENTIONED IN TEXT

<table>
<thead>
<tr>
<th>SAMPLE NUMBER</th>
<th>LAT.</th>
<th>LONG.</th>
</tr>
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<tbody>
<tr>
<td>75-1</td>
<td>51°04'</td>
<td>92°42'</td>
</tr>
<tr>
<td>282</td>
<td>51°12'</td>
<td>92°50'</td>
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</table>

Intermediate flow

Trachytic texture defined by 1-2 mm laths of plagioclase heavily saussuritized in a matrix of coarse secondary plates of chlorite. Occasional primary clinopyroxene grains occur in the middle of chlorite plates. Accessories include Fe-Ti oxides and carbonate.
<table>
<thead>
<tr>
<th>SAMPLE NUMBER</th>
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<th>LONG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>73-12-471</td>
<td>51°03'</td>
<td>92°35'</td>
</tr>
<tr>
<td>Coarse-grained mafic flow</td>
<td></td>
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<tr>
<td>Flow to three mm, heavily saussuritized plagioclase laths in a matrix of uralitized augitic clinopyroxene</td>
<td></td>
<td></td>
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<tr>
<td>73-12-497</td>
<td>51°05'</td>
<td>92°33'</td>
</tr>
<tr>
<td>Intermediate Lapilli tuff</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Matrix consists of very fine-grained biotite, chlorite, albite, epidote, and quartz with relics of the same mineralogy but less mafic and finer grained. Phenocrysts of primary clinopyroxene partially altered to biotite scattered in matrix. Large lithic clasts (5-10 mm) are less mafic than matrix and have irregular subangular outlines.</td>
<td></td>
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<tr>
<td>73-12-481</td>
<td>51°06'</td>
<td>92°32'</td>
</tr>
<tr>
<td>Intermediate crystal tuff</td>
<td></td>
<td></td>
</tr>
<tr>
<td>About 15 percent 1 mm, subhedral plagioclase crystals in a matrix of fine-grained chlorite, biotite, epidote, albite and quartz all after glass shards.</td>
<td></td>
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<tr>
<td>73-12-739</td>
<td>51°05'</td>
<td>92°00'</td>
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<tr>
<td>Diopside</td>
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<td></td>
</tr>
<tr>
<td>Relict ophtitic texture defined by 1-2 mm laths of albite plagioclase and epidote and laths of tremolite-actinolite with minor chlorite. Ungulate layering present, mafic-rich banding preserved augitic clinopyroxene.</td>
<td></td>
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<tr>
<td>73-12-715</td>
<td>51°02'</td>
<td>92°37'</td>
</tr>
<tr>
<td>Intermediate Lapilli tuff</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Siliceous beds comprising rounded quartz phenocrysts surrounded by very fine-grained quartz and feldspar. Intermediate beds consist of large plates of secondary chlorite with a matrix of fine-grained chlorite, albite, epidote, and quartz. Intermediate beds contain occasional angular clasts of long tube pumice characterized by rounded quartz lindicles in a matrix of fine-grained chlorite, feldspar and epidote.</td>
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<tr>
<td>SAMPLE NUMBER</td>
<td>LAT.</td>
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<tr>
<td>03-12-1010</td>
<td>51°07'</td>
<td>92°37'</td>
</tr>
<tr>
<td>Intermediate lapilli tuff</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fifty percent subangular fine grained pumiceous clasts now devitrified to finger-print pattern of biotite, plagioclase, and quartz in a matrix of relict devitrified glass consisting of very fine grained plagioclase and epidote with minor feldspar microlites.</td>
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<tr>
<td>73-12-2141</td>
<td>51°01'</td>
<td>92°37'</td>
</tr>
<tr>
<td>Intermediate lapilli tuff</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large clasts (2-3 by 3 cm) consisting of relict subhedral plagioclase now albite and epidote in a granular matrix of broken quartz and feldspar phenocrysts and finely divided biotite, quartz, and feldspar. The matrix is similar to the fragments except for the development of larger flakes of biotite and more Fe-Ti oxides.</td>
<td></td>
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<tr>
<td>73-12-2152</td>
<td>51°11'</td>
<td>92°31'</td>
</tr>
<tr>
<td>Mafic flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine felted mass of tremolite-actinolite, saussuritized plagioclase with accessory Fe-Ti oxide minerals.</td>
<td></td>
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</tr>
<tr>
<td>73-12-2456</td>
<td>51°09'</td>
<td>92°33'</td>
</tr>
<tr>
<td>Intermediate lapilli tuff</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Matrix of fine grained quartz, albite, epidote, and chlorite as a cloudy mass around occasional slightly coarser grained clasts.</td>
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<tr>
<td>73-12-2481</td>
<td>51°11'</td>
<td>92°39'</td>
</tr>
<tr>
<td>Spherulitic felsic tuff</td>
<td></td>
<td></td>
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<tr>
<td>Spherulites comprised of albite, epidote, and quartz with minor sericite. Matrix is the same mineralogy plus chlorite.</td>
<td></td>
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</tr>
<tr>
<td>73-12-2822</td>
<td>51°07'</td>
<td>92°35'</td>
</tr>
<tr>
<td>Mafic hyaloclastite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angular plates of very fine grained granular spherule, chlorite, epidote, albite, and Fe-Ti oxides after glassy fragments in a matrix of chlorite, epidote, albite, and large secondary carbonate grains.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>76-1-359</td>
<td>51°01'</td>
<td>92°35'</td>
</tr>
<tr>
<td>Felsic crystal tuff</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ten percent 1-3 mm. sutured quartz crystals in a matrix of .01 mm quartz, albite, plagioclase, and chlorite. Also present are relict lithic clasts defined by variations in color index.</td>
<td></td>
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</tr>
</tbody>
</table>
SAMPLE NUMBER

73-12
Cherty Tuff
Thin bedded (5mm) fine grained assemblage of biotite, quartz, epidote, and albite with proportion of biotite and grain size decreasing upward through beds. Upper quartz rich portion greater than 80 percent quartz less than .007 mm.

73-12
Lithic wacke
Framework grains of rounded quartz and secondary subhedral biotite in a matrix of fine grained biotite quartz and feldspar. About 25 percent of the section is clasts of very fine grained biotite, epidote, albite, and quartz defining relict pumiceous textures.

73-12
Cherty tuff
Base of individual beds have lenses of plastic clasts now albite and epidote in a matrix of quartz and chlorite changing upward to fine grained rounded granules of quartz and albite with minor rods of epidote.

73-12
Peridotite
Rounded cumulate relict olivine (now alc and carbonate) and larger subhedral augitic clinopyroxene in a matrix of Fe-Ti oxide and talc.

73-12
Dunite
Rounded subhedral relict olivine (now feathery tremolite) in a matrix of opaque Fe-Ti oxides and chlorite. Occasional 2-3 mm. wide cracks filled with asbestos from amphiboles.

73-12
Dunite
Large relict olivine with grains outlined by disseminated Fe-Ti oxides and chlorite. Mineral assemblages now carbonate, talc and Fe-Ti oxides.
APPENDIX G

SUPPLEMENTAL STRUCTURAL DATA

This appendix includes data for structural elements from within and outside the graben to supplement the structural geology section of chapter 3.
Figure G-1: Poles to Bedding Outside Graben (plotted on Lambert Equal Area Net)
Figure G-2: Normals to Bedding Planes in Graben (plotted on Lambert Equal Area Net)
Figure G-3: Lineation and Fold Axis Directions in Graben (plotted on Lambert Equal Area Net)
Figure 8-4: Lineations Outside Graben (plotted on Lambert Equal Area Net)
Figure G-5: Normals to Foliation Planes (plotted on Lambert Equal Area Net)
APPENDIX H

Rare-Earth Element Mobility

1) General Statement

The REE and many other trace elements have commonly been assumed to remain immobile during spilitization, metasomatism, halmo ́lysis, general hydrothermal alteration and metamorphism (Pearce and Cann, 1973; Winchester and Floyd, 1976; Ferrara et al, 1976; Koljonen and Rosenberg, 1975). Therefore, variation in trace element abundances have been used in a variety of classifications of the tectonic environments for mafic rocks (Pearce and Cann, 1973). However, for example, Kay and Senechal (1976) concluded that REE alone cannot be used to distinguish basalt from mid-ocean ridges (MORB) from small ocean basins and island arcs for the rocks of the Troodos ophiolite. There is some literature on mobility of the REE, which has been integrated with a study of REE mobility in basaltic rocks of low metamorphic rank by Hellman et al (1979). The study concludes that there are four types of REE mobility.

Type 1

Gross mobility of all REE, resulting in REE enrichment and generally parallel movement of the chondrite normalized pattern with irregular preferential enrichment of the LREE, as shown in Figure H-1. This type of mobility imprints
Figure H.1: Sketch of types of REE mobility.
Note that the preferential mobility of La, Ce, Eu, and Yb may be found associated with the other types of REE mobility. (After Hellman et al, 1979)
an alkalic character to tholeiitic rocks. Examples of this type of alteration include the Bhoiwada section of spilitized basalts on Bombay Island (Hellman and Henderson 1977), the altered sea floor basalts described by Ludden and Thompson (1978, 1979), and sea-flow basalts from the Shatsky Rise (Masuda and Nagasawa, 1975).

Based upon this sort of mobility, Ludden and Thompson (1978, 1979) advance the view that petrological conclusions should be drawn only from analyses of fresh basaltic glass. The interior of an Archean pillow is less altered than the rim (Bargar, 1979). Bargar et al. (1977) reported similar results for ocean ridge basalts therefore, pillow centers have been samples wherever possible, but comparisons to the rim have not been made. The sort of alteration reported by Ludden and Thompson (1978 and 1979) may well be restricted to sea-floor fractures, and in any instance their altered material come in many cases from pillow exteriors. REE mobilization may not always occur during alteration as Frey et al (1974) and Smewing and Potts (1976) report on an LREE-depleted altered basalts. Hellman et al (1979) suggest REE absorption on clay minerals etc. may explain enrichment (Roaldset, 1973, 1975). This type of REE alteration is the most insidious as it will cause changes in shape of the patterns for LREE depleted and flat REE patterns (Hellman et al., 1979). Collerson and Fryer (1978) have suggest CO$_2$ complexing of the HREE enriching the heavy end of the pattern in some rocks.
Type 2

Mobility redistributes the REE patterns resulting in enrichment in all REE or depletion in all REE, a general broadening of the pattern (Hellman et al., 1979).

Type 3

REE mobility is a general REE depletion which according to Hellman et al. (1979) can be caused by a combination of hydrothermal leaching, phase dilution and volume increase, although volume increase is not a significant problem. Phase dilution refers to the substitution of zeolite, calcite, prehnite etc for primary minerals. Wood et al. (1976, cited by Hellman et al., 1979) suggest that the zeolites, opophyllite, celadonite, aragonite and chalcedony dilute REE concentrations.

Type 4

REE mobility is element selective resulting in variably positive and negative anomalies for: 1) Ce (Masuda and Nagawawa, 1975). Negative Ce anomalies can be caused by type 1 mobility in which Ce moves into the rock in proportion to its content in the sea water (Ludden and Thompson, 1978) i.e. a lesser degree of enrichment.
2) Eu (Sun and Nesbitt, 1978).

3) La enrichment not related to general LREE enrichment (Robertson and Fleet, 1976) occurs in upper pillow lavas of Troodos.

4) Yb enrichment has been reported by Robertson and Fleet (1976) for a sub-number lava and an altered pillow.

In contrast to the above, Menzies et al. (1979) have experimentally determined that the REE are immobile under conditions of 500 bars, 150-350°C and water/rock of 10 to 125. However they concede that changes in the light REE are possible from retrograde effects. The assemblages described from the above experimental work consist of a chlorite-smectite phase plus anhydrite which does not correspond to the assemblages observed in the Uchi-Confederation metavolcanic rocks.

Most of the studies of REE mobility have concentrated upon mafic rocks, with the exception of Nesbitt's (1979) study of the weathering of a granodiorite in which enrichment of the HREE during weathering was demonstrated.

2) Results from the Confederation Lakes Area

REE patterns for Archean basalts are generally richer in LREE than modern mid-ocean ridge basalts (Frey et al. 1974; Arth and Hanson, 1975) raising the possibility that this pattern in the basalt of Confederation Lakes of all three cycles was caused by type 1 mobility of Hellman et
al., (1979). If this hypothesis is accurate it results in selective light REE enrichment of virtually all Archean basalts (cf Arth and Hanson, 1975; Condie, 1976) implying that exactly the same sort of rock-fluid interaction occurred in all Archean terrains. The lack of major element mobility occurring in pillow interiors of both modern (Baragar et al., 1977; Humphris and Thompson, 1978, 1978a) and Archean pillows (Baragar et al., 1979) argues strongly against this REE mobility effect as does the consistency of modelling results obtained from Archean basalts in general (Condie, 1976; Arth and Hanson, 1975). Many of the intermediate volcanic rocks analyzed from the Confederation Lakes area are pillow flows and the same arguments with respect to the unlikelihood of alteration affecting the REE apply. The mafic unit most likely to show alteration effect in the REE chemistry are the Cycle III basalts which are heavily epidotized and display a slight enrichment in La (Fig. 5-17). The alteration, if present does not alter the petrogenetic conclusions significantly.

The major alteration effect noted in the felsic meta-
volcanic rocks of all three cycles is an enrichment in the heavy REE in Cycles III which is explained by carbonate complexing of the HREE (Collerson and Fryer, 1978).
APPENDIX I

PUBLICATIONS

a) Thurston and Breaks, (1978)
b) Thurston (in press)
C) Gupta, Thurston, and Dusanowskj (1979)
METHAMORPHIC AND TECTONIC EVOLUTION OF THE UCHI ENCLAVE, IN THE ENGLISH RIVER SUBPROVINCE

F.C. Husdon and W. U. Sweet

Abstract

The Uchi enclave, a subdivision of the Superior Province of the Canadian Shield, is a belt of metamorphic and granitic rocks with minor metasedimentary rocks, surrounded by the English River subprovince, a "greenstone belt" composed of metasedimentary and volcanic rocks. The lithologic transition between the two subprovinces is marked by an east-trending zone of crenulation. The Uchi subprovince is characterized by low-pressure subgraniotectonic events, whereas the English River subprovince is characterized by high-pressure subgranitization. The Cretaceous rocks found within the English River subprovince include metapelites, metavolcanic rocks, and metasediments. The English River subprovince is divided into two zones: the high-grade zone, characterized by high-grade metamorphism, and the intermediate zone, characterized by low-grade metamorphism. The Cretaceous rocks found within the Uchi subprovince include metapelites, metavolcanic rocks, and metasediments. The high-grade zone is characterized by high-grade metamorphism, and the intermediate zone, characterized by low-grade metamorphism.

Résumé

La zone de la province de l'Uchi est une subdivision de la province du Superior, dans le Boreal de l'est, et elle est composée de roches métamorphiques et granitiques, ainsi que de quelques roches métamorphiques. La transition s'étend sur une large zone de la province de l'English River et est caractérisée par une forte pression de subgraniotectonique. Les roches de la province de l'Uchi sont caractérisées par des faibles pressions de subgraniotectonique. Les roches de la province de l'English River sont caractérisées par des faibles pressions de subgraniotectonique. La province de l'Uchi est divisée en deux zones: la zone haute de pression, caractérisée par une forte pression de subgraniotectonique, et la zone intermédiaire, caractérisée par une faible pression de subgraniotectonique. Les roches de la province de l'English River sont caractérisées par des faibles pressions de subgraniotectonique. La province de l'Uchi est divisée en deux zones: la zone haute de pression, caractérisée par une forte pression de subgraniotectonique, et la zone intermédiaire, caractérisée par une faible pression de subgraniotectonique. Les roches de la province de l'English River sont caractérisées par des faibles pressions de subgraniotectonique.

INTRODUCTION

A metaraprap map of northwestern Ontario north of the Wabigoon Belt was compiled at a scale of 1:1 000 000 from published reports and work in progress by the geological survey of the Ontario Ministry of Natural Resources. Data for large parts of the study area are based on 1:200 000 maps (Wiley and Nielsen, 1966; Thucson and Carter, 1970; Thucson et al., 1974). The compilation has shown analogs with younger terranes which contribute to the understanding of the evolution of the Superior Province and the Uchi enclave.

GENERAL GEOLOGY

The English River subprovince (Fig. 1) is a greenstone terrane consisting of a northern supracrustal domain of metamorphosed and metavolcanic rocks. To the north, the metavolcanic rocks are overlain by the yellow-gray, schistose greenstones of the Baraga Supergroup (Miller and others, 1974; Thucson et al., 1976). The metavolcanic rocks are stratigraphically consistent with the stratigraphy of the Baraga Supergroup in the Lake Superior area of the Uchi subprovince (Thucson, 1971) and are also probably equivalent to the upper volcanic cycles. The
The southern boundary of the English River Subprovince is problematic in stratigraphic terms with the Uchi Subprovince to the north, but is marked by the Sydney Lake Fault System (Kramar, 1971; Storrie, 1976, 1977). Portions of the southern plutonic domain of the English River Subprovince are mafic-tonalite to 3170 Ma in age (Brown et al., 1974) whereas the metamorphism of the Uchi Subprovince are 2960 to 2740 Ma in age (Kramar and Davis, 1971; Maas and Thurston, 1978).

The Uchi Subprovince, north of the English River Subprovince, is a granite-greenstone belt. It is dominated by several major to felsic volcanic piles. These are interconnected by the dollar facies baratitic flow to form a relatively continuous, metamorphic-facies domain complex extending from Lake Winnipeg to the Archean-Paleozoic contact west of Hudson Bay.

Northwest of this subprovince lies the Berens River Subprovince (Wilson, 1973) bounded by faults and consisting of gneisses, schists, and orthogneisses with paragneisses containing remnants of sedimentary belts now metamorphosed to upper greenschist facies.

The Cross Lake Subprovince, north of the Berens River and Uchi subprovinces, is an east-west trending greenstone-terrace belt. It is dominated by greenstones, high-grade schists, and high-grade mylonites (MacGregor, 1971) separated by 1000 m thick voids filled with high-rank phaneritic mylonites (Thurston et al., 1975).

**Figure 1.** Geologic subprovinces and the general distribution of metamorphic zones in northwestern Ontario.
pyroxenes in major flows and relitic snowlake texture in ryolitic rocks are well preserved (Thorston, 1978). Low grade domains range from mid-green schist (biotite zone) to the green schist-amphibolite facies transition. The latter, marked by extensive recrystallization, is confined to the larger metavolcanic-metasedimentary belts. Medium grade domains are characterized by assemblages of the lower to mid-amphibolite facies high grade domains by mid to upper amphibolite facies. The transition from medium to high grade is marked by the reaction:

\[ \text{muscovite + quartz} \rightarrow K\text{feldspar} \rightarrow Al_2SiO_5 \text{polymorph} + H_2O/\text{melt} \quad (R.1) \]

Scattered areas of granulite facies metamorphic assemblages are found in the southern portion of the English River Subprovince. Assemblages in aluminous metasediments indicate that, in general, metamorphism was of the low to intermediate pressure type typical of many shield areas (Urush et al., 1976), shown by the presence of andalusite at moderate grades and staurolite at higher grades. Kyanite is found only in a few areas where tectonic over-pressures are likely to have been a factor, such as near the faulted northern boundary of the Berens River Subprovince (Wilson, 1971).

There is, however, a tendency to progress from medium grade assemblages containing cordierite without almandine in the metavolcanic-metasedimentary belts to cordierite with almandine in the northern part of the English River Subprovince, suggesting an increase in relative pressure associated with the higher grade (Winkler, 1974, p. 91). Metamorphic and deformational histories of the English River and Uchi subprovinces are similar (Thorston, 1978: Brooks and Bond, 1975) involving a maximum of five metamorphic events (Table 2). This interpretation is similar to the derived by McRitchie and Water (1971) for the Manigotagan gneisses.

