PALEOMAGNETIC RESULTS
FROM TWO HYDROTHERMALLY ALTERED UNITS
IN THE SUPERIOR PROVINCE

by

Vincenzo Francesco Costanzo-Alvarez

A Thesis submitted in conformity with the requirements for the Degree of Doctor of Philosophy in the University of Toronto

© Copyright by Vincenzo F. Costanzo-Alvarez 1990
ABSTRACT

Two problems of Precambrian paleomagnetism, namely the scarcity of well-dated paleopoles for this geological era, and the aggravating effects of retrograde hydrothermal alteration on the rocks from which the scanty paleomagnetic record available derives, are evaluated by the study of two specific test-cases in the northcentral and northwestern Superior Province. The formations studied are: the unaltered granitic batholiths and hydrothermally altered supracrustal units of the Archean Red Lake Greenstone Belt (northwestern Ontario), a major gold-producing region; and the Keweenawan-age carbonatites and Archean anorthosites of the Kapuskasing Structural Zone (KSZ, northcentral Ontario), an early Proterozoic belt that has been hypothesized as a cross-section of the continental crust.

For the Red Lake greenstone belt, natural remanent magnetization (NRM) component RLR (D=191°, I=-76°, α95=13°, k=41°, N=3 intrusions (11 sites)), a primary thermal remanence (TRM) carried by fine-grained magnetite and deuterite hematite and dating from $\sim$2700 Ma ($^{40}$Ar/$^{39}$Ar cooling age), has been isolated in three granitic batholiths: Little Vermillion (VB), Hamell Lake (HL) and Killala Baird (KB). The primary nature and thermal origin of this component is mainly indicated by the pristine appearance of opaque minerals in thin section, its high coercivities (>30 mT), high unblocking temperatures (>500°C) and strength of magnetic intensity (as high as 4500 mA/m). Component RLR thus represents one of the oldest $^{40}$Ar/$^{39}$Ar dated paleomagnetic components for Laurentia. In addition, and also in the Red Lake greenstone belt, NRM component RLG (D=180°, I=-58°, α95=3°, k=902, N=4 intrusions (9 sites)), a thermochemical remanent magnetization (TCRM) carried by secondary hematite, has been isolated. This component is the characteristic remanence of the Dome stock (DS), the Howey diorite (HD) and the Dickenson Mine's (DM) felsic and mafic dikes which have been hydrothermally altered. An age of $\sim$2580 Ma is derived for this component by purely paleomagnetic means implying a temperature of acquisition of $\sim$260°C. Its thermochemical origin was deduced mainly from the high degree of alteration of opaque minerals and silicates observed in thin sections and the magnetic properties of the RLG carriers, such as relatively high coercivities (>40 mT) and unblocking temperatures (>500°C) even though they have weak magnetization intensity values (as low as 3 mA/m). A third remanence RLN (D=352°, I=79°, α95=4°, k=165, N=5 intrusions (34 sites)), is common in all the intrusions sampled. It could, in some cases, be the normal-polarity counterpart of RLR, but its
generally low coercivities and unblocking temperatures favour a recent viscous origin in most cases.

The paleopoles for components RLR and RLG form an age sequence on the late Archean-early Proterozoic apparent polar wander path for Laurentia which is opposite to that previously accepted, but which agrees with recent paleomagnetic results from other workers and with new U/Pb ages for the Matachewan/Hearst dikes paleopoles (=2450 Ma). The redefined APWP for the latest Archean and earliest Proterozoic also suggests a rate of paleolatitudinal change for Laurentia of ≈2.5 cm/yr which disagrees with previous higher estimates using the old definition of the path, but does agree with the rate of paleolatitude change calculated for other cratons for the same interval of time and with modern plate velocities.

For the southern lobe of KSZ (Chapleau Block), a steep up direction of remanence (component B) had previously been isolated in the Archean Shawmere anorthosite by Costanzo-Alvarez & Dunlop (1988) and Symons et al. (1988), and interpreted either as a TCRM genetically linked with the intrusion of the nearby ≈1100 Ma old Nemegosenda carbonatite or as a TRM acquired during uplift and cooling of the Chapleau block at ≈1950 Ma. As part of a test of the first hypothesis, the same direction of remanence (B1) was isolated in both normal and reversed polarities (B1N: D=308°, I=52°, α95=3°, k=800, N=4 intrusions (18 sites) and B1R: D=109°, I=-49°, α95=11°, k=40, N=4 intrusions (22 sites)), as the oldest remanence of a series of Keweenawan-age alkaline complexes that intrude the Chapleau block, namely the Shenango River, Nemegosenda Lake and Lackner Lake alkaline complexes and the Borden township magnetic anomaly.