Table 1

<table>
<thead>
<tr>
<th>Metamorphic Assemblages in the Cross Lake, Uchi, and English River Subprovinces, Northwestern Ontario.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Michalet metamorphics</strong></td>
</tr>
<tr>
<td>Chlorite</td>
</tr>
<tr>
<td>Epidote-Clinozoisite</td>
</tr>
<tr>
<td>Actinolite</td>
</tr>
<tr>
<td>Pele-Hornblende</td>
</tr>
<tr>
<td>Dark hornblende</td>
</tr>
<tr>
<td>Stilpnomelane</td>
</tr>
<tr>
<td>Clinozoisite</td>
</tr>
<tr>
<td>Orthopyroxene</td>
</tr>
<tr>
<td>Biotite</td>
</tr>
<tr>
<td>Al-pyroxene</td>
</tr>
<tr>
<td>Ca-plagioclase</td>
</tr>
<tr>
<td>Na-plagioclase</td>
</tr>
<tr>
<td><strong>Iron-Formations</strong></td>
</tr>
<tr>
<td>Chlorite</td>
</tr>
<tr>
<td>Stilpnomelane</td>
</tr>
<tr>
<td><strong>Pelites and serpentines</strong></td>
</tr>
<tr>
<td>White mica</td>
</tr>
<tr>
<td>Chlorite</td>
</tr>
<tr>
<td>Biotite</td>
</tr>
<tr>
<td>Andalusite</td>
</tr>
<tr>
<td>Staurolite</td>
</tr>
<tr>
<td>Cordierite</td>
</tr>
<tr>
<td>Almandine</td>
</tr>
<tr>
<td>Chloritoid</td>
</tr>
<tr>
<td>Staurolite</td>
</tr>
<tr>
<td>Na-plagioclase</td>
</tr>
<tr>
<td>Ca-plagioclase</td>
</tr>
<tr>
<td>Fissure volcanics</td>
</tr>
<tr>
<td>White mica</td>
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<tr>
<td>Chlorite</td>
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<tr>
<td>Biotite</td>
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<tr>
<td>Pumpellyite</td>
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<tr>
<td>Stilpnomelane</td>
</tr>
<tr>
<td>Epidote-clinozoisite</td>
</tr>
<tr>
<td>Actinolite</td>
</tr>
<tr>
<td>Hornblende</td>
</tr>
<tr>
<td>Almandine</td>
</tr>
<tr>
<td>Na-plagioclase</td>
</tr>
<tr>
<td>Ca-plagioclase</td>
</tr>
</tbody>
</table>
Table 2
Metamorphic and deformational events in the
Uchi and English River subprovinces
(After McRitchie and Weber, 1971)

<table>
<thead>
<tr>
<th>Event</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Original sedimentary and volcanic fabric</td>
</tr>
<tr>
<td>D1</td>
<td>Isoclinal folds in volcanic sequences and nappes in the Red L.-Bert L. areas</td>
</tr>
<tr>
<td>M1</td>
<td>Development of planar fabric preserved as 'inclusion' grains in staurolite, biotite, and amphibole,</td>
</tr>
<tr>
<td>and epidote</td>
<td></td>
</tr>
<tr>
<td>M1A</td>
<td>Main regional metamorphic event. Development of chlorite, biotite, staurolite, muscovite, cordierite,</td>
</tr>
<tr>
<td></td>
<td>stilbite, epidote. Migmatization of meta-igneous and sedimentary rocks.</td>
</tr>
<tr>
<td></td>
<td>Development of chlorite, biotite, staurolite, muscovite, cordierite, stilbite, epidote.</td>
</tr>
<tr>
<td></td>
<td>Regional migmatization of M1 event. Development of chlorite, biotite, staurolite, muscovite,</td>
</tr>
<tr>
<td></td>
<td>cordierite, stilbite.</td>
</tr>
<tr>
<td>D2</td>
<td>Regional tectonism, rotation of M1, migmatisation associated with migmatization, growth of granite</td>
</tr>
<tr>
<td></td>
<td>and the Uchi volcanics</td>
</tr>
<tr>
<td>M2</td>
<td>Matrix garnet, and development of mylonitic cleavage.</td>
</tr>
<tr>
<td></td>
<td>Development of mylonitic cleavage in the D2 foliation.</td>
</tr>
<tr>
<td>D3</td>
<td>Late transcurrent faulting in the D3 foliation.</td>
</tr>
<tr>
<td>M3</td>
<td>Minor recrystallization associated with D3.</td>
</tr>
</tbody>
</table>

The late St. Joseph area. The main features of this event, as observed immediately adjacent to the faults, are recrystallization of muscovite and chlorite, formation of hematite, cordierite, epidote, and diaphanous replacement of M1 textures.

Transcurrent faults such as the Bear Lake Fault are much later than these faults. The Lake recrystallization associated with these faults is a much later metamorphic event, M4 (Thurston, 1976).

METAMORPHISM IN THE ENGLISH RIVER
AND UCHI SUBPROVINCES
Northern Diapiric Domain

Several workers have documented a progressive increase in metamorphism, from low grade to high grade, to high grade in the southwards and the northern metasedimentary rocks of the English River Subprovince (McRitchie and Weber, 1971; Jackson, 1973; Dower, 1966). The progressive regional metamorphic patterns are commonly displaced by extensive postmetamorphic fault systems that appear to have been initiated by the tectonic transport between the two subprovinces. For example, the Sydney Lake Fault System is cut by the Cretaceous faults of the English River Subprovince (McRitchie and Weber, 1971). The postmetamorphic faults and the Cretaceous faults of the English River Subprovince are a widespread phenomenon involving at least 30% of the subprovince.

Five-ship metamorphic zones, including the St. Joseph area (Table 3), and briefly discussed in Table 3, are characterized by assemblages recorded in pelitic and semi-pelitic rocks and

1. LOW GRADE
(1) chlorite-biotite zone
2. MEDIUM GRADE
(2) staurolite-chlorite-biotite zone
(3) stilbite-muscovite zone
3. HIGH GRADE
(4) sillimanite-K feldspar zone
(5) cordierite-sillimanite-K feldspar zone

A plausible reaction for formation of M2 staurolite (Table 2) may be similar to that experimentally determined by Hessecke (1969):

\[ \text{chlorite + muscovite + staurolite + biotite + quartz + vapour} \]

Chlorite and muscovite are widespread in pelitic rocks of the chlorite-biotite zone of the low-grade metamorphic zone, immediately adjacent to the staurolite zone to the north. Chlortoid does not appear to be a significant phase in the chlorite-biotite zone. Chlorite, biotite, and muscovite also represent integral phases in the 51 degree of the St. Joseph area. Cordierite, a low-grade aluminosilicate, surfaces and is present with stilbite, muscovite, sillimanite, and biotite as a high-grade assemblage, prior to elimination of M2.
Staurolite with increasing metamorphic grade. The following experimentally determined reaction (Nisbet and Winkler, 1968) appears to be applicable:

\[
\text{Chlorite + muscovite + quartz \rightarrow biotite + sillimanite + vapour}
\]

Relicts of staurolite occur in the centres of some cordierites, but the relationship of these minerals is not clear. It is also uncertain whether staurolite developed within the sillimanite or within the andalusite - Ti field of stability. These staurolites have not been noted with any of the Al₂SiO₅ minerals, although in the Sudbury area of Lake St. Joseph (Fig. 1) to the east, coexisting staurolite and andalusite pegmatoids have been observed (Banks and Banks, 1976).

It seems plausible that the path of metamorphism breached the andalusite - sillimanite boundary within the staurolite zone prior to the first appearance of cordierite. It should be mentioned that a zone of high level cataclastic deformation (Lake St. Joseph Fault Zone) crosses the staurolite zone. This zone of brittle failure postdates the youngest Archean granulite phases (leucocratic quartz monzonite) at a regional metamorphism, although no significant change, in metamorphic grade is apparent across the fault. The main effect of this fault was to facilitate H₂O ingress into wall rocks causing retrogression of H₂O metamorphic assemblages, exemplified by complete replacement of staurolite by chlorite and muscovite. Obduction of primary structures in the high grade zone is related to biotite and pervasive matrix changing.

Mineral assemblages corresponding to each of the zones listed in Table 3 may be explained in terms of experimentally and/or petrographically named metamorphic reactions. The observed increase in grade metamorphism is exemplified from non-migmatised metasedimentary assemblages in the minimum grade zones to an orderly succession of migmatitic stages at high grade (Banks and Banks, 1977).

Figure 2. Distribution of metamorphic zones, stages, and metamorphic equilibrium stages at Uchi Subprovince-English River Subprovince interface, Lake St. Joseph area.
<table>
<thead>
<tr>
<th>ZONE</th>
<th>ASSEMBLAGE</th>
<th>ROCK TYPE</th>
<th>ZONE</th>
<th>ASSEMBLAGE</th>
<th>ROCK TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Grade</td>
<td>Medium Grade (cont.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chlorite-Biotite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chl - Mu - Bio - Ep + Gl</td>
<td>W</td>
<td>Sericite</td>
<td>Bio - Mu</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>Mu - Chl - Gl - Tour</td>
<td>W</td>
<td>Muscovite</td>
<td>Bio - Mu - Alm</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>Bio - Chl - Ep - Act</td>
<td>W</td>
<td></td>
<td>Bio - Chl - Mu - Alm</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Biq - Mu - Chl - Gl</td>
<td>P</td>
<td></td>
<td>Bin - Mu - Sill</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Bio - Ep - Mu</td>
<td>W</td>
<td></td>
<td>Bio - Sill + Tour + (St)</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Chl - Act - Ep</td>
<td>M</td>
<td></td>
<td>Bin - Sill</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Act - Hb - Bwr</td>
<td>M</td>
<td></td>
<td>Bin - Cord - Sill + Alm + Tour</td>
<td>W</td>
<td></td>
</tr>
</tbody>
</table>

|      | Medium Grade |            |
| Skaerlite-Chlorite-Biotite |            |            |
| Kio - Chl - Bio | W       |           | Kio - Cord | W       |
| Bio - Mu | W       |           | Bio - Cord | W       |
| Si - Bio - Chl - Mu = Chl, Mu | P       | Sericite | Bio - Alm | W       |
| Mu - Bio - St - Alm = (Alm) | P       | Felsite | Bio - Alm - Cord | P       |
| Bio - Si - Mu = Chl, Mu | P       |           | Bio - Kspar - Cord - Sill | P       |
| Bio - Chl - Mu = (St, And) | P       |           | Bio - Cord - Sill - Alm + Kspar | P       |
| Bio - Sill - Alm = Gl + (Alm) | P       |           | Bio - Sill - Cord - Alm | P       |
| Sill - Bio - Mus = Chl | P       | Almandine | Bio - Alm | W       |
| Bio - Alm - Sill - Tour = Gl | P       | Cordierite | Bio - Sil = Mu | W       |
| Tour = (St) | P       | K-felsite | Bio - Cord - Alm = Sill | P       |
| Trem - Bio | UM       | Low Pressure | Bio - Opx - Opx - Hbl + Alm = Qtz | M       |
| Bio - Cord - Alm + (St) | P       | Granulite | Bio - Cord - Alm + Kspar = (Sill) | P       |

<table>
<thead>
<tr>
<th>Abbreviations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Act = actinolite</td>
</tr>
<tr>
<td>Alm = almandine garnet</td>
</tr>
<tr>
<td>And = andalusite</td>
</tr>
<tr>
<td>Bio = biotite</td>
</tr>
<tr>
<td>Chl = chlorite</td>
</tr>
<tr>
<td>Cord = cordierite</td>
</tr>
<tr>
<td>Ep = epidote/chloro zoisite</td>
</tr>
<tr>
<td>Gt = garnet</td>
</tr>
<tr>
<td>Hbl = hornblende</td>
</tr>
<tr>
<td>Kspar = K felspar</td>
</tr>
</tbody>
</table>

Minerals enclosed by rounded brackets () represent pertholithic M3 relics. Phases enclosed by squared brackets represent M3 dykes and authigenic mineral phases.

Quartz and plagioclase common to all assemblages except those of UM bulk composition.
Within the medium-grade zones, sedimentary bedding structures and framework grains in wackes are generally not completely low-grade documents. Limbs, bedding, and rootless centripetal folds of hydrothermal mobilization (quartz veins) are, however, evident in the transition area between the staurolite-chlorite-biotite and sillimanite-muscovite zones. The transition from medium to high-grade metamorphism corresponds to disappearance of biotite and entry into P-T conditions conducive to widespread development of muscovite, which also melts at lower pressure. The metamorphic index of muscovite generally corresponds to the sillimanite-Kfeldspar zone. Sillimanite decomposes, and in place of pyrophyllite, talc, and anhydrous mica, mica, and muscovite are the only mica minerals in the area.

Near the cordierite-plagioclase-Kfeldspar地段, the major rock type is strongly metamorphosed with hornblende, actinolite, and cordierite. These rocks are more advanced in transition to advanced, highly advanced, and high-grade hornblende facies types.

**Low Pressure Granite Facies Metamorphism**

Several significant areas of the English Trench Subprovince have been affected by the granulite facies regional metamorphism. Three areas, intermittently spanning a strike length of 1.1 km, have been delineated to date (Fig. 1).

1. **Unidentified Lake:** Unidentified Lake is located in the central Klondike Range, 8 miles northwest of the Canadian border.

2. **Chatkaka Lake:** Chatkaka Lake is located in the central Klondike Range, 8 miles northwest of the Canadian border.

3. **Unidentified Lake:** Unidentified Lake is located in the central Klondike Range, 8 miles northwest of the Canadian border.

**Southern Plutonic Domain**

Vaccination and intensity of regional metamorphic grade within the southern plutonic domain of the English River Subprovince is more enigmatic than that in the north because of the following factors:

1. A blanket of dome complex is present to second high-grade metamorphic assemblages.
2. Widespread intra-plutonic veins of K-feldspar, cordierite, and plagioclase are common in most metamorphic layers. In general, the proportion of metamorphic plagioclase decreases almost linearly with the grade of metamorphism.
3. A large proportion of this material has been extensively converted to leucosome and melanosome components.

**Conclusion**

The following field and mineralogical features of the English Trench Subprovince, together with the distribution of rocks belonging to the low-pressure subprovince, suggest that these rocks have experienced a metamorphic facies transition to advanced, highly advanced, and high-grade hornblende facies.

**Acknowledgments**

The authors gratefully acknowledge the contributions of the following individuals to this study:

1. K. B. L. 100 kPa.
2. Also see Limbath and Heli (1968).
appearance of orthopyroxene in some wackes may however, be explicable in terms of the semiquantitative invariant reaction (Grant, 1971, p. 506):

\[ \text{plagioclase + garnet + orthopyroxene + cordierite} \rightarrow K\text{feldspar + melt} \quad (R.6) \]

The zone of granulite metamorphism in the eastern Lac Seul area, situated about 30 km south of the St. Joseph, faces series (Fig. 2) may represent a continuation of the interpreted path of metamorphism outlined in Figure 3, and is reminiscent of the thermal-kinematic model proposed by H. S. (1970). It is possible that progressive removal of fluid phase components via anatectic melts engendered by intersection of the path of metamorphism with multi-producing-peridotite reactions at high grade conditions, may ultimately yield relatively hydrous bulk compositions capable of yielding granulite assemblages.

Metamorphic Conditions

Delineation of the path of progressive regional metamorphism southwards from the Uchi Subprovince-English River Subprovince interface (Fig. 3) may be estimated from the aforementioned invarities in conjunction with several important observations:

1. high-pressure phases such as kyanite or high-temperature high-pressure phases as sapphire are unknown in the English River Subprovince,
2. cordierite is an exceedingly widespread phase in the northern supracrustal domain of the English River Subprovince especially in high-grade metamorphic zones

3. decomposition of staurolite does not coincide with sudden appearance of metasomatic mafic portions stability of staurolite, in other words, does not extend into regions where Mg-muscovite (K-feldspar-ilmenite zone) is absent (P > 4.5 kbar) (Winchell, 1906, p. 199, 218).
4. the disappearance of Mg-muscovite in the presence of quartz generally coincides with pervasive metasomatic migmatisation of pelitic-wacke assemblages (P > 3 kbar),
5. appearance of mobilite-dominant, cumbrite-stages resulting from advanced stage fusion (diapirism) approximately coincides with cordierite-alkali-feldspar-K-feldspar zones,
6. sphene, becomes widespread only in the high-grade zones suggesting increasing pressure for the facies series represented in the Lake St. Joseph area,
7. localized partial melting of amphibolite bulk compositions under low pressure conditions indicates that melt approximates P + Q ≈ P ≈ 2.5 kbar, T > 700°C.

Assuming P + Q total = P + Q + P = P + Q + P + Q, estimates of P-T conditions are as follows:

- **Medium Grade**: 550-600°C, 3-4.5 kbar
- **High Grade**: 650-750°C, 3-7.5 kbar

**Granulite** > 770°C, > 2.5 kbar

**LEGEND**

1. H. S. (1969),
2. H. (1968),
3. Shanley and Suit (1969),
4. upper pressure stability of magnesio cordierite after Shanley and Sut (1969) and Shawt et al. (1974),
5. upper pressure stability of Fe cordierite Richardson (1976),
7. Althaus et al. (1976),
8. S. T. and Karakakea (1971),
9. After Mehl in et al. (1970) and Tuttle and Bowen (1958),
10. Grant (1973), Aluminosilicate system after Holdaway (1971),
11. B. S. (1969),
12. beginning of melting curve for quartz bearing amphibolite and hornblende pyroxene greenschist after B. S. (1969),
13. boundary between high grade and granulite conditions based on breakdown for common hornblendes in presence of quartz (B. S. (1969) and extrapolated beyond 3 kbar.
14. boundary between low and intermediate pressure granulite fields as defined by upper pressure stability of garnierite + plagioclase in basaltic compositions with 100 mgs/mg = F = 60, Green and Rigby (1967).
These coefficients are indicative of an average geothermal gradient between 25°C/km and 50°C/km, possessing mineralogical characteristics of the low-pressure-intermediate series of Myshkin (1961, p. 28), 303).

Two styles of metamorphism are represented in the area: static metamorphism in which primary structures (pillow in mafic flows, fragments in pyroclastic rocks) and textures are well preserved and, dynamic metamorphism, characterized by more intense deformation, effecting destruction of original textures and original structures by flattening, elongation, or obliteration by penetrative deformation. Static metamorphism is preferentially distributed in the metavolcanic-metasedimentary belts and may yield gradually to dynamic metamorphism in the gneiss-belt terranes.

Relationship to Granitic Rocks

Granitic plutons in the English River and Uchi metavolcanic-metasedimentary subprovinces are either forcefully emplaced granitic stocks of mesothermal affinity having relatively wide (1-2 km) contact aureoles of foliated, amphibolitized felsic supraclastic rocks, or diapiric stocks commonly within supraclastic belts surrounded by relatively narrow zones of hornblende and pyroxene hornfels facies rocks.

The low grade metamorphism of the Uchi Subprovince supraclastic belts, except for the contact effects at the margins of the belts, is centred on the Confederation Lake area. In the volcano terranes to the East and West, metamorphic grade gradually increases; the grade is particularly high in the Munzina-Fort Hope belt.

In general the sodic granite rocks are associated with the lower grade rocks of the Uchi Subprovince (Thorston, 1978). Segerson and Turner (1976) note an association of the sodic granite suite with lower metamorphic grade areas and paragonite-rich granites with higher grade areas. This tendency is weakly displayed within the English River Subprovince.

Thus, high grade belts of supraclastic rocks occur between voided granitic plutons. Metamorphic structures indicative of anthraxlites are rare where granitic rocks are in contact with metavolcanic belts.

Relationship to the Gravity Field

The gravity field of the western portion of the Uchi Subprovince consists of gravity highs over supraclastic belts and lows over the surrounding granite areas. In detail the highs are associated not only with thick sequences of mafic flows but also with the terranes of lowest metamorphic grade within the belt (Barlow et al., 1976).

In the English River Subprovince the northernsupracrystal domain as a whole is underlain by a gravity high of about 70 mgals above regional background (West, 1976). The southern granitized plutonic domain of this subprovince is also associated with a local gravity high amounting to about 15 mgals above regional background (V.K. Gupta, pers. comm.). It is thus evident that regional gravity highs are not strictly correlated with low grade greenstone terranes but may also coincide with high grade gneissic belts, particularly with those areas exhibiting low pressure granulite facies assemblages.

Relationship of Metamorphism to Stratigraphy and Tectonics

The low to very low grade domain occur in the central parts of the metavolcanic-metasedimentary belts, and due to the syenitic nature of most belts, there are also the stratigraphically higher parts of the successions. Proximal felsic metavolcanics and metasediments are generally found in lower grade domains. Metamorphic boundaries within the belts appear to crosscut stratigraphic units. Thus the boundary between the low grade terrane of the Uchi Subprovince and the medium grade terrane of the English River Subprovince on the boundary between the low grade terrane of the Uchi Subprovince and the medium grade terrane of the English River Subprovince.
The salient features of the region are the transition from the Uchi Subprovince low grade domain to the English River Subprovince high grade domain and the accretion of the Sydney Lake Fault System with the subprovince boundaries. The metamorphic pattern is probably due to vertical movement of the Sydney Lake Fault System, as published by Wilson (1970) and Mitchell and Wilcox (1971) who also documented a right-lateral offset of almost 10 miles (16 km) based on dislocation of the contact of a quartz diorite pluton south of Wasagami Lake in Manitoba. To the east, in the area south of Red Lake, Stone (in press) suggested a minimum right-lateral displacement of 27 km.

Metamorphic data from the vicinity of the Sydney Lake Fault suggest a minimum vertical movement of 4 km. On this basis, the structure of the area (Stone in press) has inferred vertical movement of 3.5 km. Muscovite-bearing metapelites on the north side of the fault are evidence of K-feldspar- and biotite-bearing assemblages on the south side of the structure, 20 km away. The interpretation of large magnitude has been described in the work of Proenza (1972) and Proenza et al. (1976), where large scale nappes and allochthonous fragments of metavolcanic belts to 500 km from their source.

Nappes in the Sydney Lake Fault zone are interpreted to be the result of overthrusting of south-southwest blocks by detachment of water moving up the fault zone, but down the thermal gradient produced by upwarped material from the south side of the fault. Overthrusting the coldest rock on the north side of the fault. (Paty and Fyfe, 1972).

Mendelssohn et al. (1975) have noted a symmetrical metamorphic zonation in the Mendelssohn gneiss, the western extension of the English River Subprovince, which from north to south proceeds from chlorite zones to orthopyroxene gneiss to migmatite zones.

Tawney (1975) from work in the Scandinavian Caledonides and metamorphic stratigraphy and in the Canadian Shield, the theoretical work of the English River Subprovince may have developed in a similar manner.

The structure of the Confederation Lake metavolcanic-metasedimentary belt comprises a medial syncline and an eastern north-south striking antiform separated by the Uchi Lake Fault (Fryer, 1976). To the west of the fault, the metavolcanic domain is low amphibolite facies. The eastern half of the fault is a lower grade facies. The fault is a splay of the Sydney Lake Fault System itself, by analogy with the faults and associated fold pattern described by Harris (1970), is thought to be a thrust fault. This fault predates the intrusion of the late gneisses in the region.

Thrust foliations may have occurred in areas where the stratigraphic succession of the metavolcanic-metasedimentary belt does not correspond closely with the variation in metamorphic grade assemblages. Grant et al. (1965) concluded that the assemblages in the English River Subprovince are due to thrusting of sediments into the metavolcanic belt. Available evidence from the margin of the English River Subprovince suggests that the metavolcanic belt is an overthrust southward onto the metavolcanic belt.

The Type Lake-Bee Lake metavolcanic-metasedimentary belt in the area of the Sydney Lake Fault System may be an overturned antiform (Stolbovc, 1964). Skelton (1967) suggested that the Bee Lake succession is monoclinal, representing the south limb of the antiform. The author, however, noted that if it is not part overthrust, as indicated by folding and by a stratigraphic sequence which progresses, from north to south, from the lower greenschist facies and metavolcanic to the upper portion of the belt, the sequence of some localities yield evidence of overthrusting with dips of 24° to 69° to the north, consistent with the Bee Lake belt and may suggest an allochthonous fragment. Relationships in the Rice Lake belt to the west are clearer, the area shown in Figure 4 (section E-C) by Sluggs et al. (1976), the nappes are more clearly defined at the southern edge of the belt, and the thickness of the nappes, in particular, is better understood at the southern edge of the belt. (McCann, 1965).

The Red Lake belt represents the map of a nappes which is folded into the surrounding granitic rocks and basement. The upper limb of the nappes, extending to the south, is preserved along the flank of the Rainfall Lake and Sydney Lake gneiss domes (Fig. 1) and is compensated for by a southward, en-echelon, Stephanian deformation of the Rainfall Lake and Sydney Lake gneiss domes (Fig. 1). The nappes hypothesis provides the best explanation of the structural pattern in this area.

Quinlan et al. (1978) have suggested that the density inversion produced by the syenitic rocks is produced by a density crust (S.C. 2.60) above a sialic crust (S.C. 3.04) (Fig. 6) by a gravitationally driven deflation of the dominantly weighted area into a central syncline with large-scale syncline folds and thrusts parallel to bedding. By use of a model study we suggest that the interface between the metamorphic and the décollement zone is located in the central syncline. The décollement zone, according to Fyfe et al. (1976) gravity-driven deflation would produce a thrust-folded nappes with the overlying volcanic rocks transported northward.

DISCUSSION

Although the metamorphic path indicates for the English River and Uchi Subprovinces, it is only approximate, because of the lack of mineral composition data, it is probably qualitatively reliable and therefore certain relationships can be drawn. The assemblages present in these subprovinces indicate an approximate pressure of between 3 and 4 kbar corresponding to a depth of 10.5 km to 16 km. A geothermal gradient of 30°C/km, therefore, in this area does not appear unreasonable. Richardson (1970) proposed a petrographic model of metamorphic belts in which isotherms in a sedimentary pile are displaced upward under conditions of low pressure metamorphism to form a thermal anticline. This model may be applicable to the Uchi and English River Subprovinces.
Figure 5. Cross-sections of the Red Lake belt and the Sydney Lake and Rainfall Lake gene's zones. The volcanic fragments preserved at the margins of the dome younging outward represent the lower portion of the nappe and the Red Lake belt, the nose of the nappe.

Figure 6. Reconstruction of the English River Suprakamian Subprovince interface before thrusting.
SUMMARY AND CONCLUSIONS

The map of metamorphic zones is dominated by a pattern of low grade synclinorally folded metavolcanic-metasedimentary belts in the Cross Lake subprovince, succeeded to the south by the larger, more complex generally low grade metavolcanic-metasupplementary belts of the Uchi subprovince which range in age from 2960 Ma to 2740 Ma (Nunes and Thurston, 1978). The Uchi subprovince is bordered to the south by the Sydney Lake synclastic zone. A synclastic zone succeeded southward by the metasedimentary and plutonic terrain of the English River subprovince, with both domains containing gneissic grade areas not exceeding 1000 Ma in age (Krog, et al., 1976).

The metamorphic zonation recognizes are as follows: low grade - chlorite-biotite zone; medium grade - staurolite chlorite-biotite zone; low-grade - sillimanite-sericite zone; high-grade - sillimanite-plagioclase zone. Large areas in the area of the Uchi-English River subprovince boundary parallel the Sydney Lake synclastic zone, with an abrupt rise in grade over a distance of 70 km toward the south. In the L.W., St. Joseph region, meta- metamorphic grade rises southward within the English River Subprovince, ascending to an extensive zone of low pressure gneissect facies assemblages which overprint the island arc boundary. The metamorphic zonation is replaced by an isograd of high-grade metamorphic rocks in the eastern Yilgarn Block. The island arc boundary of metamorphic zonation is replaced by an isograd of high-grade metamorphic rocks in the eastern Yilgarn Block, Western Australia. p. 307-313 in the early history of the earth, edited by B.F. Windley, John Wiley and Sons, N.Y.


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SUBAERIAL VOLCANISM IN THE ARCHEAN UCHI-CONFEDERATION VOLCANIC BELT

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(Received July 20, 1979; revision accepted October 30, 1979)

ABSTRACT


The Uchi-Confederation Lakes area, within the Uchi subprovince of the Canadian Shield has three major cycles of mafic to felsic metavolcanic rocks forming a section 8500–11,240 m thick, folded about a central syncline. A rhyolite tuff about 300 m thick is exposed over a strike length of 15 km at the top of the second cycle. The tuff is eutaxitic in texture and consists of relict shards, fiamme and essential pumice and lithic fragments. The unit forms two flow units and one cooling unit approximately 300 m thick, with a lateral extent of 12 km, consisting of a vitriphyric base, a densely welded mid-section about 200 m thick and the upper 40 m which is less densely welded. The fiamme, up to 8 cm long and 5 cm thick, are draped over lithic fragments and wholly replaced by very fine-grained quartz. Snowflake texture is observed in feldspar grains in the relict glassy part of the unit. Pronounced reverse size grading is present with pumiceous and lithic fragments concentrated in the upper part. The upper portion contains breccia-filled fractures indicative of fumarolic activity. The unit is underlain by subaqueous ash flows and overlain bystromatolitic carbonate.

Reconstruction based upon poor stratification, reverse size grading, abundant relatively fine pumiceous clasts and great lateral extent suggest a Plinian eruption and caldera collapse. The unit represents subaerial deposition and welding based on replacement of fiamme by silica, development of snowflake texture, and deformation of fiamme and welding of shards. Submergence and deposition of shallow water sedimentary carbonate followed.

INTRODUCTION

The purpose of this report is to describe an example of Archean subaerial volcanism in the Uchi subprovince of the Canadian Shield in northwestern Ontario. Most Archean volcanism is described as subaqueous and very few data are available about volcanic processes and environments of deposition of volcanic rocks in the Archean, particularly outside the Abitibi Belt. Archean subaerial volcanism has been described in Australia (Hallberg et al., 1976), the Cross Lake subprovince (Ayres, 1977), in the Abitibi belt (Barnett

*Publication approved by the Director, Ontario Geological Survey.
and Hutchinson, 1978), and Slave Province (Lambert, 1978) but none of these occurrences correspond to the large scale cyclical volcanism of the Uchi subprovince.

GEOLOGICAL SETTING

The Uchi-Confederation area (Fig. 1) is a north-trending, dominantly volcanic branch within the east-trending volcanic-granitic Uchi subprovince of the Canadian Shield (Ayres, et al., 1971). Its stratigraphic sequence is subdivided in three mafic to felsic volcanic cycles (Pryslak, 1971), 11,000 m thick indicated by Roman numerals in Fig. 1. The sequence is folded into a north-trending synclinorium. The felsic upper portion of each cycle has been

Fig. 1. Geological map of the Uchi-Confederation metavolcanic-metasedimentary belt (after Thurston and Jackson, 1978). The Woman Lake tuff lies in the upper-felsic portion of Cycle II on the western limb of the synclinorium.
dated radiometrically by the U/Pb method on zircons (Nunes and Thurston, 1980). Cycle I is ± 2959 Ma, Cycle II is ± 2787 Ma, and Cycle III is ± 2738 Ma old. Cycle II, which contains the subaerial metavolcanic rocks described herein, is about 2700 m thick. 1600–4700 m of pillowed and massive mafic flows are at the base followed by 1000 m of intermediate subaqueous ash flows and up to 540 m of felsic tuff, lapilli tuff, lapillistone and tuff breccia.

The felsic metavolcanic rocks to be described here form the uppermost 100–150 m of Cycle II in the west limb of the synclinorium. Here, are informally designated the Woman Lake tuff solely for descriptive purposes with no connotation of formal stratigraphic nomenclature. The Woman Lake tuff occurs on the shores of Woman Lake in Mitchell Township, where it was mapped by Pryslak (1971), and can be followed for about 12 km to the north. The detailed stratigraphy of the Woman Lake tuff is shown in Table I. This report will concentrate upon those parts of the unit which exhibit welding, i.e., units 1 and 2. Each of these units has distinct size ranges (Table II) and texture of pumice, a distinct phenocryst content, and a regular succession of size and density grading within each unit which renders them mappable units.

The two welded units may be divided into sub-units based on textural variations which are typical of a single cooling unit (Ross and Smith, 1961).

**TABLE I**

Detailed stratigraphy of the Woman Lake tuff

<table>
<thead>
<tr>
<th>Top</th>
<th>12 m unwelded felsic airfall tuff, lapilli tuff, minor tuff breccia</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(a) uppermost 1.5–3 m felsic tuff breccia with 20–30% pumice, 10–15% lithic fragments, unbedded in ash matrix.</td>
</tr>
<tr>
<td></td>
<td>(b) lower 9–10.5 m airfall tuff 6–8, 4–60 cm thick normally graded tuffs with 3–5 mm feldspar and quartz grains and lithic clasts (25%) in an ash matrix.</td>
</tr>
<tr>
<td></td>
<td>4.5 m unwelded felsic lapilli tuff (20% pumice avg. 2 cm × 1 cm)</td>
</tr>
<tr>
<td></td>
<td>2 m unwelded felsic lapilli tuff</td>
</tr>
<tr>
<td></td>
<td>(a) uppermost 25–30 cm bedded parallel laminated ash</td>
</tr>
<tr>
<td></td>
<td>(b) 1.8 m felsic lapilli tuff with 20–30% 2 cm × 2 cm pumice fragments.</td>
</tr>
<tr>
<td>100–120 m welded felsic lapilli tuff (unit 2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(a) uppermost 0.2 m parallel bedded felsic tuff</td>
</tr>
<tr>
<td></td>
<td>(b) unwelded felsic lapilli tuff 2 m thick with 20–30% 1 cm × 2 cm pumice</td>
</tr>
<tr>
<td></td>
<td>(c) 47.8 m partly-welded to welded felsic lapilli tuff (a distinctive 1 m thick unit with 10% mafic lapilli occurs toward the top of this section).</td>
</tr>
<tr>
<td>50 m welded felsic lapilli tuff (unit 1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(a) uppermost 3 m—up to 45 cm × 4 cm pumice clasts (50%) in an ash matrix</td>
</tr>
<tr>
<td></td>
<td>(b) remainder of unit — 5 cm × 5 cm pumice clasts in an ash matrix with rare lithic clasts</td>
</tr>
<tr>
<td></td>
<td>(c) a 30 cm thickness about 1 m above the base is locally vitrophyric.</td>
</tr>
<tr>
<td>1 m unwelded felsic crystal lithic airfall tuff</td>
<td>thin—bedded (2–8 cm) normally graded with sparse lapilli</td>
</tr>
</tbody>
</table>

*Bottom*
TABLE II

Proportions of lithic fragments, pumiceous fragments phenoerysts and shards in the Woman Lake tuff

<table>
<thead>
<tr>
<th>Unit 2</th>
<th>Phenoerysts</th>
<th>Lithics</th>
<th>Pumice</th>
<th>Glass</th>
<th>Number of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>upper unwelded</td>
<td>nil</td>
<td>60.0–100.0</td>
<td>80.0</td>
<td>40–0</td>
<td>20.0</td>
</tr>
<tr>
<td>upper partly welded</td>
<td>0.4</td>
<td>0–7.0</td>
<td>03.0</td>
<td>33.0–37.0</td>
<td>36.5</td>
</tr>
<tr>
<td>welded</td>
<td>2.6</td>
<td>7.0–20.0</td>
<td>13.0</td>
<td>30.0–39.0</td>
<td>34.5</td>
</tr>
<tr>
<td>welded</td>
<td>0.5</td>
<td>2.1–6.3</td>
<td>02.5</td>
<td>21.1–29.0</td>
<td>24.4</td>
</tr>
<tr>
<td>lower partly welded</td>
<td>0.8</td>
<td>17.0–45.5</td>
<td>31.6</td>
<td>03.1–15.0</td>
<td>08.5</td>
</tr>
<tr>
<td>lower unwelded</td>
<td>0.9</td>
<td>11.0–27.0</td>
<td>19.1</td>
<td>05.0–23.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Size of lithic and pumiceous fragments (cm)

<table>
<thead>
<tr>
<th>Pumice</th>
<th>largest</th>
<th>smallest</th>
<th>mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>unit 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lower</td>
<td>40x2</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>upper</td>
<td>7x2</td>
<td>0.5</td>
<td>3</td>
</tr>
<tr>
<td>unit 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>upper pumice-rich portion</td>
<td>38x2.5</td>
<td>0.05x1</td>
<td>2x0.2</td>
</tr>
<tr>
<td>remainder of unit</td>
<td>5.3x2.8</td>
<td>2x0.3</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lithic</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>unit 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>upper 100 m</td>
<td>2</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>lower 20–50 m</td>
<td>3x2</td>
<td>0.5</td>
<td>0.8x0.8</td>
</tr>
<tr>
<td>unit 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>upper 40 m</td>
<td>20</td>
<td>0.5</td>
<td>0.8x0.5</td>
</tr>
<tr>
<td>lower 10 m</td>
<td>2</td>
<td>0.2</td>
<td>1</td>
</tr>
</tbody>
</table>
The subunits, shown in Fig. 2, are from base to top: 1) a lower unwelded tuff to lapilli tuff; 2) a lower partly-welded tuff to lapilli tuff; 3) a central welded lapilli-tuff to lapillistone; 4) an upper partly-welded lapilli tuff to tuff; and 5) an upper unwelded lapilli tuff to lapillistone. As these subunits based upon degree of welding are map-pable in the field and texturally distinct, they serve as the basis for the following more detailed description.

The Woman Lake tuff is underlain by massive-bedded to poorly-bedded felsic pyroclastic rocks which consist of 1) massive-bedded lapillistone overlain by finely laminated felsic tuff interpreted by the author as relatively proximal ash-flow deposits by the criteria of Sparks et al., (1973), and 2) fining upward sequences of tuff breccia to finely laminated tuffs. These rocks

---

**Fig. 2.** Detailed geology of the southernmost 2 km of Woman Lake tuff. The unit is subdivided based upon the degree of welding present (after Savory, 1976).
are not welded and are similar to subaqueous ash flow tuffs described in the Ōnikobe caldera by Yamada (1973). The Woman Lake tuff is overlain by 60 m of finely laminated stromatolithic marble, followed by the pillowed subaqueous mafic flows of Cycle III.

**PETROGRAPHY**

*Lower unwelded zone*

The lower unwelded zone is dark grey to black. Fragments vary from angular to subangular, and range from 0.3×2 mm wispy pumiceous1 fragments to lithic fragments up to 2×1 cm (Fig. 5a). The proportion of pumiceous

---

1. Pumiceous fragments identified by the criteria of Fiske (1969).
to lithic fragments ranges from 1:4 to 2:1 averaging 1.3:1 (Fig. 3). Lithic fragments are composed of a fine-grained (0.02–0.06 mm) aggregate of anhedral grains of orthoclase (10%), quartz (40%) and albite plagioclase (50%) with accessory euhedral pyroxene in the center of fragments. Pumiceous fragments consist of fine euhedral potassium feldspar, sericite and minor quartz and muscovite. The pumice forms highly elongated lenticles which are slightly enriched in sericite at the margins. The potash feldspar shows a weak preferred orientation. The fragments appear extensively flattened particularly when compared to angular to subangular lithic fragments containing well-rounded, aligned quartz lenticles which do not appear to have been flattened. The material between clasts is considered to be ash size bubble-wall shards on the basis of relict textures. Individual shards now consist of swirly masses of acicular epidote, quartz, and orthoclase at times reminiscent of fingerprint.