Along with B1N and B1R, component B2N (D=68°, I=-4°, α95=22°, k=10, N=5 intrusions (11 sites)) and B2R (D=280°, I=-2°, α95=21°, k=9, N=5 intrusions (13 sites)) have been isolated in both the Shawmere anorthosite and the alkaline complexes. These are probably later magnetic acquisitions, recording intermittent alkaline intrusive activity. The corresponding paleopoles for components B1 and B2 trace out a portion of the Logan Loop from ca. 1100 Ma to 1000 Ma.

A granulometric test, consisting of comparing relative lengths of TRM (or ARM) and magnetic susceptibility anisotropy ellipsoids (Stephenson et al, 1986), has been extensively used and developed in order to assess the nature of the B TCRMs and the extent of hydrothermal alteration in the Shawmere
anorthosite. Granulometric, rock magnetic and petrographic analyses of the Shawmcre anorthosite suggest that these TCRMs originated by growth and crystallization of secondary magnetite as a consequence of extensive hydrothermal alteration. This alteration is hypothesized to have taken place along a carbonatite trend parallel to the Ivanhoe Lake Cataclastic zone (ILCZ) connecting the alkaline complexes in the Chapleau block. These analyses also allow a preliminary mapping of the extent of hydrothermal alteration in the Shawmcre anorthosite away from the carbonatite trend. In fact, for sites close to foci of hydrothermal alteration such as the carbonatite trend itself and the ILCZ, different generations of magnetites with different grain sizes can be detected coexisting with their primary counterparts. Far away from these foci of hydrothermal activity, unaltered anorthosite samples have preserved their primary magnetic mineralogies almost untouched, as reflected by their narrow ranges of magnetite grain sizes around the PSD-SD threshold size. The modified Stephenson test proves to be especially suitable for the study of natural samples where traditional granulometric techniques generally fail to distinguish different fractions of magnetites with different grain sizes.
ACKNOWLEDGMENTS

Many people assisted me, in one way or another, for the completion of this thesis, and to all of them I am grateful.

Foremost I want to thank my supervisor Professor David J. Dunlop. During these last five years he provided me with continuous and insightful guidance, feedback, encouragement during stormy times when I could not even see the light at the end of the tunnel, generous financial support from research grants and most important of all, the treasure of his friendship.

Long enlightening discussions with Drs. M.P. Bates (University of Toronto), C.J. Hale (University of Toronto), H.C. Halls (University of Toronto), H. Hyodo (Hiruzen Research Institute, Okayama University, Japan), P.W. Layer (University of Alaska), L.J. Pesonen (Geological Survey of Finland), H. Ueno (Kagoshima University, Japan), S. Xu (University of Toronto) and D. York (University of Toronto) helped me to organize my ideas and to shape out tons of experimental data into a coherent story.

Lauri Pesonen spent a complete week of almost 24 hours of work daily (and nightly) doing the thermal runs of the Nemegosenda and Shenango carbonatites, he also kindly measured 21 of these samples using his facilities in the Paleomagnetic Laboratories of the Geological Survey of Finland in Espoo.

Martin Bates and Chris Hale were my "petrographic mentors" sharing with me their knowledge in the subject and helping with the setup, microphotography and analyses of opaques in thin sections using transmitted (M.B.) and reflected light (C.H.) microscopy.

Sebastian Pfleiderer patiently spent almost a week fixing a plotting program for me. He also allowed me to use his susceptibility bridge and software and shared with me his knowledge and experience in the AMS subject.
Özden Özdemir kindly allowed me to quote her susceptibility and Q, data for the Kapuskasing samples (Chapter 7) and oriented me in the experimental and analytical routines involved in the determination of hysteresis parameters.

I am specially grateful to all the people who endured the usual and sometimes not so usual hardships associated with field work, and assisted my field trips. They are:

Hironobu Hyodo and Brian Reid (Kapuskasing, August 1986).

Dawn McMaster, Paul Layer, Maurice Lavigne (OGS) and Brian Atkinson (OGS) (Red Lake, October 1986).

Wyn Williams (Kapuskasing, October 1987)

Dean Lee and Jim McCurdy (Kapuskasing, August 1988)

Martin Bates (Kapuskasing, September 1988)

In addition, the Ontario Geological Survey and Campbell and Dickenson Mines provided invaluable logistic support during the three weeks of field work in Red Lake, namely free flight hours, motor boats, a car, maps and the access to the mines.

Dr. J.A. Percival, from the Geological Survey of Canada, supplied maps and much unpublished data, and helped me in planning the field trips to Kapuskasing.