The relict shards are fine grained and show a foliated aspect relative to the coarse, massive anhedral grains present in pumice fragments. The two components are distinguished by the massive relict vesicular texture of the latter vs. the foliated, fine-grained texture of the former. Euhedral orthoclase phono- crystals now replaced by muscovite comprise 0.9% of the unit. Groundmass and veinlets are now crypto-crystalline quartz, orthoclase and sericite.

Lower, partly-welded zone

The lower partly-welded zone has been mapped along strike for about 12 km (see Fig. 2). In outcrop, the zone is marked by the first appearance of cutaxitic texture and an increase in the abundance and size of fiamme (Fig. 5b). The zone is the remainder of the lower welded lapilli tuff (Table I) and the basal part of the upper welded lapilli tuff. In the lower unit, lithic fragments are more abundant than pumiceous fragments (Table II) except for the uppermost 3 m of the unit in which pumiceous fragments comprise up to 50% of the unit, representing reverse size grading of the pumiceous clasts. Pumice fragments are darker grey than the white to pale green groundmass and are lenticular in shape. The pumice fragments are only somewhat flattened (maximum size 3 x 3.8 cm/scale for the coarse top of unit 1) and are bent around lithic and accidental fragments of re-worked tuff (Fig. 5b). Lithic fragments are on average smaller with an average size of 0.8 x 0.3 cm.

In thin section individual flattened areas with varying epidote content are interpreted as devitrified bubble-wall shards. The devitrified glass has a foliated texture imparted by aligned quartz lenticles and epidote grains. Pumice fragments are coarser grained (0.012–0.4 mm) and consist of 0.012–0.04 mm anhedral grains of microcline and quartz with minor sericite. Lithic fragments are the coarsest component of the rock. Anhedral, relatively straight-sided grains of orthoclase, albite and quartz (average size 0.1 mm) form sub-angular fragments ranging from 0.5 mm to 2 mm size. Finer pumice fragments 0.2 x 1 mm consist of very fine-grained quartz as vermiciform bands.
draped over fragments and phenocrysts. The alignment of the wispy pumice fragments and relict shards defines a foliation. Shards are most visible where they drape over fragments. The relict shards are much finer in grain size adjacent to fragments which is suggestive of welding. Broken sericitized orthoclase crystals form a minor portion of the rock.

Central welded zone

Above the lower partly-welded zone is the central welded zone, characterized by abundant fiamme, lithic fragments and a well-developed eutaxitic texture. The zone extends the full 12 km length of the unit. The zone is contained entirely within the upper part of unit 2. North of the area described herein the unit is supplemented by partly-welded lapilli tuff. The unit consists of lapilli tuff to tuff breccia, with pumiceous fragments predominating over lithic fragments. The pumice fragments are fiamme as they are extensively flattened and the terminations are wispy and flame-like (Fig. 5d). The fiamme are deformed adjacent to other fragments (Fig. 6a). Lithic fragments are subangular to rounded and massive in hand specimen.

The groundmass consists of very fine-grained (0.006 mm) elongated irregular grains of potash feldspar and quartz, accessory epidote and sericite with about 25% larger (0.2 mm) scattered anhedral grains of granophyric albite-quartz intergrowths. The fine-grained quartz and orthoclase are considered to be axiolites based on their strong preferred orientation. The albite and quartz intergrowths have abrupt contacts with the surrounding matrix. Scattered through the groundmass are about 5% greenish 0.8 mm to 1 mm euhedral to subhedral grains of sericitized orthoclase (Fig. 6b). In some instances fiamme are deformed around the orthoclase phenocrysts. The preferred orientation of the phenocrysts defines a foliation about 40° to 50° to the eutaxitic texture. Thin quartz veinlets parallel the phenocryst foliation (Fig. 6c).

Fiamme are coarser grained than the matrix and consist predominantly of quartz; however, a few fiamme consist of orthoclase, sericite, albite, quartz, traces of epidote and opaque iron oxides. The margins and central parts of some fiamme are sericitized. Lenticles composed of polycrystalline quartz occur in the matrix parallel to the eutaxitic foliation and are interpreted as collapsed pumice fragments.

The long axes of the axiolites of quartz and orthoclase in the groundmass have a preferred orientation at an angle to the eutaxitic foliation. This preferred orientation of axiolitic quartz and orthoclase is similar to the snowflake texture described by Torske (1976) in the Ordovician rhyolite from Stord (Norway). The axiolite foliation is parallel to the orientation of the orthoclase phenocrysts and to minute quartz veinlets.

The foliation and axiolitic texture is absent in the immediate vicinity of the orthoclase phenocrysts or lithic and pumiceous fragments (Fig. 6b). Around the phenocrysts the groundmass tends to be very fine-grained and...
massive. Secondary calcite and occasional randomly oriented muscovite flakes occur in the groundmass and are interpreted to be relatively late stage.

**Upper partly-welded zone**

The central welded zone, wholly within unit 2, the upper welded lapilli tuff, grades into the upper partly-welded zone by a decrease in the degree of the flattening of pumiceous fragments (Fig. 4). The zone extends from the northern part of Woman Lake (Fig. 2) southward for about 10 km. The upper and lower partly-welded zones are texturally and mineralogically similar, except that the upper zone contains a higher proportion of pumice to lithic fragments than the lower partly-welded unit (Table 1). The pumiceous fragments are deformed, wavy, bent around lithic fragments and consist of sericite, orthoclase, albite and quartz. The groundmass lacks the foliated axiolitic orthoclase and quartz but rectangular phenocrysts of albite bordered by sericitic matrix occur.

![Diagram](image)

*Fig. 4. Flattening ratio of pumiceous clasts in the Woman Lake tuff. Measurements are by the method of Peterson (1961) (after Savory 1976).*

**Upper unwelded zone**

The upper unwelded zone varies from lapilli tuff to lapilli stone and is composed of sub-rounded to rounded pumiceous lapilli varying in size from 5 mm
Fig. 5a. Hand specimen of the lower unwelded tuff with angular to subangular lithic clasts, in a matrix of slightly deformed to undeformed shards (Specimen SS—20b) (Coin, 18 mm diameter).

Fig. 5b. Hand specimen of lower partly-welded subunit with contorted pumiceous clasts deformed around lithic fragments. Pumice fragments are somewhat elongated but with rounded terminations. (Specimen SS—19). (coin, 23 mm diameter)
Fig. 5c. Exposure of central welded zone of the Woman Lake tuff with abundant deformed pumiceous clasts (fiamme) replaced by silica in a glass rich matrix.

Fig. 5d. Hand specimen from central welded zone showing flame-like terminations of fiamme, now replaced with quartz shards and fiamme deformed around lithic fragments and extreme elongation of pumiceous clasts. (Specimen SS-17) (coin, 23 mm diameter)
Fig. 6a. Hand specimen from central welded zone showing elongated pumiceous clasts bent around lithic clasts (Specimen SS-14, 12.1 x 4.5 cm).

Fig. 6b. Photomicrograph of central welded zone with an orthoclase phenocryst in the center and a wispy pumiceous clast to the right. The formerly glassy, shard-rich matrix has undergone vapor phase recrystallization (Crossed nicols Specimen SS-17, field of view in 3.6 x 2.4 mm).
Fig. 6c. Photomicrograph of granophyric albite-quartz intergrowth in a matrix of fine axiolites of quartz and orthoclase showing a high degree of preferred orientation. (Crossed nicols, LA plate, field 0.85 x 0.1 mm. photo by J.J. Macek, Specimen SS-17).

Fig. 6d. Branching fumarolic fractures filled with products of fumarolic alteration, chlorite, quartz, albite and pumiceous fragments in a pumiceous matrix.
to 8 cm. The zone is contained entirely within the upper portion of unit 2. The unit is extensively fractured and most clasts are cracked. Bedding is present but poorly developed as seen in Fig. 6d, an outcrop north of the area. In Fig. 2 an which the upper portion of the subunit is reverse graded—comprised wholly of 2–8 cm rounded pumiceous clasts. Fracturing is particularly well developed in the upper part of subunit where some branching fractures up to 25 cm long and 1–2 cm wide have been observed; they are filled with a chlorite mesostasis containing angular to streamlined mm size fragments similar to composition to the surrounding unit (Fig. 6d). In thin section, pumiceous fragments are composed of polycrystalline quartz and orthoclase aggregates with sericite in the intergranular spaces, replacing orthoclase, and forming fragment rims. Quartz lenticles occur within the fragments, rendering them similar in overall texture to those of the underlying unit. The fine-grained groundmass is composed of quartz, orthoclase and sericite with minor disseminated pyrite. Angular sericitized orthoclase phenocrysts are occasionally present. They are distinguished from the phenocrysts in the central welded zone by their lack of preferred orientation.

Above the upper unwelded zone is a fine- to medium-grained, thinly (1 cm) laminated intermediate tuff found only on the shore of Woman Lake west of north point immediately below the marble. The unit is about 4 m thick and composed of microcline (45–40%), epidote (30%), actinolite (15–20%), and quartz (5%) with accessory magnetite, sphene, and hematite. The textures present consist of ragged lath-like actinolite and euhedral epidote with interstitial irregular masses of sericitized orthoclase. The magnetite is anhedral and has in places been oxidized to hematite. Occasional 0.5–1 cm rounded pumiceous fragments occur throughout the unit.

INTERPRETATION

Sparks et al. (1973) describe ignimbrites, the body of rock resulting from the process of pyroclastic flow, as a relatively homogeneous rock type with zonation as a result of 1) differences in the degree of welding, 2) subdivision into flow units, and 3) layering because of grain size variation. The Woman Lake felsic tuff has many features ascribed to a pyroclastic flow origin; the presence of bubble-wall shard matrix, both pumiceous and lithic fragments, and a lack of well-developed bedding (Sparks et al., 1973; Duffield et al., 1979).

Sparks et al. (1973) have subdivided single ignimbrite flow units into several “layers” with layer 1, commonly a cross-bedded, well-stratified unit caused by base-surge activity preceding the Plinian activity that gives rise to ignimbrites. Layer 2, the main body of the ignimbrite, is subdivided into a lower part, subunit 2a which is the more poorly sorted, and finer-grained part of the unit; subunit 2b comprising, according to Sparks et al. (1973), greater than 90% of the thickness of the unit, is homogeneous, poorly sorted and comprised of fragments ranging from shards to blocks. Layer 3, a
finely stratified ash deposit of shards is poor in crystals and lithic fragments and overlies layer 2. Layer 2a, not seen at Woman Lake, is often not present according to Sparks et al. (1973). Layer 2b comprises most of the Woman Lake tuff; layer 3 is present sporadically.

Differences in the degree of welding has been the basis for description of the Woman Lake felsic tuff. The Woman Lake felsic tuff is believed to comprise two flow units as described in Table I. The similarity of the lithic and pumiceous clasts and matrix in both units strongly suggests both units were derived from the same vent with a minimal time difference.

Orthoclase phenocrysts are concentrated in the lower part of the upper-welded lapilli tuff, as they behave similarly to lithic fragments concentrating at the base of ash flows (Walker, 1973). Lithic clasts are more abundant throughout unit 1 and in the base of unit 2, demonstrating normal density grading (Table II). Conversely, pumiceous fragments are more abundant in the upper part of each ash flow showing normal density grading. A normal size grading of lithic fragments and reverse grading of pumiceous fragments suggests a pyroclastic flow origin for the unit. The repeated normal density grading and reverse size grading demonstrates the presence of two separate flow units (Sparks, 1973). Broken sericitized orthoclase phenocryst fragments at the base of unit 2 in the lower partly-welded zone and the central welded zone are further evidence of an ash-flow origin, as Rast (1962) observed broken phenocrystals to be common in ignimbrites.

Welding and recrystallization

Variations in the degree of welding have formed the main basis for subdivision of the Woman Lake tuff which is a single cooling unit according to the criteria of Smith (1960). Zonation in ash flows has been documented on the basis of four types of recrystallization: 1) devitrification, 2) vapor phase crystallization, 3) granophyric crystallization, and 4) fumarolic alteration (Smith, 1960).

Devitrification textures and recrystallization is extensive throughout the unit, as is true of most Archean rocks, but certain devitrification textures are considered to be of a pre-metamorphic origin, particularly the development of axiolites of quartz and feldspar in the partly-welded and welded units. This is based on the similarity of this texture in the Woman Lake tuff to similar features in younger, unmetamorphosed examples (Geijer, 1913; Ross and Smith, 1961; Snyder, 1962; Anderson, 1969). The axiolites are best developed in the welded zone, but are present in both the lower and upper partly-welded zone, replacing shards. Devitrification textures in lithic fragments consist of occasional development of spherulitic feldspar.

Vapor phase crystallization consists of silicification of pumice in the welded unit, and development of quartz-filled hairline fractures parallel to the inferred vapor transport direction upward through the unit. Pumice in the partly-welded zones is not as extensively replaced by silica as in the
welded zone; if the observed silicification of pumice were a metamorphic phenomenon one would expect uniform silicification of pumice. The phenomenon is reported in younger rocks where vapor phase crystallization of cristobalite and tridymite is found replacing pumice (Ross and Smith, 1961). In the Woman Lake tuff metamorphism has inverted these phases to quartz.

Orthoclas phenocrysts found in the lower part of unit 2 are probably primary in origin. Zones of K depletion marked by the lack of sericite in the matrix surrounding the phenocrysts are probably a vapor phase alteration phenomenon in which there has been local small scale addition to the orthoclase phenocrysts during devitrification. This interpretation is strengthened by the observed absence of relict shard textures in a zone 1–2 mm wide, adjacent to the phenocrysts.

Granophytic recrystallization, also restricted to the welded zone, consists of the granophytic intergrowth of quartz and albite in plate-like masses surrounded by oriented quartz and feldspar axiolites.

Recrystallization in the fumarole regime consists of masses of devitrified glass and pumice fragments now consisting of dark brown chlorite with minor albite feldspar and quartz filling fractures and in part obscuring adjacent pumiceous lapilli. Streamlining of fragments is caused by the gas-dominated nature of the fumarolic activity.

**Welding**

Post-depositional textural changes due to welding such as deformation of pumice and shards have been described above. Flattening of pumiceous lapilli, (measured after the technique of Peterson (1961) for an index of the degree of welding, indicates that the central welded unit contains the most intensely deformed pumice (Fig. 4). The measurements of pumice deformation ignore tectonic strain, but analysis of paleostrain of variolites in the overlying basalts of Cycle III suggests that tectonic strain may be ignored (Leonard, 1979). The deformation of relict shards also indicates the degree of welding to be greatest in the central welded zone. Development of axiolites in the usual (Ross and Smith, 1961), sense of the term along shard boundaries is obscured by metamorphic recrystallization. The welding in the Woman Lake tuff is not the diagenetic process of shard recrystallization and loss of shard morphology seen in some deep sea cores (H. Schminke, personal communication, 1979) in that concomitant deformation of lensoid pumiceous clasts is also observed; this leads to the conclusion that the observed deformation of shards is indeed a welding phenomenon.

**Discussion and Conclusions**

The Woman Lake felsic tuff is an ignimbrite based upon the reverse size grading of pumiceous clasts, normal density grading of clasts, general lack of bedding in the unit, presence of Sparks et al's (1973) units 1, 2b and 3 of a
typical ignimbrite. The Woman Lake felsic tuff comprises two flow units based upon an abrupt change in the size of pumiceous clasts, phenocryst mineralogy, and abundance of pumice at the top of unit 1, the lower ash flow. The Woman Lake tuff is a single zoned cooling-unit (Smith, 1960; Ross and Smith, 1961) based upon the zonation of flattened and attenuated pumice and deformed glass shards. Post-depositional recrystallization, comprising de-vitrification, vapor phase crystallization, granophyric crystallization and fumarolic crystallization or alteration in the upper welded subunit, also suggest welding of an ash flow unit as a single cooling unit.

Ash flows are reported mainly from the subaerial environment (Smith, 1960; Ross and Smith, 1961; Roobol and Smith, 1976), but submarine ash flow deposits are known in the Onikobe caldera (Yamada, 1973) and elsewhere (R.V. Fisher, pers. comm., 1979). The sedimentary structural sequences present in the subaerial ash flows as described by Yamada (1973) and Fisher (1977) are not present in the Woman Lake tuff. These include development of convolute bedding in the upper fine-grained portion of ash flows and the presence of fine sandy interbeds in the coarser units. Welding of ash flow deposits has been taken to be a valid indicator of subaerial deposition (Ross and Smith, 1961); however, Frances and Howells (1973) have suggested that welding can occur in a submarine environment in tuffs of Ordovician age in Wales. The welding described by Frances and Howells consists mainly of compaction of shards and pumice with little vapor phase recrystallization. The intensity of the vapor phase recrystallization in the Woman Lake tuff, particularly the extensive replacement of fiamme by quartz, suggests that the Woman Lake tuff was deposited subaerially. The overlying stromatolitic carbonate was deposited in shallow water, as stromatolites are restricted to the photic zone, (Playford and Cockbain, 1976) therefore I suggest that during Cycle II volcanism the Uch-Chifedehation volcanic pile reached the point where small areas were above water. Later, rapid subsidence, without major erosion of the rubbly top of the Woman Lake tuff, was followed by deposition of shallow water sediments.

The lateral extent of the Woman Lake tuff and correlative submarine units with a minimum volume of 63 km$^3$ of material was erupted at the close of Cycle II volcanism (no allowance is made for compaction or strain). Using the criteria of Walker (1973) which are based upon the lateral extent of the deposit, and the degree of fragmentation of the distal portion of the eruptive product, the Woman Lake tuff is the product of a Plinian eruption.

Ignimbrites have been shown by Sparks and Wilson (1976) to be due to the gravitational collapse of Plinian eruption columns. A chemically zoned magma chamber with a frothy, gas-rich top promotes development of a Plinian eruption column; later decreasing gas content causes column collapse. Sparks and Wilson suggest that non-welded ignimbrites succeeded upwards by welded units, as occurs in the Woman Lake tuff, is caused by higher emplacement temperatures for the upper units brought about by the smaller proportion of air added to the eruptive column once collapse of the column occurs.
Significance of subaerial volcanism

Subaerial volcanism has been infrequently described in volcanic piles of Archean age. Examples include the Marda complex, a late, stratigraphically high, andesite to rhyolitic complex in West Australia (Hallberg et al., 1976), the Back River area (Lambert, 1978), in the relatively small scale cyclical volcanism of the Setting Net belt of NW Ontario (Ayres, 1977), and in the area of the Agnico Eagle deposit of the Abitibi Belt (Barnett and Hutchinson, 1978). Subaerial volcanism is rarely described in large volcanic belts outside the Abitibi area. Abundant pillowed mafic flows and associated hyaloclastic rocks suggest that the lower part of most Archean volcanic piles is submarine, and while the criteria of Jones (1969) have led some (Wilson et al., 1974; De Rosen-Spence, 1975) to suggest that some Archean mafic volcanic sequences are of shallow water origin; pyroclastic rocks are more sensitive indicators of depositional environment. L.D. Ayres (pers. comm., 1975) has suggested, based upon McBirney's (1963) minimum depth for pyroclastic activity and the probable slope of shield volcanics or strato volcanoes in the Archean piles, that subaerial volcanism must be more common in the Archean than has been reported heretofore. This communication serves to document another example.

Evidence for magma mixing as the petrogenetic mechanism consists of the presence of mafic lapilli at the top of unit 2 suggesting that Sparks and Sigurdsson's (1977) mechanism of magma mixing as a trigger for pyroclastic activity may have been active. Chemical evidence described by Thurston (1980) suggests magma mixing also.

The presence of demonstrably subaerial volcanism at the culmination of Cycle II suggests that the volcanic pile probably grew in height until subaerial. The subaerial sequence is well preserved in large part because of the intensity of welding, rather than having been eroded away. Subsidence, perhaps along faults, followed permitting deposition of the subaqueous metavolcanic rocks of Cycle III, suggesting that widespread vertical movements may be important in determining the products of Archean volcanism.