Another special chapter in these acknowledgments is owed to: Lily Babayan, Li Guo, Jim McCurdy and Wayne Powell, the summer students and lab assistants behind scenes who did most of the dirty job of preparing and spinning hundred of samples and punching thousand of numbers in the computer without even knowing exactly what they were doing.

My housemate Martin Raillard, a graduate student from the Botany Department, lent me part of
his Arctic field equipment for the fall field trips to Red Lake and Kapuskasing, he also allowed me
to use his laptop to do most of the writing of this thesis. His cheerful approach to life and his
naive approach to the explanation of the B component in the Shawmere anorthosite added a lot of
humor and happiness to the seriousness and rigor of these last five years of graduate work.

Wyn Williams read part of the manuscript and made important corrections in the grammar.

I also want to thank Khader Khan and Raul Cunha for their expertise, speed and patience in
drafting most of the figures, Judith Kostilek for her skillful photographic work and Carolyn Moon
for her assistance with Wordperfect.

The Venezuelan Government, the Physics Department at the University of Toronto and the Natural
Science and Engineering Research Council of Canada assisted me financially through a CEPET
Fellowship, an E.F. Burton Fellowship and a Lithoprobe grant to Dr. D.J. Dunlop.

Last but no less I want to thank my brother Sabatino and my father Vincenzo, to whom this
thesis is dedicated. During all these years of struggle they have been for me a continuous source
of inspiration, encouragement and advice.
# TABLE OF CONTENTS

Abstract ........................................................................................................ ii

Acknowledgments ........................................................................................ v

Table of Contents ....................................................................................... viii

List of Figures .............................................................................................. xii

List of Tables ............................................................................................... xviii

Chapter 1 Introduction .................................................................................. 1

1.1 Two problems in Precambrian Paleomagnetism and two test-cases in the Superior Province ......................................................... 1

1.2 A 2700 Ma Paleopole for Laurentia. ...................................................... 3

1.3 Thermochemical overprints in Precambrian units of the Superior Province ................................................................. 3

Chapter 2 Geology ......................................................................................... 5

2.1 The Superior Province ........................................................................... 5

2.2 Red Lake Greenstone Belt ..................................................................... 6

2.3 Shawmere anorthosite and Kapuskasing alkaline complexes .............. 8

   Kapuskasing Structural Zone .................................................................. 8

   Shawmere Anorthosite ........................................................................... 9

   Alkaline complexes and carbonatite intrusions in the Chapleau block .... 10

Chapter 3 Sampling, Measurements and Analysis ...................................... 15

3.1 Sampling ............................................................................................... 15

3.2 Paleomagnetic analyses ....................................................................... 16

3.2 Petrographic analyses .......................................................................... 19

3.3 Magnetic properties measurements ..................................................... 19

3.4 Stephenson Test ................................................................................... 20

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Chapter 4  Paleomagnetism of Archean Formations from the Red Lake Greenstone Belt, Northwestern Ontario: A new definition for the Archean Apparent Polar Wander Path of Laurentia ........................................... 23
4.1  Introduction ........................................................................... 23
4.2  Paleomagnetic results .......................................................... 24
    Component RLN results ......................................................... 32
    Component RLR and RLG results ........................................... 32
4.3  Discussion ........................................................................... 42
    Component RLN .................................................................... 42
    Component RLR: Hammell Lake, Little Vermillion and Killala Baird Batholiths ................................ 45
    Component RLR: Trout Lake Batholith ................................... 49
    Component RLG: Dome Stock, Howey diorite and Dickenson Mine ........................................... 50
    Late Archean - Early Proterozoic Apparent Polar Path of Laurentia .......................... 52
4.4  Conclusions ........................................................................... 56
Chapter 5  Magnetic Petrology of the Red Lake samples .................... 58
5.1  Introduction ........................................................................... 58
5.2  Magnetic characterization of the Red Lake samples .................... 59
5.3  Analysis of thin sections ....................................................... 70
5.4  Conclusions ........................................................................... 82
Chapter 6  Keeweenawan-age magnetizations of carbonatite complexes and remagnetizations of the Shawmere anorthosite in the Kapuskasing Structural Zone ......................................................... 84
6.1  Introduction ........................................................................... 84
6.2  Results for the Shenango Alkaline complex .............................. 89
6.3  Results for the Nemegosenda Carbonatite ................................. 96
6.4  Results for the Borden Anomaly and the Lackner Lake carbonatite ........ 102
6.5 Component B2 results .............................................. 102
6.6 Results for the Shawmere Anorthosite .......................... 109
6.7 Summary of results and Paleopoles ............................... 124
    Component B1 ..................................................... 124
    Component B2 ..................................................... 130
    Borden anomaly components ..................................... 131
    Shawmere anorthosite components .............................. 131
6.8 Conclusions ................................................... 133

Chapter 7 Grain size of magnetite in samples from the Shawmere anorthosite ........ 135

7.1 Introduction .................................................. 135
7.2 Alternating field characteristics and hysteresis properties .......... 136
7.3 Anisotropy of remanence and susceptibility ("Stephenson Test") 141
    The Stephenson Test ............................................ 141
    Site 39 .................................................................. 146
    Site 13 .................................................................. 146
    Site 15 .................................................................. 151
    Sites LLL-3 and LLL-5 ............................................. 151
    Sites SH-1 and 41 .................................................. 156
    Sites SH-2 and 16 .................................................. 159
7.4 Analysis of thin sections ........................................... 162
7.5 Chemical overprinting in the Shawmere anorthosite .................. 162
7.6 Conclusions ................................................... 170

Chapter 8 Conclusions ............................................... 172
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1</td>
<td>Summary of Results</td>
<td>172</td>
</tr>
<tr>
<td></td>
<td>Red Lake Greenstone Belt</td>
<td>172</td>
</tr>
<tr>
<td></td>
<td>Shawmere anorthosite</td>
<td>174</td>
</tr>
<tr>
<td></td>
<td>The modified Stephenson Test</td>
<td>176</td>
</tr>
<tr>
<td>8.2</td>
<td>General implications and future work</td>
<td>177</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>179</td>
</tr>
<tr>
<td>Appendix A</td>
<td>Hysteresis Loops for some of the Shawmere anorthosite samples</td>
<td>186</td>
</tr>
<tr>
<td>Appendix B</td>
<td>P-Q correlations (modified Stephenson test) for some samples from the Shawmere anorthosite</td>
<td>192</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

2.1 Geological setting for the Red Lake Greenstone belt and the Kapuskasing Structural Zone (KSZ) in the Superior Province ................................................. 6

3.1 Magnetic mineralogy heterogeneities in site TLC (Trout Lake batholith, Red Lake greenstone belt) .................................................. 18

4.1 Geological map of the sampling area (Red Lake greenstone belt) ............ 25

4.2 Thermomagnetic curves for samples from the Dome stock, and Little Vermillion and Killala Baird batholiths (Red Lake greenstone belt) 26

4.3 Equal area stereographic projection with unit and final means of components RLN, RLR and RLG (Red Lake greenstone belt) ................. 27

4.4 Histograms of median destructive fields for the three Red lake components ... 28

4.5 Examples (orthogonal and equal area stereographic projections and AF intensity decay curves) of univectorial components RLN NRMs for selected specimens from Little Vermillion lake, Hamell lake and Killala Baird batholiths ..................... 33

4.6 Petrographic (reflected light photomicrograph) and paleomagnetic characterization (orthogonal and equal area stereographic projections and AF intensity decay curve) of component RLR in sample VBB-6-2 (Little Vermillion batholith) .............. 35

4.7 Petrographic (reflected light photomicrograph) and paleomagnetic characterization (orthogonal and equal area stereographic projections and AF intensity decay curve) of component RLR in sample KBF-2-1-1 (Killala Baird batholith) .................... 36

4.8 Petrographic (reflected light photomicrograph) and paleomagnetic characterization (orthogonal and equal area stereographic projections and AF intensity decay curve) of component RLG in sample DSC-5-4-1 (Dome stock) .............................. 37

4.9 Examples (orthogonal and equal area stereographic projections and unblocking temperature intensity decay curves) of components RLR NRMs for selected specimens from Little Vermillion lake, Hamell lake and Killala Baird batholiths .................... 39

4.10 Site VBA (little Vermillion batholith), component RLR, paleomagnetic results (equal area stereographic projections) ................................... 40

4.11 Examples (Equal area stereographic projections) of components RLG NRMs for selected specimens from Dome stock and Howey diorite ....................... 41

4.12 Late Archean and early Proterozoic apparent polar wander path (APWP) for North America (old and redefined versions) ................................. 43

4.13 Summary of results of a storage test performed on two samples carrying component RLN (Little Vermillion and Hammell lake batholiths) .................. 46