ACKNOWLEDGEMENTS

The author commenced work in the Uchi-Confederation belt in 1973 for the Ontario Division of Mines (now Ontario Geological Survey) building upon the firm foundation of previous work by A.P. Pryslak who informed the author of the unusual textures in the Woman Lake tuff. Preliminary work on the Woman Lake tuff was conducted by S.E. Savory (1976). Further work on the cyclical volcanism of the Uchi-Confederation volcanics (Thurston, 1980) of which this forms a part has been conducted at the University of Western Ontario with an Ontario Ministry of Natural Resources bursary for which the author is grateful. Drafting was done by D. Bain and T. Setterfield. Typing of the various drafts was done by M. Janson, A. Havard and A. Branicky.
The author has benefited from discussions of the problems of Archean volcanism with A.P. Pryslak and R.W. Hodder. The author has also benefited from reviews of the manuscript by R.W. Hodder and V.G. Milne. Two photomicrographs were taken by J.J. Maciek of the Manitoba Mines Br. for which the author is grateful.

REFERENCES


PLATE 1 CAPTIONS

Photo 1
Hand specimen of the lower unwelded tuff with angular to subangular lithic clasts, in a matrix of slightly deformed to undeformed shards (Specimen SS-20h). Diameter of coin 18 mm.

Photo 2
Photomicrograph of the lower unwelded subunit. Shards and lenticular pumice fragments are bent around a lithic fragment. Crossed nicols 25x.

Photo 3
Hand specimen of lower partly welded subunit with contorted pumiceous clasts deformed around lithic fragments. Pumice fragments are somewhat elongated but with rounded terminations. (Specimen SS-19). Diameter of coin 23 mm.

Photo 4
Hand specimen of lower partly welded subunit with grey lenticular shards devoid of pumice fragments and subangular lithic clasts. Specimen is 0.5 cm wide.

Photo 5
Photomicrograph of lower partly welded unit. Barely recognizable shards are deformed around a lithic fragment. Pumice wings are also deformed around clasts (Crossed nicols 25x Specimen SS-19).

Photo 6
Exposure of central welded zone of the Woman Lake tuff with abundant deformed pumiceous clasts (fiamme) replaced by silica in a glass rich matrix.

Photo 7
Hand specimen from central welded zone showing flame-like terminations of fiamme, now replaced with quartz shards and fiamme deformed around lithic fragments and extreme elongation of pumiceous clasts. (Specimen SS-17). Coin 23 mm diameter.
Photo 8

Photomicrograph of central welded zone with an orthoclase phenocryst in the center and a wispy pumiceous clast to the right. The formerly glassy, shard-rich matrix has undergone vapor-phase recrystallization (Crossed nicols 25x, Specimen SS-17).

Photo 9

Photomicrograph of central welded zone matrix with granophyric albite-quartz intergrowths surrounded by axiolites small of quartz and orthoclase. (Crossed nicols 25x, field 0.35 x 0.45 mm, Specimen SS-17).

Photo 10

Photomicrograph of granophytic albite - quartz intergrowth in a matrix of fine adiolites of quartz and orthoclase showing high degree of preferred orientation (Crossed nicols, 1 plate, field 0.85 x 0.7 mm, Specimen SS-17).

Photo 11

Photomicrograph of a sericitized orthoclase phenocryst from the central welded unit. Note the zone surrounding the phenocryst which is depleted in sericite.

Photo 12

Hand specimen of the upper partly welded unit showing blocky fractured pumice fragments, undeformed, with interclast-space filled with dark quartz.

Photo 13

Photomicrograph of the upper partly welded zone showing slightly attenuated pumice fragments and recrystallized matrix now composed of anhedral orthoclase, quartz, and sericite. (15 120x crossed nicols, Specimen SS-13).

Photo 14

Upper unwelded zone. Elongated unwelded pumice fragments, rimmed by chloritic material, with no matrix present in the pumiceous top of the unit.
CONSTRAINTS UPON MODELS OF GREENSTONE BELT
EVOLUTION BY GRAVITY MODELLING IN THE
BIRCH-UCHI GREENSTONE BELT

by

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Publication approved by the Director, Ontario Geological Survey.
Submitted to: Precambrian Res.
ABSTRACT

Eight two-dimensional gravity models, incorporating most of the major hypotheses proposed for the development of pre cambrian greenstone belts are computed. Maximum use is made of geological and geophysical constraints, in an attempt to explain the disparity between the 11,000 m measured stratigraphic thickness and the maximum 5,000 m interpreted vertical extent of a portion of the Birch-Uchi metavolcanic-metasedimentary belt.

The two-dimensional modelling concentrates on an east trending profile across a dominantly volcanic portion of the belt comprising three superposed basalt to rhyolite cycles. It is supplemented by a computed second vertical derivative map of the gravity field.

Metamorphic and geophysical considerations show simple, isoclinal, parallel folding of the mapped stratigraphic thickness to be unacceptable. Proposed mechanisms which could explain the shallow interpreted vertical extent are a density gradient, a granite root, more complex folding of the belt and restriction of the metavolcanic basin. Taken individually, however, none of these mechanisms are fully adequate.

The model which best fits the gravity and geological data suggests that the shallow vertical extent is the result of both magmatic stoping by a subjacent granitic magma chamber during the caldera stage of cycle 3 volcanism and partial melting of the basaltic rocks during earlier cycles of volcanism.
INTRODUCTION

In recent years the Ontario Geological Survey has embarked on a detailed gravity surveying program over selected Archean metavolcanic-metasedimentary belts in Ontario. As a result of a continuing series of detailed geological mapping projects by the Survey, the regional geological framework of many of these belts is now available. One such belt, the topic of study, is the Birch-Uchi greenstone belt situated within the Uchi Subprovince of the Superior Province of the Precambrian Shield of northwestern Ontario (Figure 1). Detailed geological mapping in this belt has been in progress for the last ten years (Goodwin, 1967; Pryslak, 1971, 1971a; Thurston, 1978; Thurston and Jackson, 1978). A detailed gravity survey over this belt was carried out in the summer of 1975 (Barlow et al., 1976; Gupta & Wedge, 1980).

Most geological studies list the typical vertical extent of Archean greenstone belts in the 10 to 15 km range, based on measured stratigraphic thickness (Thurston, 1978; Pryslak, 1971; Viljoen and Viljoen, 1970) and several gravity studies have also suggested similar vertical extent. For example, 

*Vertical extent is herein defined as the maximum extent in the vertical dimension of the supracrustal rocks. Approximately synonymous terms in the literature have included "depth", "depth of infolding" or "depth extent".*
Archipald et al. (1976), on the basis of regional gravity and deep seismic work, suggest maximum allowable vertical extent of about 14 km for the greenstone belts of the Eastern Goldfields Province, Western Australia. Wilson (1971) states that in the Kenora Block of Ontario the interpretation of gravity anomalies caused by individual greenstone belts indicates that their depths range from 6 to 12 km. The large depth has been re-emphasized again in a later publication by Wilson et al. (1974) where depths in excess of 12 km for the greenstone belts of the Kenora area in Ontario are postulated.

Based on an irregular gravity profile, Grant et al. (1965) calculated a 7.6 km depth to basement for the Red Lake greenstone belt in Ontario, just west of the study area.

More recently, however, several gravity studies have suggested that greenstone belts have, in reality, a much shallower vertical extent of only 5 km or so, making the correlation between geological mapping and gravity interpreted depths problematic. For example, Darracott (1974) has shown that the Seronera greenstone belt in northern Tanzania has a "maximum depth" of only 5.8 km. Darracott (1975) suggests an average "depth extent" of 3 to 4 km for the Barberton greenstone belt of South Africa, with a maximum possible depth-extent of 6 km. For the same belt, Burley et al. (1970) report a "maximum depth" of 3.2 km whilst the measured stratigraphic thickness of Viljoen and Viljoen (1970) is over 15 km.
In the Superior Province of the Canadian Precambrian Shield, a shallow depth extent ranging from 3 to 5 km for the greenstone belts of the Timmins-Senneterre mining areas of Ontario and Quebec has been estimated from the gravity data by Gibb et al (1969). Brisbin (1971) reports a depth to base of 5.5 km for the Wallace Lake greenstone belt of Manitoba. From a detailed gravity study of the Sturgeon Lake greenstone belt in Ontario, Dusanowskyj (1976) reports a maximum calculated depth of 5 km whereas the measured stratigraphic thickness is more than 10 km. Gupta and Ward (1980) have recently interpreted more than 20 detailed gravity profiles across the Birch-Duch and the Red Lake greenstone belts of Ontario. None of their two-dimensional models require the belts to be more than 5 to 6 km deep as compared to the measured stratigraphic thicknesses ranging between 10 to 12 km (Thurston, 1978; Fryslak, 1971; Goodwin, 1967; J. Pirié, personal communication, 1979). The discrepancy between the gravity-calculated vertical extent and the stratigraphically measured thicknesses led Gorman et al (1978) to suggest that "areas where thrust faulting occurred in greenstone belts may be located by the discrepancy between the measured thicknesses of the belt and its gravitational response".

The discrepancy between stratigraphic thickness and vertical extent poses an interesting problem to geologists
and geophysicists. We attempt to explain this by examining several models of greenstone belt development, constraining these with gravity data. The purpose of investigating the gravity models of various hypotheses of greenstone belt evolution is:

i) to eliminate those hypotheses which do not fit with the gravity data and,

ii) to provide geological constraints for a theoretical modelling procedure and hence inter-relate both the gravity data and the geology in the Birch-Uchi belt.
GENERAL GEOLOGY

Thurston et al (1975) have recently summarized the geology of the Birch-Uchi belt which consists of three mafic to felsic volcanic cycles emplaced over a 220 m.y. time span. The felsic top of cycle 1 has been dated by U/Pb on zircons as 2959 m.y. and the felsic top of cycle 3 as 2738 m.y. (Nunes and Thurston, 1979). Thurston and Breaks (1978) have suggested a gravitationally driven deformation scheme for this area based upon the model of Gorman et (1978). Dense dominantly basaltic volcanic rocks (mean density = 2.94 g/cm³, Gupta and Wadge 1980) erupted onto a tonalitic basement (mean density 2.69 g/cm³, Gupta and Wadge, 1980) producing a gravitationally unstable situation. As the dense volcanics of the volcanic belt, driven by gravity, subside into a central syncline, marginal thrusting occurs. As well, a deep, dominantly basaltic keel to the belt is produced coincident with the synclinal areas.
GRAVITY SURVEY

Collection of Gravity Data

Gravity data in the Birch-Uchi belt were collected during the summer of 1975 by the Ontario Geological Survey (Barlow et al., 1976). The average gravity station density in metavolcanic-metasedimentary areas was approximately one station per 2.5 km². This was considered sufficient to allow a detailed interpretation of the major geological features of the belt. The gravity measurements, at over 2500 stations, were reduced using the data reduction system of the Gravity and Geodynamics Division, Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa. Individual Bouguer values are considered accurate to ± 0.5 mgal.

Processing of Gravity Data

The randomly spaced data were digitized on a grid with spacing of 1.6 km using a general purpose contouring program which generates the grid by constructing a smooth surface passing through every data point. The resultant Bouguer map contoured at 2 mgal intervals is shown in Figure 2.

A second vertical derivative map of the Bouguer gravity was also computed on a 1.6 km by 1.6 km grid, using an optimum second derivative filter designed from Wiener filter theory (Clarke 1969). The purpose of compiling the second vertical derivative is to emphasize local anomalies...
arising from shallow geological sources and isolate them from the regional background.

Density Sampling

In order to assist the gravity interpretation, fresh rock samples were collected at or near gravity station sites during the course of the survey. Densities were determined in the field using an Ohaus triple beam balance. The mean densities used to model the various lithologic units are listed in Table 1. The intermediate and felsic metavolcanic units were combined into a single unit with a mean density of 2.73 g/cm$^3$ for use in the gravity modelling. Also, a single weighted density for all metavolcanics was computed, for use in certain models, based on the proportions of mafic intermediate and felsic volcanics estimated by Thurston (1978) and Goodwin (1972, 1977) in the Uchi Subprovince. Using their proposed ratios and adopting densities from Table 1, the calculated weighted mean density is 2.87 g/cm$^3$.

General Correlation of Maps with Geology

On the Bouguer gravity map (Figure 2) the Birch-Uchi greenstone-belt is characterized by distinct gravity highs caused by the supracrustal rocks which are surrounded by gravity lows caused by oval-shaped granitoid plutons and batholiths. The margins of these gravity highs display steep gravity gradients that coincide remarkably well with the "greenstone-granite" boundaries. Throughout its entire
length (30 km) and width (between 6 and 33 km) the various arms of the Birch-Uchi belt are recognizable on the basis of positive Bouguer anomalies which follow them.

Many localized shallow geological features which are barely visible on the Bouguer gravity map are intensified on the second vertical derivative map (Figure 4). Strong positive and negative second derivative anomalies correspond remarkably well with the surface exposures of the mafic and felsic metavolcanic units, respectively. In certain regions, the zero trace of the second derivative near the greenstone-granite contact marks their boundary. It is interesting to note that in the central portion of the Birch-Uchi belt, the narrow, linear belts of positive second derivative anomalies show excellent correlation with the mapped mafic members of three volcanic cycles (Figure 4). A linear, 48 km long, zone of negative second derivative anomalies follows the felsic metavolcanics of the third cycle which are concentrated along the synclinal axis about which the metavolcanics are folded. The second derivative of the gravity field thus clearly supports the existence of three groups of rocks in the Birch-Uchi belt which have been termed cycles based upon chemistry and distribution in time (Thurston et al. 1978).
MODEL PROFILE

A profile Z2 (for location see Figure 2) was selected for this study for several reasons:

a) The geology along the profile has been mapped in detail by Thurston (1978); Pryor (1971a); and Goodwin (1967). The volcanic assemblage outcrops in a "textbook" pattern depicting typical Archean cyclical volcanism. It consists of 2200 m of basaltic flows, overlain by 1500 m of intermediate and minor felsic pyroclastic rocks of cycle I. These rocks are succeeded without apparent unconformity by 2300 m of basaltic and andesitic flows, 300 m of intermediate subaqueous pyroclastic rocks and, 150 m of subaerial rhyolitic ash flows (Thurston, 1979). Overlying this sequence is 60 m of stromatolitic marble, 1500 m of basaltic flows, 2000 m of intermediate and minor felsic pyroclastic rocks and, 400 m of felsic pyroclastic rocks.

b) The profile intersects most of the mapped geological contacts and the gravity contours at nearly 90°.
c) The gravity station spacing along the profile averages one station per 1.6 km, which is about the thickness of the intermediate and felsic portions of each cycle.

d) A good correlation exists between the Bouguer gravity and the surface geology.

**Regional - Residual Separation**

The Bouguer gravity map, the corresponding geology and the location of the gravity profile ZZ' are shown in Figure 2. In order to simplify the modelling procedure, the mean background density of the surrounding granitic rocks was taken to be 2.64 g/cm$^3$. The effect of this assumption upon the modelling of the vertical extent of the metavolcanic rocks is minimal, in the order of a few tenths of a km. The advantage of choosing 2.64 g/cm$^3$ is that this allows the background to be anchored at the minima of the Bouguer anomaly, so that the residual anomaly would be totally positive, and could be attributed wholly to the density contrast between the granitic and metavolcanic rocks.

This juxtaposition of granite *sensu stricto* with supracrustal rocks is in agreement with general models of greenstone belt structure and evolution proposed by Windley (1973) and Baragar and McGlynn (1976). Any use of other granitic compositions such as trondhjemite (average density 2.69 g/cm$^3$) would only complicate selection of a proper level of background gravity.
This background density (2.64 g/cm$^3$) was used for all the models studied except the granite root model (Model 7) in which the background density is 2.69 g/cm$^3$ (See Figure 3).
MODELS OF THE GREENSTONE BELT

The gravity models were computed using a two-dimensional line integral program (Nagy, 1964) which computes the gravitational effects of two-dimensional masses of arbitrary cross-section. The shapes of the geological bodies were approximated by n-sided polygons. For some models, the differences between the residual and calculated anomalies were minimized by adjusting the models and recalculating the anomalies until a good fit was achieved. The geologic cross-section along profile 22' has been drawn from Thurston and Jackson (1978) and was used as a constraint in developing the gravity models.

The gravity models presented fall into three classes. Models (1 and 2) based on the simple, parallel folding of the measured stratigraphic thicknesses that result in a vertical extent of 9 km. The models of the second group (Models 3 and 4) extrapolate the greenstones, using their mapped surface dips and stratigraphic thicknesses, to 9 km vertical extent by incorporating two differing compensating mechanisms: a density gradient in Model 3 and a granitic root in Model 4. The third and final group of Models (5 to 8) restricts the vertical extent of the greenstones to 5 km by introducing various structural and tectonic possibilities.
GROUP 1

Model 1. Parallel Fold Model - Vertical Dips at Surface

This is a highly simplified model (Figure 5) which takes the vertical dips at surface, contacts and stratigraphic thicknesses as mapped on the east limb of the synclinorium and symmetrically extrapolates these to the west limb by the process of parallel folding (Ramsey, 1967, p.365), along a synclinal axis which is located near kilometre 42 of the profile.

Based on the stratigraphic thickness of the Birch-Uchp belt (not corrected for tectonic strain) the cross-section of this model yields a vertical extent of 9 km. The steeply dipping, folded sequences are approximated in this model by alternating rings of mafic and intermediate to felsic metavolcanics of mean density 2.93 g/cm$^3$ and 2.73 g/cm$^3$, respectively. The estimate of the standard deviation between the calculated and the residual anomaly is 11.6 mgal and the coefficient of correlation 0.826.

Model 2 (Parallel Fold Model - Mapped Dips)

The second model (Figure 6) is derived similarly to model 1 by parallel folding of the metavolcanics. However, this model uses the stratigraphic thicknesses, surface contacts and dips actually mapped on each limb (Pryslak, 1971a; Thurston and Jackson 1978). The modelling of this configuration yields a total vertical extent of 9 km folded
along a central synclinorlal axis located on the surface
near kilometre 42 of the profile.

GROUP II

Model 3 (Density Gradient Model)

Models 1 and 2 clearly demonstrate that, without some
moderating mechanism, the vertical extent of the meta-
volcanics cannot nearly be that suggested by the surface
dimensions. Model 3 (Figure 7) adopts the lithological
structure of Model 2 but, in addition, allows the density
contrast between the metavolcanics and the granitic rocks to
decrease gradually with depth (Dusanowsky and West, 1976)
due to either anatexis of the supracrustal rocks or stoping
of supracrustal blocks into magma chambers of batholithic
dimensions. Model 3 shows that in order to maintain a
vertical extent of 9 km, the equivalent of a uniform gradient
of approximately -0.03 g/cm$^3$/km in the density contrast is
required to bring the calculated and the residual anomaly into
approximate agreement.

Model 4 (Granite Root Model)

An alternate mechanism for bringing the computed gravity
anomaly over the metavolcanic belt (vertical extent 9 km) into
agreement with the observed gravity is presented in Model 4
(Figure 8). This model stems from the greystone - granite
basement relationships commonly suggested for Archean
greystone belts as postulated by Baragar and McGlynn (1976)
and Young (1978). These authors propose that as a result of
the intrusion of granitic diapirs and batholiths from below,
the greenstone, in most situations, does not directly
overlie basement rock. Therefore, the simple two-density
model may not be adequate.

In this model (Figure 8), the basement is assumed to be
a tonalite - trondhjemite - granodiorite (mean density
2.69 g/cm³, Gupta and Wadge, 1980). Both the greenstone
(mean density 2.87 g/cm³) and lighter, intrusive granitic
rocks (mean density 2.64 g/cm³) are now anomalous with
respect to the density of the basement. Figure 8 shows the
residual gravity profile ZZ' drawn from a graphically
separated residual Bouguer anomaly map of Gupta and Wadge
(1980) in which a background density of 2.69 g/cm³ was used
for regional - residual separation (also see Figure 3).