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.14</td>
<td>Preliminary $^{40}$Ar/$^{39}$Ar curves for the Red Lake greenstone belt (after McMaster, 1987 and Wright, 1989) showing components RLR and RLG possible ages and temperatures of acquisition</td>
</tr>
<tr>
<td>4.15</td>
<td>Paleolatiudinal positions of the western Superior Province at different times at the close of the Archean and the beginning of the Proterozoic</td>
</tr>
<tr>
<td>5.1</td>
<td>Natural remanent magnetization (NRM) versus initial susceptibility ($k_o$) diagram for the Red Lake samples</td>
</tr>
<tr>
<td>5.2</td>
<td>Saturation isothermal remanent magnetization (SIRM) acquisition curves and the corresponding AF demagnetization spectra for altered and non-altered samples carrying component RLN</td>
</tr>
<tr>
<td>5.3</td>
<td>Saturation isothermal remanent magnetization (SIRM) acquisition curves and the corresponding AF demagnetization spectra for altered and non-altered samples carrying component RLG and RLR respectively</td>
</tr>
<tr>
<td>5.4</td>
<td>Orthogonal vector projections for samples VBB-4-2 and VBA-5-3 (Little Vermillion batholith)</td>
</tr>
<tr>
<td>5.5</td>
<td>Orthogonal vector projections for samples HLB-5-3 and HLC-5-1 (Hammell lake batholith)</td>
</tr>
<tr>
<td>5.6</td>
<td>Orthogonal vector projection for sample KBD-2-2-3 (Killala Baird batholith)</td>
</tr>
<tr>
<td>5.7</td>
<td>Orthogonal vector projections for samples DSD-4-1 and DSC-2-3-1 (Dome stock)</td>
</tr>
<tr>
<td>5.8</td>
<td>Orthogonal vector projections for samples HDA-4-2 and DMD (Howey diorite and Dickenson mine)</td>
</tr>
<tr>
<td>5.9</td>
<td>Reflected light photomicrographs of a thin section from site VBA (Little Vermillion batholith)</td>
</tr>
<tr>
<td>5.10</td>
<td>Reflected and transmitted light photomicrographs of a thin section from the Hammell lake batholith</td>
</tr>
<tr>
<td>5.11</td>
<td>Transmitted light photomicrographs of a thin section from the Hammell lake batholith</td>
</tr>
<tr>
<td>5.12</td>
<td>Transmitted light photomicrographs of a thin section from the Hammell lake batholith</td>
</tr>
<tr>
<td>5.13</td>
<td>Transmitted light photomicrographs of a thin section from the Trout lake batholith</td>
</tr>
<tr>
<td>5.14</td>
<td>Reflected light photomicrographs of a thin section from site VBB (Little Vermillion batholith)</td>
</tr>
</tbody>
</table>
5.15 Transmitted light photomicrograph of a thin section from the Killala Baird batholith. 78

5.16 Reflected and transmitted light photomicrographs of a thin section from the Hammell lake batholith 79

5.17 Transmitted light photomicrograph of a thin section from the Dome stock 80

5.18 Reflected light photomicrographs of a thin section from the Howey diorite 81

6.1 A geological map of the sampling area of the southern lobe of the Kapuskasing structural zone (KSZ) after Costanzo-Alvarez and Dunlop (1988) 85

6.2 Sketch map of the alkaline complexes and the Shawmere anorthosite in the KSZ 86

6.3 Geological maps plus sampling sites of the Nemegosenda and Lackner lake carbonatites 87

6.4 Geological maps plus sampling sites of the Shenango and Borden alkaline complexes 88

6.5 Equal area stereographic projection with sites and final means of component B1N and B1R in the Shenango alkaline complex 93

6.6 Components B1N and B1R: stereographic and orthogonal vector projections in the course of AF demagnetization for samples SHE-6-5-2-1 and SHE-1-3-3-1 (Shenango alkaline complex) 94

6.7 Components B1N and B1R: stereographic and orthogonal vector projections in the course of AF demagnetization for samples SHE-6-1-1-1, SHE-8-3-2-1 and SHE-6-2-1 (Shenango alkaline complex) 95

6.8 Intensity decay curves during AF and thermal demagnetization for samples SHE-6-1 and SHE-8-2 (Shenango alkaline complex) 97

6.9 Intensity decay curves during AF and thermal demagnetization for samples SHE-2-1 and SHE-4-2 (Shenango alkaline complex) 98

6.10 Equal area stereographic projection with sites and final means of component B1N and B1R in the Nemegosenda carbonatite 100

6.11 Components B1N and B1R: stereographic and orthogonal vector projections in the course of AF demagnetization for samples NE-6-1-1-1 and NE-4-6-2 (Nemegosenda carbonatite) 103

6.12 Results for a baked contact test carried out on mafic gneisses at site 49 in the western contact of the Nemegosenda carbonatite 104

6.13 Intensity decay curves during AF and thermal demagnetization for samples NE-5-1, NE-3-6, NE-4-6, NE-4-5, NE-1-4 and NE-2-4 (Nemegosenda carbonatite) 105
6.14 Intensity decay curves during AF and thermal demagnetization for samples NE-1-1, NE-1-2, NE-6-5 and NE-4-5 (Nemegosenda carbonatite) ................................................................. 106

6.15 Equal area stereographic projection with sites and final means of component B1N and B1R in the Lackner Lake carbonatite and Borden magnetic anomaly ............................................. 108

6.16 Equal area stereographic projection with units and final means of component B2N and B2R .................................................................................................................... 112

6.17 Component B2R: stereographic and orthogonal vector projections in the course of AF demagnetization for samples SHE-4-4-1 (Shenango), NE-3-2-2 (Nemegosenda), 68-2-3-3 (Borden) and 54-8-3-1 (Lackner) ........................................................................................................ 113

6.18 Component B2N: stereographic and orthogonal vector projections in the course of AF demagnetization for samples SHE-4-5-2 (Shenango), 68-5-2-3 (Borden) and 53-6-2-1 (Lackner). ................................................................. 114

6.19 Shawmere anorthosite site means (equal area stereographic projection) ................................................................. 117

6.20 Equal area stereographic projection with site and final means of component B1R and steep up in the Shawmere anorthosite ........................................................................... 118

6.21 Component B1R: stereographic and orthogonal vector projections in the course of AF demagnetization for samples SH-6-5-1-2, SH-7-3 and LLL-4-2-2 (Shawmere anorthosite) ................................................................. 119

6.22 Steep up component: stereographic and orthogonal vector projections in the course of AF demagnetization for samples SH-7-2-2, LLL-2-1-1-1, LLL-3-4-1-1 and LLL-5-8-1 (Shawmere anorthosite) ................................................................. 121

6.23 Intensity decay curves during AF demagnetization for samples LLL-2-1, LLL-2-3, SH-6-6 and SH-7-5 (Shawmere anorthosite). ................................................................. 122

6.24 Intensity decay curves during AF and thermal demagnetization for samples LLL-5-8, 40-5 and 39-2 (Shawmere anorthosite) ................................................................. 123

6.25 Equal area stereographic projection of final means of component B1N and B1R including all the unit means ..................................................................................... 128

6.26 Middle and Late Proterozoic apparent polar wander path of North America (Logan loop) ................................................................. 129

7.1 A simplified Lowrie-Fuller test for some Shawmere anorthosites from sites 13, 39, 15 and LLL-3. ................................................................. 137

7.2 Natural remanent magnetization (NRM) versus initial susceptibility (k0) diagram for the Kapuskasing samples ................................................................. 138
7.3 $H_R$ and $M_{RS}/M_{S^*}H_R/H_C$ domain-structure diagnosis diagrams after Dunlop (1981) with Shawmure anorthosite data ........................................... 140

7.4 Variations of the $p_6$ intercepts with intrinsic susceptibility for different particle shapes ........................................... 143

7.5 Diagram showing the correlation between the relative lengths of the principal axes of susceptibility ($p$) versus 5 mT IRM ellipsoids ($r$) for six different ranges of grain sizes of magnetite (after Stephenson et al (1986)) ........................................... 144

7.6 Comparison between principal axes of susceptibility and 0.16 mT (not demagnetized) or 0.06 mT (demagnetized to 80 mT) TRM ellipsoids for a sample from site 39 ............... 147

7.7 SIRM acquisition and AF demagnetization curves before and after heating to 700°C for a pilot sample from site 39, plus the p-q correlations for a 0.16 mT (not demagnetized) and a 0.06 mT (demagnetized to 80 mT) TRM ellipsoid. ........................................... 148

7.8 Comparison between principal axes of susceptibility and a 0.06 mT (demagnetized to 50 mT) TRM ellipsoid for a sample from site 13 ........................................... 149

7.9 SIRM acquisition and AF demagnetization curves before and after heating to 700°C for a pilot sample from site 13, plus the p-q correlation for a 0.06 mT (demagnetized to 50 mT) TRM ellipsoid. ........................................... 150

7.10 Comparison between principal axes of susceptibility and a 0.16 mT (not demagnetized) TRM ellipsoid for a sample from site 15. ........................................... 152

7.11 SIRM acquisition and AF demagnetization curves before and after heating to 700°C for a pilot sample from site 15, plus the p-q correlation for a 0.16 mT (not demagnetized) TRM ellipsoid. ........................................... 153

7.12 Comparison between principal axes of susceptibility and 0.16 mT (not demagnetized) and a 0.06 mT (not demagnetized) TRM ellipsoids for a samples from sites LLL-5 and LLL-3. ........................................... 154