By placing lighter granitic rock below the metavolcanics,
their gravitational effects partially counteract each other.
By adjusting the dimensions of the granitic "root", it
becomes possible in the gravity model to significantly increase
the vertical extent of the greenstone belt. In the case under
study, with a 17 km granitic root, a 9 km deep metavolcanic
pile, with steep dips, was successfully modelled (Figure 8).

GROUP III

Model 5 (Uniform Density Model)

If the compensating mechanisms proposed in models 3
and 4 are discarded the only alternative, to bring the
observed and computed gravity anomalies into close agreement is to reduce the actual vertical extent of the belt. Model 5 (Figure 9) provides an initial estimate of the vertical extent to be considered. A uniform density of 2.87 g/cm³ was assigned for the entire greenstone belt on the basis of the mapped mafic-intermediate - felsic metavolcanic proportions in the Birch-Uchi belt (Thurston, 1978; Goodwin 1972, 1977).

This averaging of densities also tends to eliminate uncertainties about the detailed configuration of folding. The calculated vertical extent of the belt in this model is only 5 km.

Model 6 (Basin Model)

Model 6 (Figure 10) disregards the synclinal structure interpreted from the geological mapping of the belt and adopts a very simplistic structure. It assumes that the mapped intermediate to felsic metavolcanic units of each cycle on either side of the belt are not connected by synclinal folding. Each unit is assumed to lie along the trace of a synclinal axis, resulting in a series of tight isolinal folds, or in local basins across the entire belt. The resultant model (Figure 10) shows that the intermediate to felsic units have about 1 km depth-extent. A homoclinal sequence consisting dominantly of basalts with minor felsic centers of limited vertical extent would differ little from this situation in terms of the gravity model.
Model 7 (Re-Folded Model)

In Model 7 (Figure 11) the synclinal nature of the belt is restored and the three mafic to felsic cycles are shown connected at depth. The steep dips mapped at the surface, however, are assumed to be due to high-frequency, tight, isoclinal folding. This mechanism allows the "enveloping surfaces" (Figure 11) of the mafic and felsic members of the cycle volcanism to have significantly shallower dips, while the units themselves possess steep dips as mapped on the surface.

The computed depth of the greenstone belt in this model (Figure 11) is about 4 km.

Model 8 ("Rootless" Greenstone Model)

In this model (Figure 12) the surface dips, locations of the lithologic units and synclinal structure are all preserved. The steep dips mapped at the surface, however, are assumed to represent the actual units "standing on end". The vertical extent of the greenstone sequence is modelled on the supposition that:

1) the roots of the greenstone belt have been removed by fragmentation and foundering during plutonism into a deeper region of the crust where they were subject to anatexis (Anhaeusser, 1975).
2) Large scale thrusting has either exaggerated the measured stratigraphic thickness or produced a series of thin stacked thrust sheets (Gorman et al. 1978; Thurston and Brekke 1978); see also the tear away model of Dušanowskyj and West (1976).

The rootless model (Figure 12) would give rise to the profile shown in Figure 12. The estimate of the standard deviation between the calculated and the residual anomaly is 1.5 mgal and the coefficient of correlation 0.99.
DISCUSSION AND CONCLUSIONS

Simplé, parallel folding of the mapped stratigraphic thicknesses, as portrayed in model 1 (parallel fold model - vertical dips, Figure 5) and model 2 (parallel fold model - mapped dips, Figure 6) produces large discrepancies between the observed and computed residual anomalies. For models 1 and 2, the large standard errors of 11.6 and 18.9 mgal respectively suggest that the greenstone belt does not nearly have the vertical extent suggested by its measured stratigraphic thicknesses and interpreted synclinal structure.

Model 3 (density gradient model, Figure 7) shows a much improved fit between the observed and computed gravity data. As the mechanism responsible for the decrease in density contrast with depth, stoping seems more likely than anatexis because:

a) The density of supracrustal lithologies rises with depth as they are converted to amphibolite or granulite facies assemblages. This requires the lithologies to be part of relatively dry systems not subject to extensive anatexis under amphibolite facies conditions. Assemblages in supracrustal lithologies in high-grade areas of the Shield such as the Kapuskasing Structural Zone (Thurston et al, 1977) support this view.

b) Alternatively an anatexis model involving partial melting of supracrustal lithologies is possible. If this is an
open system. removal of granitic melt increases the density of the supracrustal lithologies as

In model 4 (granite root model, Figure 8), a vertical extent of 17 km was assigned to the "granitic root" underlying the metavolcanics. Similar depths for batholiths have been interpreted elsewhere from gravity data. For example, the Robinson Lake batholith in the Sturgeon Lake greenstone belt area is about 18 km deep (Dusanovsky, 1976); the Aulneau pluton near Lake of the Woods area extends to a depth of 16 km (Wilson et al., 1974). Model 4, is particularly attractive in the Birch-Uchi belt where it has been noticed (profile 22' shows evidence of this) that the gravity lows caused by the intrusive granitic rocks adjacent to the greenstone belts, attain their minima near metavolcanic-granitic contacts rather than away from them. Since the extent of the granitic root is almost completely arbitrary, a reliable determination of metavolcanic depth extent is not possible. Still, the model suggests that the belt can attain considerable vertical extent by this method.

In opposition to the geophysical possibility of Model 3 and 4, however, metamorphic evidence in this portion of the belt argues against a 9 km vertical extent. Thurston and Breaks (1978) have observed that assemblages indicative of a minimum depth of burial of = 10 km are present at the
surface in the central portion of the belt. The tholeiite solidus at 5 kb is 680°C (Hels, 1976) therefore a minimum additional depth before partial melting of tholeiitic basalts will occur is about 5 km, an interesting coincidence which agrees well with the following gravity models.

Model 5 (uniform density model, Figure 9) is a first approximation which attempts to fit the vertical extent of the belt to the observed gravity profile without any extraneous compensating mechanism. For simplicity's sake it takes into account only the gross structure and not the detailed configuration of the belt. The model gives a vertical extent of 5 km for the metavolcanics. This value could be changed slightly by varying the mafic - intermediate - felsic metavolcanic proportions used in calculating the average density. However, the 5 km vertical extent is in surprisingly good agreement with the maximum vertical extent suggested by the metamorphic considerations above.

Model 6 (the basin model, Figure 10) also gives a maximum vertical extent of about 5 km. It must be disregarded for the study area in that Thurston et al (1978) can correlate lithologies, whole rock chemistry and, mode of eruption of cycle 2 pyroclastic rocks on both limbs of the fold. This correlation, coupled with the presence of opposing top criteria, renders the syncline the most likely interpretation. However, this model may fit in greenstone
belts where simple, homoclinal, steeply dipping sequences with minor felsic units occur, such as in portions of the Kootibé sub-province.

Model 7 (re-folded model, Figure 11) assumes that the deformation of the belt began with the folding of the supracrustal rocks about north trending, steeply plunging axes. This resulted in closely spaced, isoclinal folds such as have been mapped in Earngey and Agnew Townships (Thurston, 1978). Continued compression in a generally east-west direction refolded the earlier folds and resulted in the formation of the synclinorium and the anticlinorium. This model is somewhat similar to that proposed by Anhéusser (1975).

This model may have credibility if it is assumed that the steep dips mapped at the surface are due to tight folding of the lithologic units which themselves have a much shallower integrated dip (i.e. shallow dipping "enveloping surfaces") but there is no structural geologic evidence of this thus far.

Model 8 ("rootless" greenstone model, Figure 12) seems the most likely model for the following reasons:

1) it fits the gravity data within the 5 km limit suggested by metamorphic considerations.

2) it agrees with the stratigraphic thicknesses, dips and structure interpreted from surface mapping.
3) the shape and vertical extent of the belt interpreted from gravity can be explained by recognized geological mechanisms:

a) production of felsic melts from amphibolite melting processes (with or without mixing with other liquids).

b) magmatic stopping during resurgent caldera activity of cycle 3 volcanism.

Stopping as a means of removing the root of a greenstone belt has already been discussed in connection with Model 3 (density gradient model).

As regards the production of felsic melts, evidence from rare earth element studies of the metavolcanics in the study area (Thurston and Fryer, 1979) suggests that many of the felsic magmas have originated by melting of amphibolite (Helz, 1976; Arth and Hanson, 1975) and magma mixing of tholeite and trondhjemitic liquids (Thurston and Fryer, 1979) to produce rhyodacite and rhyolite liquids. In addition, within the third cycle, units of the upper felsic portion lie within a fault-bounded block (Thurston and Jackson, 1978). They trend northeast rather than north as does the rest of the belt and these units plunge at 40° NE rather than steeply to the west (Asbury, 1975; Thurston et al, 1978) have suggested that the felsic portion of cycle 3 within the fault-bounded block lies within a sector graben (Williams, 1941).
resulting from a cauldron subsidence followed by subsequent volcanic activity. Implicit in the suggestion of a cauldron subsidence is the presence of a subjacent felsic magma chamber (Smith and Bailey, 1968). The possible extent of the magma chamber is indicated by the coincidence of the sector graben (Thurston et al., 1978) and a pronounced 48 km linear low on the second derivative map (Figure 4). However, the northern portion of the low is associated with the post metamorphic Okanse batholith (Thurston and Jackson, 1978).

The magma chamber, represented by a thinning of the greenstone belt around 42 km, is less evident in Model 8 (Figure 12) than in the preceding models. This can be explained by the, probably, excessive vertical extent of the central felsic unit, which in the modelling process forces volcanics deeper in order to compensate. Decreasing the vertical extent of the felsic unit in the modelling would allow the interpreted vertical extent of the mafic metavolcanics to decrease and assume a more "cavernous" shape.

This study clearly points out the necessity of integrating geological data with gravity modelling studies in order to constrain both geological and geophysical hypotheses. The central gravity low on the profile provides further evidence for the resurgent caldera hypothesis and the extremely limited vertical extent of the metavolcanic-metasemimentary belt. The study also indicates that parallel isoclinal folding as
depicted in many cross sections of Archean greenstone belts is unrealistic if projected to great depth. The deep synclinal keels of greenstone belts, suggested by Gorman et al. (1978) may be finally consumed in late tectono-magmatic events.
ACKNOWLEDGMENTS

The authors wish to express their thanks to Bruce C. Wilson for many stimulating discussions on the subject throughout the study period. We thank Drs. R.A. Gibb, W.C. Brisbin, K.D Card and B.F. Gorman for reviewing the manuscript and offering many constructive comments. We are indebted to Dr. N. Ramani and P. Mark for assistance with computer plotting at the autocartography laboratory of the Ontario Geological Survey. This paper has been published with the permission of the Director, Ontario Geological Survey.
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### TABLE 1 Densities (Uchi Subprovince)

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<th>Rock Type</th>
<th>N</th>
<th>R</th>
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<td></td>
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<td>All samples (not weighted)</td>
<td>914</td>
<td>2.58-2.89</td>
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**NOTE:** N = number of samples; R = density range in g/cm$^3$; $\bar{\rho}$ = mean density in g/cm$^3$; $s$ = standard deviation in g/cm$^3$. 
FIGURE CAPTIONS

Fig. 1  Key map showing location of the Birch-Uchi greenstone belt.

Fig. 2  Bouger gravity (Contour interval 20 gravity units) and geological map of the Birch-Uchi greenstone belt. Location of Profile ZZ' is also shown.
Geologic legend:
S = Felsic to Intermediate Intrusives;
3 = Intermediate to Ultramafic Intrusives;
1 = Metasediments; 2 = Felsic to Intermediate Metavolcanics; l = Intermediate to Mafic Metavolcanics; Subprovince Boundary; Fault.

Fig. 3  Profile ZZ' showing the Bouger anomaly and the chosen regional background levels.

Fig. 4  Second vertical derivative of the Bouger anomaly map for the central portion of the Birch-Uchi greenstone belt. Contour interval is 0.5 mgal/km². Positive contours are shown in dark, negative contours in light and the zero contour is shown by solid black line. The surface geology and the mapped positions of the volcanic cycles 1, 2 and 3 are superimposed.

Fig. 5  Profile ZZ', Model 1 (Parallel fold model - Vertical dips at surface, showing the residual and computed gravity anomalies. Densities in g/cm³; 0 is the estimate of standard deviation in mgal and C is the correlation coefficient. Explanation of geologic units and symbols: 5 = Undifferentiated felsic to intermediate intrusives, 5b = Granodiorite; 5d = Quartz Monzonite; 3a = Metasediments; 2a = Intermediate Metavolcanics, 2b = Felsic Metavolcanics; 1a = Mafic Metavolcanics; A = Anticline; S = Syncline.

Fig. 6  Profile ZZ', Model 2 (Parallel fold model - mapped dips).

Fig. 7  Profile ZZ', Model 3 (Density gradient model).

Fig. 8  Profile ZZ', Model 7 (Granite root model).

Fig. 9  Profile ZZ', Model 5 (Uniform density model).

Fig. 10  Profile ZZ', Model 6 (Basin model).

Fig. 11  Profile ZZ', Model 8 (Re-folded model).

Fig. 12  Profile ZZ', Model 4 ("Rootless" greenstone model).
The Uchi Confederation greenstone belt is a complex of metavolcanic and metasedimentary rocks with dissymmetric granites of Archean age within the Uchi subprovince of the Superior Province of the Canadian Shield (Ayres et al. 1971) (Figure 1). This greenstone belt trends north for 84 km, is 32 km wide, and has estimated total stratigraphic thickness of 8200 to 11,240 m folded about a central syncline and an anticline on the east side of the belt. The belt is bounded to the south by the English River subprovince, a gneissic belt (Ayres et al. 1971; Beu & Hayes 1974; Beu & Hayes 1975) and to the north, east, and west by granitic rocks.

Condon (1981) divided metavolcanic rocks of the belt into two cycles, Lower and Upper Cycles with a middle, a third, and lowermost cycle not recognized by Condon in 1971 and called Cycle I on Figure 2 (Thurston 1978). Cycle II, the lowermost unit in the stratigraphy, is the east limb of the central syncline and is the core of the Uchi Lake gneiss.

**CYCLE I**

Cycle I (Figure 1) is the west limb. It is a basal ultramafic unit 2000 m thick, overlain by a mixed unit of felsic pyroclastic and metasedimentary rocks forming a wedge 10 km by 1000 m thick. It is second basaltic to hyaloclastite flow unit overlain by a second intermediate subaqueous pyroclastic breccia of probable ash flow origin (Thurston in press). Volcanic rocks of Cycle I are overlain by 900 m of mafic at the northwest end and olivine tholeiite for the remainder and sheeted at the south end of the zone. The southern limb of the syncline in Cycle I is also exposed on east flank of the Lake of the Woods to the east. The north limb of Cycle I on the east flank of the syncline is well to the south. The east limb of the syncline is well into the gneissic English River subprovince (Bateman 1978) which persists southeast into the gneissic English River subprovince (Beu & Hayes 1975).

![Figure 1: Key map showing location of the Uchi Confederation Lakes Area.](image-url)
Figure 2: Geological Map of the Uchi-Confederation Lakes Area. Geology after Thurston and A. P. Prydz: ODM Preliminary Maps and unpublished material. Lines A-B etc. are locations of stratigraphic sections on Figure 3.
Figure 3. Stratigraphy, Section Uchi Confederation Lakes. See Figure 2 for location of sections.

CYCLE II

Cycle II has a base of amygdaloidal pillow basalts flows, 2,300 m thick which overlie the marble topping Cycle I (Figure 3). A 60 m thick band of oxide-facies iron formation occurs midway through the basalts of Cycle II on the east limb of the syncline. This correlates with a chert unit on the west limb of the syncline. Fine-banded hematite iron formation occurs about 200 m thick underlie the chert on the east limb (Figure 3). Basals are overlain by subsequent purplish-rhine pyroclastics rocks of intermediate composition which form several thin units of pyroclastics from 2,500-3,000 m thick, consisting of 10 subaerial volcanism. A U/Pb radiometric age on zircons from the felsic part of Cycle II has an age of crystallization of 2600 ± 10 m.y. (Nichols and Thurston 1978). Felsic volcanic rocks are overlain, on the west limb of the syncline, by a sequence of pillow basalts, extremely shelly 400 m thick (Flynn and Clerkson 1978).

CYCLE III

The basaltic base of Cycle III is 500 m of pillow basalts flows, followed by 5 m of "massive" pyroclastic flows (terminology after Gillis et al. 1975) (Figure 3). This is succeeded, with no evidence of an unconformity, by a further 1000 m of pillow basalts and andesites.
ite with minor andesite flows toward the top. These bas-
altic and andesite rocks are overlain by quartz and feldspar.
phyric flows of intermediate composition that are partially welded tuffs, and lapilli tuffs and minor ryho-
ite and rhyolite tuff. The upper part of Cycle II is inter-
rupted by a fault-bounded graben within which dominan-
tly andesite and intermediate volcanic rocks called the Min-Mine
Series (Suppek, 1977) have a northeast-southwest structural trend that is somewhat parallel to the northerly trend of the surrounding rocks. The graben, or the basin of the Min-Mine, is filled with volcanic rocks that are mostly andesite and andesite-dacite. The Min-Mine Series is composed of a number of units, each of which is characterized by a distinctive suite of volcanic rocks. The units include the Min-Mine Delta, Min-Mine Lake, and Min-Mine Range.

MINERALOGY AND PETROLOGY

The Uchi Confederation Lakes area is in the lower Laurentian regolith of regional metamorphism described as a low-grade Abukuma type (Thurston and Breaks, 1976). Mineralogy is almost entirely secondary. Basaltic rocks are characterized by feldspar, quartz, and clinopyroxene. Andesite and dacite show a diversity of minerals, including plagioclase, quartz, hornblende, and biotite. Accessory minerals include zircon, tourmaline, and epidote. The composition of the rocks is controlled by the tectonic setting and the degree of metamorphism.

STRUCTURAL GEOLOGY

Northeast trending faults of the Uchi Confederation belt are folded along the Regional tectonic trend of the area. The faults are characterized by a combination of strike-slip and normal faulting. The major faults are the Uchi Lake fault zone, the Min-Mine Lake fault, and the Min-Mine Range fault. These faults are responsible for the development of the Min-Mine Series, which is characterized by a sequence of volcanic rocks that are interbedded with sediments.

TECTONICS

The predominantly volcanic lithologies of the Uchi Conference area are interpreted as having formed in a series of basins that are oriented north-south. The basins are characterized by a sequence of volcanic rocks that are interbedded with sediments. The basins are separated by fault zones that are oriented north-south. The basins are characterized by a sequence of volcanic rocks that are interbedded with sediments. The basins are separated by fault zones that are oriented north-south. The basins are characterized by a sequence of volcanic rocks that are interbedded with sediments.
Figure 4. Block diagram of Earny, Bickett, Agnew and Costello Townships.

LEGEND

1. Mafic Metavolcanics
2. Intermediate & Felsic Metavolcanics
3. Metasediments
4. Granitic Rocks
<table>
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<tr>
<td>M&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Main regional metamorphic event: development chlorite, biotite, hornblende, muscovite, cordierite, andalusite. Relocalization of micas in English River subprovince probably initiated during this event. Regional folding, rotation of M&lt;sub&gt;1&lt;/sub&gt; porphyroblasts associated with emplacement of granitic intrusions in early volcanic sequence.</td>
</tr>
<tr>
<td>D&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Matrix stretching and development of main axial plane schistosity of biotite and muscovite parallel to D&lt;sub&gt;2&lt;/sub&gt; folds. Further reorientation of micas in English River subprovince; minor stages of mobilization controlled by axial surfaces of mesoscopic D&lt;sub&gt;2&lt;/sub&gt; folds. Large scale folds.</td>
</tr>
<tr>
<td>M&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Muscovite parallel to D&lt;sub&gt;2&lt;/sub&gt; axial planes, pinching and twisting of chlorite and andalusite.</td>
</tr>
<tr>
<td>D&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Late stage development of mylonite on strike slip shear. Retrograde muscovite and chlorite in shear zones.</td>
</tr>
<tr>
<td>M&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Late transcurrent faulting, Red L. fault. Minor recrystallization assoc. with D&lt;sub&gt;3&lt;/sub&gt;.</td>
</tr>
<tr>
<td>D&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Minor recrystallization assoc. with D&lt;sub&gt;4&lt;/sub&gt;.</td>
</tr>
</tbody>
</table>
GEOCHEMISTRY

Approximately 235 whole and partial analyses of metavolcanic rocks in the Uchi-Confederation Lakes area have been made by previous workers (Goodwin 1967; Lacro 1970; Brem 1972; Peyskak, pers. comm. 1975; Johns 1976; and Thurston 1978). In addition, the author has 122 additional analyses of major and trace elements including a suite of 73 analyzed for major, trace and rare earth elements (Thurston and Frize 1978). The principal conclusions of this latter work are summarized in the following pages.