7.13 SIRM acquisition and AF demagnetization curves before and after heating to 700°C for a pilot sample from site LLL-5, plus the p-q correlations for 0.16 mT (not demagnetized) and a 0.06 mT (not demagnetized) TRM ellipsoids. ........................................... 155

7.14 SIRM AF demagnetization curves before and after heating to 700°C for a pilot samples from sites LLL-2, SH-1 and 41. ........................................... 157

7.15 SIRM AF demagnetization curves before and after heating to 700°C for a pilot samples from sites SH-2 and 16 ........................................... 160

7.16 Transmitted light photomicrographs of thin sections from sites 39 and 13 (Shawmure anorthosite) ........................................... 164
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.17 Transmitted light photomicrographs of a thin section from site 41 (Shawmere anorthosite)</td>
<td>165</td>
</tr>
<tr>
<td>7.18 Transmitted light photomicrographs of a thin section from site SH-2 (Shawmere anorthosite)</td>
<td>166</td>
</tr>
<tr>
<td>7.19 Transmitted light photomicrographs of a thin section from sites LLL2, LLL3 and LLL5 (Shawmere anorthosite)</td>
<td>167</td>
</tr>
<tr>
<td>7.20 Transmitted light photomicrographs of a thin section from site LLL-3 (Shawmere anorthosite)</td>
<td>168</td>
</tr>
<tr>
<td>7.21 Qₜ ratios and pₒ intercepts plotted versus distance from the hypothetical carbonatite trend</td>
<td>169</td>
</tr>
<tr>
<td>A.1 Hysteresis loop and magnetization versus DC demagnetization field diagrams for a sample from site 39 (Shawmere anorthosite)</td>
<td>187</td>
</tr>
<tr>
<td>A.2 Hysteresis loop and magnetization versus DC demagnetization field diagrams for a sample from site 13 (Shawmere anorthosite)</td>
<td>188</td>
</tr>
<tr>
<td>A.3 Hysteresis loop and magnetization versus DC demagnetization field diagrams for a sample from site 15 (Shawmere anorthosite)</td>
<td>189</td>
</tr>
<tr>
<td>A.4 Hysteresis loop and magnetization versus DC demagnetization field diagrams for a sample from site LLL-3 (Shawmere anorthosite)</td>
<td>190</td>
</tr>
<tr>
<td>A.5 Hysteresis loop and magnetization versus DC demagnetization field diagrams for a sample from site LLL-5 (Shawmere anorthosite)</td>
<td>191</td>
</tr>
<tr>
<td>B.1 P-q correlations for samples from site LLL-2</td>
<td>193</td>
</tr>
<tr>
<td>B.2 P-q correlations for samples from site SH-1</td>
<td>194</td>
</tr>
<tr>
<td>B.3 P-q correlations for samples from site 41</td>
<td>195</td>
</tr>
<tr>
<td>B.4 P-q correlations for samples from site SH-2</td>
<td>196</td>
</tr>
<tr>
<td>B.5 P-q correlations for samples from site 16</td>
<td>197</td>
</tr>
</tbody>
</table>
LIST OF TABLES

4.1 Site and unit means for component RLN ........................................ 29
4.2 Site and unit means for component RLR ........................................ 30
4.3 Site and unit means for component RLG ........................................ 31
4.4 Component RLN unit mean directions and vgp after AF demagnetization .... 42
4.5 Component RLR unit mean directions and vgp after AF demagnetization .... 45
4.6 Component RLG unit mean directions and vgp after AF demagnetization .... 51
4.7 Drift history of the Superior Province Late Archean-Early Proterozoic .... 54
6.1 Shenango river alkaline complex components B1R and B1N .................. 91
6.2 Nemegeosenda carbonatite B1R and B1N components .......................... 99
6.3 Lackner lake and Borden anomaly B1R and B1N components ............... 107
6.4 Alkaline complexes and Shawmere anorthosite B2N and B2R components .. 110
6.5 Shawmere anorthosite B1R component ......................................... 116
6.6 Shawmere anorthosite steep up component .................................... 116
6.7 Paleomagnetic poles for the different units and components ............... 126
6.8 Overall mean directions, averaging all units, and their corresponding paleomagnetic poles ................................................................. 127
7.1 Hysteresis parameters for Shawmere anorthosite samples .................. 139
7.2 Stephenson test parameters for the Shawmere anorthosite .................. 161
CHAPTER 1

INTRODUCTION

1.1 Two problems in Precambrian Paleomagnetism and two test-cases in the Superior Province.

In his extensive review on the paleomagnetism and Precambrian evolution of Gondwana, McWilliams (1981) pointed out that among the difficulties in interpreting paleomagnetic data from Precambrian orogens, compared to their younger analogs, is the relatively poor temporal data density. In fact, published compilations of paleomagnetic data show that for the period 2800 to 570 Ma ago the density of paleopoles is depleted by a factor of at least 10 when compared to the 200 to 0 Ma interval. The Precambrian paleomagnetic data base for North America, described by Roy (1983) as a non systematic sampling of a non continuous paleomagnetic record, is no exception.