The credibility of the following section is dependent upon the geochemical nature of the metamorphism and any early halomelitization. Accordingly, the basaltic rocks were plotted on the CaO vs. MgO diagram of Hupphirns and Thompson (1978) which shows that Mg has been added to the chlorite basalts and Ga to epidote-rich basalts. Miyakirgis (1978) plot of Na2O/K2O vs. Na2O-K2O illustrates profound disturbance of the alkalies in the basaltic rocks.

The presence of isotope trends involving fractional crystallization or crystallization of unrecognized igneous minerals species on AF-M diagrams and other plots is taken as evidence of lack of gross chemical change. Where possible, major element trends are confirmed by use of relatively immobile trace elements such as Ti, Sr, Nb, Y, Cr, Ni, and Ba etc. (Floyd and Winchester 1978).

Basalts of Cycle I are olivine normative tholeiites based upon the AFM plot and the Jensen plot (Jenson 1976). Cycle II basalts are quartz normative tholeiites by the same classification (Figure 7). The basalts of Cycle III are quartz normative high alumina tholeiites. There is not a coherent relationship between FeO* FeO*MgO, and Cr or Ni, therefore percent TiO2 has been used as a measure of differentiation in the basaltic rocks. Using this parameter, Cycle II basalts for example, has two Fe enrichment trends. Each Fe enrichment trend is marked by increasing Fe, Ti, and P; increasing Mg, Cr, and Ni, AL, Ca, and Sr (Figure 8). The ratio Ti/Ni is relatively constant throughout. This pattern is interpreted as oliv-
increasing an abundance. Zr increases like Y then keeps increasing as Y levels off and P decreases. This pattern is interpreted as fractionation of olivine, plagioclase, and apatite (Zielinski 1975).

Felsic rocks of Cycle I are calc-alkaline dacites (52.67 percent SiO₂ anhydrous), low Sr/Y ratios (67.75 percent SiO₂ anhydrous) and high Si alkali. As a group they are low K feldspars, based upon normative feldspar composition. The high Si alkali are possibly related to the other groups by fractionation of quartz, plagioclase, and biotite. A plot of Zr vs. Sr/Y (Figure 9) shows (1) a scarcity of intermediate rocks (2) that the felsic rocks are not related to the mafic rocks by fractional crystallization.

The felsic metavolcanic rocks of the east limb of Cycle II and the internal cycles are calc-alkaline DSV (Condie 1976) with high Cr and Ni in the feldspars and low Si alkali. With increasing Si, Al, Fe, Ti, Ca, and P decrease, Cr and Ni decrease, Ba has irregular scatter P decreases and Na and Ti decrease. Zr is generally minor, large abundances correlate with abundant Y. This pattern is a function of fractionation of plagioclase, an oxide phase, and apatite (Zielinski 1975). The minor Zr etc. suggests origin of the group by liquid immiscibility rather than fractional crystallization which yields greater abundances of LIL elements.

On the east limb where there are eutaxitic alkali with abundant flamm (Savory 1976), high K and low Na and P are thought to represent a combination of subcontinental leaching and chemical changes upon dehydration, (Lipman 1967; Scott 1971). The remainder of the east limb alkali are Na rich trondhjemitic alkali similar to the east limb.

The high alumina basaltic and andesitic rocks of Cycle III have variolitic textures through g 60-90 m interval (13) of the way through the unit. Chemical trends indicative of liquid immiscibility are found in the major elements (Figure 9). Roddick and Weiblen 1970; (Condie et al. 1976) and the trace elements (Watson 1978) at the variolitic zone and toward the top of the basaltic unit where there are high Fe (19 percent Fe₂O₃) basaltic. It is suggested that basalt of Cycle III evolved by fractionation of olivine and plagioclase to an andesitic composition at which point they split into a two fluid system, each represented by the high Fe basaltic, the other the dacites and rhyolites derived therefrom. Extremely large abundances of the LIL elements occur in the associated felsic rocks resulting volatilizing transport (Collinson and Fryer 1978; Fryer and Edgar 1977).

The geological significance of South Bay being placed in Cycle III is based on high LIL element abundances (Zr, Y, Th, etc.) andREE patterns (f18) with high abundances in the felsic rocks. This suggests that volatilizing transport in the sense of Collinson and Fryer (1976) and Fryer and Edgar (1977) was active. The implication is that a large scale hydrothermal system modified the
chemistry of Cycle III felsic volcanics and was also probably responsible for concentrating the base metals.

REE CHEMISTRY

The REE pattern of the Cycles I and II basaltic rocks is essentially flat. Cycle III basaltic rocks have greater REE abundances than the basaltic rocks of Cycle I. The internal cycle is strongly fractionated with patterns similar to Cycle I. Cycle III felsic rocks have almost flat patterns with little fractionation, as well as similar patterns with patterns similar to Cycle I. Cycle III felsic rocks have almost flat patterns with little fractionation. Coupled with the large LIL abundances, this indicates that the heavy REE is the most plausible alternative.

SOUTH BAY MINE

South Bay Mine is comprised of a series of stacked orebodies consisting of massive sulphides grading to copper, zinc, and silver. The deposit was first indicated by an airborne IP survey in 1968 and reached production early in 1969 (Austen 1969; Reed and Austen 1972). Copper-zinc-silver ore is milled at the rate of 500 t.p.d., and the mill produces two concentrates, copper-zinc-silver which is shipped to Noranda, and silver which is shipped to the Western European market.

At January 1st, 1975, undiluted ore reserves (including those already mined) from surface to the 1,300 foot level, totalled 1,600,000 tons averaging 2.38% copper, 14.5% zinc, and 3.5 oz./ton silver.

DISCOVERY: The deposit was indicated by an airborne IPP survey as a single line anomaly. Although the orezone was nowhere exposed, the presence of rhyolite and quartz feldspar porphyry outcrops in the close vicinity led to early diamond drilling and discovery of ore grade.
massive sulphides under about 20 feet of glacial overburden.

GEOLOGICAL SETTING: The orebodies are hosted by felsic pyroclastic rocks, (Prytak 1970:3, b) near the top of the acid phase of Cycle III of the Ochi metasediments. The volcanic sequence here faces northwestwards, a little east of the trace of the (faulted) axis of a synclinorium from east to west, the sequence consists of:

(a) Quartz feldspar porphyry, (QFP)
(b) Cherty argillite.
(c) Tuff breccia and tuff. Massive and
(d) Rhyolite tuff, breccias, flows Minor Dis-
with argillite.
(e) Later felsite dikes, and less Sulphide
commonly, and vice dikes intrude
all the above.

Extensive alteration, which generally envelopes the massive sulphides, may be the same age as the felsite dikes.

Structural attitudes are sub-vertical and the trends swing from north-east to north-westersly in the north, with much variation determined in large part, by the irregular intrusive QFP/volcanic flow interface (Asbury 1975:10) (Figure 11)

QUARTZ FELDSPAR PORPHYRY (QFP): This large unit is considered to be a high level intrusion, probably an endogenous rhyolite dome (Pollock, et al. 1972). We lack observed chilled contacts and wall-rock inclusions in the mine area, but its boundary geometry, uniform and isotropic nature (except where later foliated or altered) leads us to this conclusion. Near the orebodies, the QFP is generally altered to a highly chloritized shatter breccia which is mapped separately as QFP (25) (Asbury 1973). Quartz Feldspar Porphyry (QF) is a porphyritic rhyolite rock, with ubiquitous, rather evenly distributed quartz phenocysts (2-5 m.m.) which are clear or blue, rounded to sub-rounded and sometimes shattered. Feldspar (plagioclase) laths (up to 10 m.m.) show all gradations from incipient to total sericitization. The matrix is very fine grained, consisting mainly of quartz, sericite, and minor chlorite. The phenocysts make up 30-40% of the total, about equally shared if the plagioclase is fresh. Silica content places the QFP in the rhyolite range but potassium and potash/alkali are low for a typical
rhylite. It may therefore be termed a sodalite-rhylite. Serial alteration increases progressively as the QFP (2) alteration zone is approached with development of foliation. Carbonatization (ankerite) and bleaching and sulfidation are other alteration phases less closely associated with the ore sulphides (Sauer 1973, Koschel 1975).

The QFP (2) generally occupies several hundred feet of QFP up to its contact with diorite, sulphides, or argillite in the mine area. Chlorite gradually increases and forms a well developed brecciated texture enveloping subrounded fragments of QFP (1) which are generally 0.5-1.0 mm and finely uniform, but in local areas they are up to 5 mm. Chlorite content appears to be 10-30% but includes finely divided sericite which is not easily distinguishable. The iron-rich chlorite diabase has been identified in most thin sections (Koschel 1975).

Lightly scattered pyrite is rather ubiquitous throughout altered types of porphyry, but in QFP (2) local semimassive concentrations (a few inches to several feet wide) of fine-grained pyrite are sometimes seen, commonly with minor fine phalorite. Elsewhere, galenas has been noted in small concentrations, in fractures and quartz veins.

The QFP is seen in contact with massive ore, dacite tuff and breccia, cherty argillite and rhylite units (Figure 12). Its interface is extremely irregular with embayments and bulges in dimensions up to several hundred feet. Silicified extensions into the dacite unit are not uncommon and display flow features (Parsons 1969).

DACITE BRECCIA AND TUFF. This unit is the host rock to the ore and like the QFP (2) it heavily altered by dark chlorite. The fragments, from sub to lapilli size (3-4 cm.), are of felsic volcanic nature; QFP fragments have not been observed. Fragment sizes increase considerably toward nodes or thickened sections of breccias.

In part, the fragmentation may be a steam-brecciation effect which would apply equally to QFP (2) and exotic fragments are rare. Of interest is the presence of fragments of massive pyrite (which may sometimes be rimmed by minor sphalerite) in the near hangingwall of the massive sulphides. Whether these are intact fragments or selective replacements of felsic fragments, has not been established. The absence of zinc, copper, or mixed massive sulphide fragments, plus sulphur isotope ratios (Secorhime 1973) suggest these fragments have not been derived from present ore-bodies. The dark chlorite alteration, which is the dominant characteristic of this unit, absorbs similar alteration in the QFP (2) as a complementary part of the alteration envelope. The dacite breccia has a strike length of 750 feet and a thickness from 50 to 200 feet (Figures 13 and 14).

CHERTY ARGILLITE. This sometimes laminate, siliceous sediment is developed in the lower levels where it ranges up to 75 feet thick and in rhylite units adjacent to the dacite breccia. It is sometimes in contact with...
OFFZ and occur within dacite tuff/brecia. Sometimes mineralized, it lacks ore concentrations. The unit shows a close spatial relationship to massive ore in stone 24514 between 950 and 1200 levels. This is the only part of the mine where good metal zoning is developed with high grade (6 - 40%) zinc overlying lower grade zinc and copper ore. These features are similar to those found in the Rio Tinto ores of Spain.

MASSIVE SULPHIDES: Massive sulphide ore lenses occur as generally bulbous, irregular bodies up to 100 feet wide, 300 feet long and 300 feet high. They consist dominantly of pyrite (up to 80%) with sphalerite and chalcopyrite as the other principal sulphides. Minor sulphides are pyrrhotite, galena, arsenopyrite and silver minerals (Bridge 1972). Gangue, commonly 50% of the ore is dominantly dacite and lapilli fragments plus quartz and carbonate, with minor sericite and chlorite. The gangue minerals occur variably as disseminated dust to veinlets.

The ore ranges from very fine grained pyrite to coarse, nearly monomineralic light sphalerite, but is typically a finely banded series, the bands being respectively dominant in pyrite and sphalerite, with chalcopyrite as a remobilized phase.

Pyrite shows spheroidal textures, well seen when defined by contrasting chalcopyrite. These textures were noted and examined in polished sections (Yoshida 1977). Hard spheroids of pyrite have apparently been resistant to deformation, which has affected the more ductile chalcopyrite and sphalerite (Carkrey 1977). The sulphides, as a whole, have thus behaved as an incompetent formation against quartz feldspar porphyry, as evidenced by scallop structures at the contacts (Ashby 1975). An analysis of banding within the massive sulphide (Carkrey 1977) has confirmed the zoned and normal nature of the deposit and defined the ages of pyrite which have reacted...
separately to stress Early pyritic spheroids and fragments are representative of early layering while later pyrite and economic sulphide have developed a metamorphic fabric analogous to those developed in Ymetamorphosed sedimentary terrain.

PHYOLITE FLOWS, TUFF AND BRECCIA: Spheroidal and massive flows with subordinate tuff, chert and breccia characterize the siliceous rocks of the hanging wall. The rocks are weakly altered with carbonate, sericite and quartz as predominant phases.

Spheroidal flow units are the most distinctive rocks noted in drill core and underground workings. In these flows tightly packed spheroids up to 8 mm. long are present in a matrix of quartz, chlorite and sericite. The primary nature of the spheroids is best demonstrated by layering within individual flow units and Parsons (1969) attributed these features to devitrification of glassy flows.

Arbrey (1975) used spheroids along with other primary features as an indicator of strain which took place during deformation of the volcanic pile.

The spheroidal flows are inter-banded with massive flows, breccias and tuff which overlie the main dacite breccia unit. In addition to colour and hardness, primary features such as spheroids, hydrous clastic and flow bands are used to distinguish the chlorites from the underlying dacite breccia and flows.

FELSITE DIKES: The felsite dikes intrude all rocks and the ore sulphides, but are most common near the orebodies in the altered rocks (dacite and QFP (2)). Here they are bulbous and irregular in shape. They are fine-grained unaltered rocks consisting mainly of quartz and
oligoclase but with ubiquitous brown carbonate. Disseminated pyrite cubes are quite common. There is a grain-size gradation from contact to centre, with thicker dikes having small feldspar + quartz phenocrysts. Minor taking of the QFP wall has been observed. Most of the dikes are non-foliated, a feature that may reflect their high quartz-feldspar content.

WALLROCK ALTERATION. Three phases of hydrothermal alteration have been recognized in the mine workings to date and a fourth "silicification" phase also be related to the present ore zone.

Dark chlorite (dialphane) is the most prevalent hydothermal phase and demonstrates a close spatial relationship to sulphide lenses. The mineral is most prevalent within the matrix of the zoelite breccia and QFP (2) but similar changes fill fractures in foliated dikes and overlying phyllic flows. Koschal (1975) found that the intensity of chlorite alteration in QFP (2) increased with depth to the 600 foot level of the mine and underground mapping has shown that chlorite alteration is strongest within and adjacent to nodules of "thickened sections" of zoelite breccia.

Silicification alteration is ubiquitous within the QFP (1) at the mine and shows an antithetic spatial relationship to dark chlorite phases. Sericite is most strongly developed within the QFP (2) and flow rocks at the margins of the main chlorite zone but is also present along with chlorite in migmatite phases of QFP (2). In addition to the matrix of breccia, sericite forms from the breakdown of plagioclase within the host rock.

In relation to both chlorite and sericite alteration, Koschal suggested the introduction of extension, mag
nesium and potassium beyond that to be expected from alteration of ferramagnesian and potassic feldspar in the QPF and adjacent volcanics.

Ankerite has been identified as the main carbonate phase within the alteration halo (Koschal, 1975). The mineral is most readily observed along with sericite in QPF (I) and massive flow rocks. Within the chlorite zone ankerite is found disseminated within the breccia matrix and as fracture fillings of all rock types.

Silicification in the form of graphic texture and quartz overgrowths is best observed in thin sections from bleached rock units. The spatial relationship of this alteration to sulphides has not been fully examined but evidence of silicification is found in footwall and hanging-wall rocks.

Palagonite and clay minerals have been identified as alteration phases which occur with sericite and carbonate phases (Koschal, 1975). More extensive thin section studies are required to ascertain the extent of these latter phases.

It must be emphasized that wall rock alterations and especially the chlorite phase of alteration has played a significant role in the search for ore at depth. In addition to increasing the size of target, the chlorite alteration phases show a sympathetic volume relationship to massive zinc-copper-sulphides.

CONCLUSION: While South Bay is classified as a volcanicogenic massive sulphide orebody in felsic volcanic rocks, it shows several variant characteristics. The footwall QPF has been considered a high-level intrusive.

Figure 15. Section 11 + 500 (look north), No. 12, Orebod, South Bay Mine, Selco Mining Corporation Limited.
ROAD LOG  

DAY 1  
Transport from Toronto to Dryden via Transair. Met bus at Dryden airport.

Drive 60 km west on highway 17 to Vermilion Bay. The highway 17 leg of the trip crosses metasedimentary rocks of the Wabigoon subprovince. We turn north along highway 105 we traverse a major part of the English River subprovince. If time permits, 2 unscheduled short stops will be made either northbound or on our return to the Dryden airport. Arrive scheduled in Ear Falls at about 8:30 P.M.

DAY 2  
Turn left from Trillium Motel onto highway 105 for about 0.2 km then left onto highway 657 to Goldpine. After 1.2 km turn left onto the South Bay Mine Road Chequamegon for 77 km to the South Bay Mine Gatehouse. Check in at gatehouse. All visitors must:
1) have company permission to enter property
2) Log in and out at gatehouse.
3) Wear hard hat, safety glasses and safety boots.

For details of mine, refer to South Bay Mine section of this field trip guide.

The visit will take the whole morning. Reassemble at the bus after completion of the mine visit for surface tour conducted jointly by J. Wan and P. Thurston.

Outcrops in mine area

Note: This is an area with much vehicular traffic - walk facing traffic off the traveled portion of the road and stay away from the maintenance garage.

STOP 1. About 90 m SSW of the headframe, on the north side of the road to the mine stop. This outcrop extends about 20 m north of the road. At this point the outcrop consists of alternating porous, well-defined northwest striking bands. Detailed inspection shows some bands up to 0.3 m thick of ashenitic felsic matrix containing up to 20 percent 5-10 m spherulites. The spherulites have a hazy light-green to clear core surrounded by a milky white rim. The spherulitic blocks are surrounded by 0.3-0.6 m thick of eroded brecciated felsic ashenitic massive rock. Fragments in the breccia can be reassembled into larger fragments.

The outcrop is interpreted as a mafic flow. The interior part of relatively thin flows have developed devitrification: 1-5 cm spherulites (Lofton 1971) consisting of radiating needles of olivine. Submicroscopic is more intensely devitrified on the exterior of the spherulite rendering them white on the periphery such that they bear a resemblance to accretionary lapilli. Development of spherulites implies some degree of proximity to a host source of spherulite development requires a time of 10°C of supersaturation for about 48 hours in this instance (Lofton 1971; Keeler and Weben 1968). The heat source is probably the subjacent endogenous dome of more porphyry. The probable feeder for the Cycle III felsic rocks (Pollack et al. 1975; Astbury 1976). Steam fracturing has produced the vesicular type breccia (Parsons 1969).

STOP 2. Walk 50 m ESE down the road past the maintenance garage and proceed uphill toward the water tower. About halfway up the hill a 0.5 x 0.5 m area of massive rhyolite is exposed. The outcrop weathered white and has bobby fractures. Irregular joints defining polygonal blocks 0.05-0.2 m on a side cut the outcrop. The joints are filled with minor chlorite. The rock is a rhyolitic ashenitic, rhyolite flow with occasional quartz and feldspar phenocrysts.

STOP 3. Proceed from the mine site by bus 2.4 km southeast from the bridge crossing the Narrows of Confederation Lake. At this point the bus will discharge passengers. Please stay off the road. Outcrops on both sides of the road for a distance of about 200 m to the northeast will be examined. The rocks here are rhyolitic pyroclastic rocks of the upper part of Cycle III. They are immediately south of the mine porphyry and may be thought of as the ejecta from that dome. The unit varies from fine 1-3 mm ash to lapilli sized lithic and crystal fragments in a tuffaceous matrix defining poorly sorted beds 0.3-10 m thick to lapilli tuff and tuff breccia. The inclusions pyroclastic rocks are also pyroclastic in composition. Note is the lack of sorting, lack of bedding, predominance of lithic fragments and ash. Many of the fragments were obviously hot and deformed. They can only have the shape of ribbon and can be hot enough to vaporize the water and steam. The fumarole nature of many of the fumaroles suggests shallow water (less than 1000 m), Ritterman 1965). Part of the basalt rock textures in the intermediate to felsic tufts to the north suggest that...
Figure 16  Geological map showing field stops
aerial origin is some recent discussions by Francis and Howells (1974) indicate that submarine welding does occur. If so, deformed ribbons or bombs, etc. are possible submarine flows.

Return to Trillium Motel Ear Falls.

D A Y 3

Travel by bus to MNR campsite 1 mile 47 on South Bay Mine road and enter boats.

STOP 4 The mine porphyry is an intrusive tholeiite, spatially associated with the cycle II felsic metavolcanic rocks. The principal features of the unit are abundant (35-40 percent) quartz phenocrysts and subordinate amounts (15-20 percent) plagioclase phenocrysts of similar size in a white to gray weathering matrix to foliated rock. The unit forms, in plan view, a domical mass in SE Denti Township (Pytko 1975). This body is 800 by 2000 m and of its two-dimensional shape, intrusive contacts, fine grained marginal zones, inclusions of wall rocks, and a poorly developed foliation parallel to the margin has been termed an endogenous dome by Pollock et al. (1972). Numerous sill-like ocelli of the main dome occur (Pytko 1970).вшись

This section, the quartz feldspar porphyry consists of 20-40 percent 2-4 mm diameter rounded quartz phenocrysts, 0-20 percent 1-3 mm diameter sericitized white phenocrysts in a matrix of fine grained quartz feldspar and minor sericite 0.05-0.2 mm in size. Scattered grains of epidote occur throughout the matrix. Sericization of feldspar phenocrysts and the matrix is more intense as the orebody is approached.

On this outcrop a faint regional foliation can be discerned. The foliation is a function of alignment of phenocrysts. Other than this "more porphyry" is massive. On the north edge of the outcrop "ghost breccia" consisting of poorly defined subangular blocks up to 0.1 m, on a side can be discerned. They are distributed irregularly through the unit and may evidence the existence of extrusive phases of the body. The "ghost breccia" fragments on this outcrop can only be seen from a boat as they occur on a vertical face.

STOP 5 This outcrop is on the top of the hill 30 m east of the shore at the locality marked on Figure 16. It is about 941.220 m beneath the orebody. It is part of a unit of dacite porphyry rocks associated with the mine porphyry. Several outcrops on the hillside have been stripped of moss and the shoreline examined in vain for evidence of bedding. The unit consists of pumiceous or scoriaceous blocks and lapilli of dacite composition forming 60 percent of the outcrop in an spherulitic ash matrix. The lack of bedding, lack of noticeable alteration, or of any evidence of a lack of contrast in composition of matrix and clasts and limited lateral extent of the unit suggest it is an east breccia.

STOP 6 The next three outcrops are intended to show a sequence of events in the development of a pillow breccia in cycle III mafic flows. Here both pillow-like units with a rounded crestation and concentric cracks and pillows with flat edging cracks are present. Careful examination of the pillow margins reveals the presence of melt (less than 1 percent) plagioclase phenocrysts and verticals. The interstitial space is infilled with gelatinous glass with flower-like patterns which have filled the pillows. This represents the first stage in the formation of pillow breccias.

The unusual glassy color of the pillow is an early stage in the development of the white basaltic which are very common in the upper portion of cycle III. As the alteration is often concentration at pillow rims it is perhaps evidence of cycle hydrothermal activity which perhaps led to the unusual LL enrichment pattern of the overlying mafic cycle of Cycle III. The alteration assemblage consists of carbonate, tremolite-actinolite, chlorite and quartz-gneissic epidote.

STOP 7 Here white weathering muscovite masses of basalt to 30 percent of the rock sit in a dark weathering matrix of basaltic glass. The unit is completely blank with no evidence of bedding. As no pillow selvages can be seen the outcrop is not a convincing example of "pillow breccia" if it is, the pillow-like masses ("pillows") must have been plastic and not confined by surrounding material so as to develop the irregular shapes observed.

STOP 8 This outcrop, still within the cycle III basalt, represents a more classical view of the broken pillow breccia type of Caribou (1963). Along the north edge of the outcrop, several fractured pillows about 0.10 m in the long dimension with selvages around a portion of their periphery can be observed. The matrix is hyaloclastite with straight edges and the curved edges seem pyroclastic fragments. In this instance less vesicular pillow of glassy basaltic felsic have fractured forming relatively straight edged fragments typical of hyaloclastite (Hornem 1972).

At other localities, isolated pillows in a calcarenite matrix are interpreted as pillows expelled onto calcarcous sediments in the thalweg.

STOP 9 Bobo Point is the site of an old gold prospect (Thomson 1938). Therefor watch for old trenches, pits, etc. Proceed east up hill (600 m) then south for about 120 m past derelict cabins to clearing.

This unit represents a carbonate andesite. The unit is about 60-90 m wide and extends for about 10 km along strike. It occurs about 1.5 mile up along the way up to the
basalts of cycle III. These varieties are concentrated in bands 0.1 m thick consisting of Javierite and olivine basalts, separated by comparatively variable-free bands. No pillows have been observed in the unit. According to the measurements by Galinas et al. (1976, 1977), the varieties have been concentrated into the variable-rich body by the process of differentiation (Galinas et al. 1976).

The preferred process for this unit is liquid immiscibility as shown by the relationship of the basaltic olivine to plagioclase. These components have been observed in several different sample ranges by Galinas et al. (1977) and are often observed to coarsen. Many of the major element criteria for immiscibility discussed by Galinas et al. (1977) and Watson (1977) are met; i.e., P2O5, the rare earth elements, Ga, Cr, Ti, Mn, Zn, Nb, Sr and Ba. The results are represented by the mafic phase. (See samples 449, 450, 451 and 452 matrix-plagioclase varieties present from this unit: 449 and 451 are matrix and 450 and 452 plagioclase.)

Other possible origins include sphenile crystals (Keller and Winkler, 1968) and metamorphism of elements (Hughes, 1977).

STOP 10 We begin here the examination of the pyroclastic rocks of cycle II. This outcrop has about 400 m below the top of cycle II. The next 3 stops represent various faces of an assemblage of subaqueous pyroclastic flows. The flows show both in a single outcrop and in a gross stratigraphic area an interval of 50-600 m or overall rising upward and thinning outward aspect similar to that described by Yamada (1973). The proximal facies consists of coarse angular unsorted poorly-bedded chaotic conglomerate with a high proportion of pumiceous clasts in a matrix of ash and broken crystals. This facies occurs on Umi Lake to the east. Outward from the vent pumiceous lapilli tuff with smaller fragments, more matrix, and better development of bedding occurs. This unit is succeeded upward, by sandy pumice tuff with interbedded fine tuff and lapilli tuff, followed upward by finely bedded tuff.

On this outcrop we examine pumiceous tuff with 30-35% angular lapilli in a fine tuffaceous matrix. Beds are 3 to 4 cm thick and graded in both a normal and a reverse fashion. The ichnology is pumiceous in nature. By Yamada's scheme (1973) the units represent the parallel laminated pumiceous tuff unit about mid-way through the thinning upward sequence. This outcrop is part of several of these subaqueous pyroclastic flows forming the cycle II pyroclastic rocks on the east limb of the fold.

On the west limb this unit is correlatable with eutaxitic textured tuffite bearing pumice with a subaerial origin (Sauer, 1972).

STOP 11 In Yamada's sequence this outcrop represents the parallel laminated fine tuff unit toward the top of Yamada's (1973) thinning upward cycle. It consists of a skeletal pumiceous fragment 12 cm in a fine tuffaceous matrix. The matrix consists of broken olivine and feldspar phenocrysts of fine ash. Convoluted bedding of the Boudou division present as well as a massive unit of the A division.

STOP 12 This land is the property of the Macksaw Rod and Gun Club of the South Bay area and as private property must be respected.

The outcrop here forms the basal part of the first of several thinning upward pyroclastic flows in Yamad's (1973) scheme. The thick unit consists of massive graded division. Subangular pumiceous dacite clasts (25 cm) predominately with occasional lithic clasts in a matrix of occasional pelitic shale clasts, broken crystals, small birefringent fragments and ash. The proportion of clasts varies from 40-50%. The unit is massive over a thickness of 0.5 m with occasional sandy pumice tuff interbeds. One fine-grained bed can be seen at the southwest edge of the outcrop.

STOP 13 Dock at end of road to Umi Lake, proceed 0.5 to 1 km south for 400 m to the Great shaft (Thomson, 1935). From the shaft proceed about 400 m south on the road, then due east for 40-50 m to the large striped outcrop. This outcrop is considered to be the horizon because it is generally conformable and the fact that it rests about a pyroclastic flow of Cycle II. The outcrop exhibits a laminated structure defined by carbonate and/or micasilicious interbeds; gold mineralization is associated with the outcrop (Thomson, 1938; Baker, 1976; Thurston, 1975). The underlying tectonically rocks form a thin cyclic alkali-rich pillow basalt unit of dacite and rhyolite. Features to be seen on this outcrop underlying the chert include rhyolite tuff exhibiting syenoidal grading, bedding and pyroclastic flow-top breccia. Above the chert on an outcrop 60 m north intermediate hyaloclastic debris consisting of isolated tuff breccias (Carey, 1953) with occasional syenoidal top forming sandstone is observed.

Proceed by boat to Umi Lake, prepare to board bus for return to Ear Falls.
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MARGINAL NOTES

LOCATION: The area is bounded by Latitudes 51°00' and 51°15"N and Longitudes 92°30' and 93°00' West; the centre of the area lies about 60' km east of Red Lake. The road, to the South Bay Mine extends to the southeastern corner of Dent Township from the town of Ear Falls 80 km to the southwest. The road provides access to the Confederation and Woman Lakes water systems, which extend nearly the whole length of the map area. Access to Honeywell, McNaughton, Agnew Townships and the eastern part of Earngey Township is by float-equipped aircraft based in Red Lake or Ear Falls.

MINERAL EXPLORATION: Past mineral exploration is the area has been described by Pryskiak (1969, 1970; 1971, 1972), Thurston (1973, 1974) and Johns and Thurston (1975). Activity in 1976 consisted of staking in western Agnew Township by Kerr Addison Mines Limited and Selco Mining Corporation Limited. Geophysical surveys were conducted over part of this area in the summer of 1976. Further diamond drilling was conducted during the winter of 1976-1977 on the property of Kerr Addisson Mines Limited in the Fly Lake area.

GENERAL GEOLOGY: The Uchi-Confederation Lakes Metavolcanic-Metasedimentary belt is a "greenstone" belt of Early Precambrian (Archean) age within the Uchi Subprovince of the Superior Province of the Canadian Shield (Ayres et al. 1971). The Uchi-Confederation Belt, a part of the Uchi Subprovince, trends north for 84 km and is 32 km wide. Estimated total stratigraphic thickness is from 8500 to 11 240 m folded about a central syncline and an anticline on the eastern side of the belt. The belt is bounded to the south by the English River Subprovince, a gneissic belt (Ayres et al. 1971; Beakhouse 1977; Breaks et al. 1974, 1975) and to the north, east and west by granitic rocks.

Goodwin (1967) divided the metavolcanics of the belt into two cycles: a lower cycle with a lower mafic and lower felsic member, an upper cycle with a mafic and a felsic member. A third and lowermost cycle, recognized by Pryskiak (1971), is designated Cycle I on figure 2 (Thurston 1978). It forms the lowest unit in the homoclinal succession forming the western limb of the central synclinorium and is also exposed in the core of the eastern anticlinorium.

Cycle I, on the western limb east of Corless Lake is composed of a basal, dominantly pillow, basaltic unit 2200 m thick, overlain by a mixed unit of felsic pyroclastic rocks and metasediments forming a wedge 10 km by 1.5 km thick. A second "basaltic to intermediate" flow unit overlies this
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Note: The table and diagram are incomplete and require further information to be filled in accurately.
The predominantly volcanic lithology of the Uchi Confederation portion of the Uchi Supracrustal Domain southward into the premetasedimentary lithologies of the Uchi Supracrustal Domain of the English River Subprovince (Breaks and Bond 1977). At the Lake Fault Zone the metamorphic grade rises from the green schist faces assemblage to the amphibolite to the amph
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Past Producers

1. Patino Mining Corp. (Old Consolidated Mine)
2. Blue, M.F. (Hudson - Patricia Mine)
3. Little Long Lac Mines Ltd. (Uchi Mine)

Producer

Selco Mining Corp. Ltd. (South Bay Mine)

Information is preliminary and incomplete. More information is available in assessment files Red Lake Resident Geologists Office.
1) the dominantly felsic metavolcanic lithologies and 2) its late, fault-bound character, is assumed to be a caldera-like structure (Smith and Bailey 1968; Lambert 1978).

The Uchi-Confederation Lake area has undergone a low-grade Abukuma type metamorphism (Thurston and Breaks 1978). Most of the area is in the lower greenschist facies (Winkler 1967).

The mineralogy of the metavolcanics is almost entirely secondary. Basaltic rocks consist of saussuritized plagioclase laths in a matrix of tremolite-actinolite and chlorite; epidote and veinlets consist of quartz, carbonate, biotite, and stilpnomelane. Accessory magnetite, ilmenite and sphene are present.

The intermediate and felsic metavolcanics contain relict glass as shards, plates or matrix which consist of very fine grained masses of epidote, chlorite, quartz, albite and pumiceous lithic clasts composed of saussuritized plagioclase, tremolite-actinolite, white mica, chlorite, biotite and quartz. Accessory minerals include sphene, zircon, stilpnomelane and magnetite with secondary carbonate, quartz, and epidote confined largely to fractures.

**STRUCTURAL GEOLOGY:** The north-trending metavolcanics of the Uchi-Confederation Lakes Belt are folded about a central synclinorium. The trace of the axial plane of the syncline lies in the upper portion of Cycle III. West of the synclinal axis the lithologies form a homoclinal sequence, with Cycle I basalts at the base, succeeded upwards by the rocks of Cycle II and III. East of the synclinal axis the rocks of Cycle III face west, Cycle II rocks face west in the area of Lost Bay. To the east, the rocks of Cycle II are complexly isoclinal folded between Lost Bay of Confederation Lake and Uchi Lake, where they are cut by the north-trending Uchi Lake Fault. East of this, Cycle I metavolcanics are exposed in the core of the Leg Lake anticlinorium.

The major fault in the area is the Uchi Lake Fault, a branch of the Sydney Lake Fault Zone (Stone 1976, Thurston and Breaks 1978). Movement on this fault is both strike-slip (Thurston and Breaks 1978, Stone 1976) and vertical in character (Thurston and Breaks 1978). Thurston and Breaks (1978) have suggested a long history of movement on this feature.

Other major fault systems are the graben in which the "Mine series" (Sopuck 1977) felsic metavolcanics of Cycle III sit and the Bear Lake Fault (Thurston 1976). The graben developed nearly synchronously with early Cycle III volcanism and was filled with Cycle III rhyolites with a north-easterly trend. The Bear Lake Fault offsets all metavolcanic units and post-dates volcanism.

**ECONOMIC GEOLOGY:** The major occurrences in the map-area have been described by Prysik (1968; 1970; 1975 and 1978) and Tivey (1975 and 1978). Work portends this map would suggest that the graben and the bulk of the Cycle III felsic metavolcanics were pre-mineralization. Accordingly there is potential for massive sulphide mineralization similar to that at the South Bay Mine, with the graben or immediately adjacent to it, especially along the bounding faults (Hodge Lydon 1977).

Examination of the Hill-LaSalle-Tivey suggests that a cherty horizon (Bateman 1977) is such, the economic potential of the ore along it (Thurston et al. 1974) is perhaps the same as for a discontinuous vein system.
The major mineral associations have been recently summarized by Johns and Thurston (1970; 1971; 1972) and by Hodgson and Lydon (1973). Work portrayed on the geology of the area using the graben containing the Archean greenstone belts and the felsic metavolcanics is presented by Goodwin (1967), who recognized there is a higher grade of Archean greenstone belts at the South Bay Mines within the Shear Zone. Deposits of silver, lead, and zinc are adjacent to it, especially within the hanging faults (Hodgson and Lydon, 1973). A Sloan-Tivey vein system has been described by Bateman (1939). As a result, the exploration potential of the occurrences of the Archean Belt (1974) is perhaps greatest in this system.
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L AND MINERAL REFERENCES

Asbestos Ni Nickel
Silver Pb Lead
Gold po Pyrhotite
Chalcopyrite py Pyrite
Copper S Sulfide minerals
Magnetite sp Sphalerite
Molybdenum Zn Zinc

SYMBOLS

Rock outcrop
- Tuff flow; top (arrow) from pillows shape and packing; overturned.
- Geological boundary, position interpreted.
- Anticline, syncline.
- Mineral occurrence.

2d Pilowed flows
2e Sphurilitic flows, tufts
2f Tuff-breccia, pyroclastic breccia
2g Tuff, lapilli-tuff
2h Chlorite-sericite schist, biotite-chlorite-sericite schist
2i Thin-bedded units
2k Medium-bedded units
2m Thick-bedded units

Mafic Metavolcanics

1
1a Unsubdivided
1b Massive flows
1c Pillow flows
1d Porphyritic flows
1e Variolitic flows
1f Flow breccia
1g Pillow breccia, hyaloclastite rocks
1h Chlorite, biotite-chlorite schists
1i Carbonized
1k Pyroclastic rocks
1m Autoclastic breccia

This unit does not appear on the map.

NOTES:

a. This is basically a Field Legend and may be changed as a result of subsequent laboratory investigations.
b. Subdivision of major rock units does not indicate age relationships.
c. Age relations between units 1, 2, 3, 4 and 5 are unknown.

The letter "G" preceding a rock unit number, for example "GS" indicates interpretation is based on geological data only.

SOURCES OF INFORMATION


Geological Mapping of Earney, Birkett, Agnew, Costello, and parts of all other townships by P.C. Thurston and assistants; the previous work of A.P. Pyrsk's as follows was used in compilation: ODM Maps P.592, P.634, P.763, P.932, P.1056, P.1057, P.1058, P.1066, P.1067, P.1211, and Skinner -Tp, unpublished, manuscript, map, Pyrsk, A.P., 1975.

Base-maps compiled by Cartography unit from base-maps of the Forest Resources Inventory, Ontario Ministry of Natural Resources.


Additional geological information from Ontario Department of Mines, Maps P.592, P.634, P.635, P.763, P.932, P.1056, P.1057, P.1058, P.1066, P.1067, P.1071, P.1211, P.1212, P.1216. Map 45e, Birch-Springpole Lakes Area; Map 47c, Uchi Lake Area.

ODM-GSC Aeromagnetic Maps No. 872G, 873G, 882G and 883G.

Magnetic declination approximately 5°16'W 1977.

Issued 1978

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Thurston, P.C. and Jackson, M.C.
Figure 2-2.
STRATIGRAPHIC MAP
CONFEDERATION LAKE AREA
Derived from Thunton and Jackson (1978)

Legend:  
- Vertical line: fold axis
- Diagonal line: fault
- Dashed line: contact
- Stripes: chemical sediments
- Pattern: granite

as Table 2-I