Along with the scarcity of Precambrian paleomagnetic data comes the problem of determining the real age of the few paleopoles available (McWilliams, 1981). $^{40}Ar/^{39}Ar$ thermochronometry has been successfully employed as a method of dating thermal magnetic remanences (TRM’s) (e.g. Berger and York, 1979; Berger et al, 1979, Berger and York, 1981), but is not reliable if the magnetization has a thermochemical (TCRM) or chemical (CRM) origin since in these cases laboratory magnetic blocking temperatures do not reflect the real temperatures in which the remanences were acquired. Hence it is important to have a complete understanding of the nature and origin of the different paleomagnetic components before any conclusion can be drawn about their ages.

The chances of having retrograde metamorphism and/or hydrothermal alteration, leading to the acquisition of partial TRMs, TCRMs or CRMs, increase with the age of the rock. A careful review of the data base available for the Precambrian APWP of North America, particularly for the close of the Archean and the beginning of the Proterozoic, reveals that most of these paleopoles have been pseudo-dated. In fact, in some cases not only have the basic problems inherent to the differences
between magnetic and isotope diffusion blocking temperatures and slow cooling been completely ignored, but also those problems concerning the primary or secondary origin and the nature of the remanent magnetizations.

This thesis describes a careful assessment of these two main problems of Precambrian paleomagnetism by the study of specific test-cases in the Superior Province of the Canadian Shield. The terrains studied are the Archean Red Lake greenstone belt and the alkaline complexes and the Shawmere anorthosite in the Kapuskasing Structural Zone (KSZ).

The Red Lake greenstone belt, a major gold-producing region in the Uchi subprovince of the Superior Province (northwestern Ontario) consists of Archean supracrustal sequences that have been metamorphosed, highly altered and deformed after the intrusion of large granitic batholiths at the end of the Archean, culminating with gold mineralization in the altered supracrustal units at the beginning of the Proterozoic. Chapters 4 and 5 report the first paleomagnetic work ever done in this greenstone belt. The formations studied are the largely unaltered granitic batholiths and some intrusions that have been hydrothermally altered probably in the same event that caused gold mineralization in the supracrustal units.

The choice of this greenstone belt was motivated by its extensively documented cooling history, a rather uncommon bonus in Precambrian terrains of the northwestern Superior Province (Corfu and Andrews, 1987; McMaster, 1987; Noble, 1989; Wright, 1989, Wright and York, 1990). In addition, the high quality of the U/Pb and \(^{40}\text{Ar}^{39}\text{Ar}\) radiometric data in the unaltered batholiths, yielding evidence of an event of initial regional cooling at an average rate of \(\approx 30\text{C}/\text{Ma}\) at about 2700 Ma ago, makes this region the perfect location for the search for a clearcut 2700 Ma paleopole. Such a paleopole could be used as a reference to settle any dispute concerning the controversial definition of the late Archean and early Proterozoic APWP for North America.

The KSZ, a metamorphic belt that separates the Michipicoten and Abitibi greenstone belts (northcentral Ontario), has been hypothesized to be an upthrust oblique cross-section of the upper two thirds of the Archean crust. The intrusions studied as part of the Lithoprobe Project (chapters 6 and 7) are the high-grade Shawmere anorthosite, in the southern block of the KSZ (Chapleau block), part of the lowermost Archean megalayer exposed by the cross-section, and a series of
alkaline complexes that intruded the Chapleau block during Keweenawan rifting and volcanism (ca. 1100 Ma) in the nearby Superior Lake region.

Costanzo-Alvarez and Dunlop (1988) have suggested that the Shawmere anorthosite was remagnetized by hydrothermal alteration associated with the intrusion of alkaline complexes in the KSZ. The test of this hypothesis (along with the characterization of a paleomagnetic component associated with gold mineralization in the Red Lake greenstone belt) is aimed to explore the nature, extent and consequences of thermochemical remagnetization processes in Precambrian terrains, on the already scanty paleomagnetic record available for this geological era.

1.2 A 2700 Ma Paleopole for Laurentia

The Precambrian APWP for North America is poorly defined, especially for the interval of time that encompasses Archean and early Proterozoic times. Moreover, there is no evidence whatsoever for a surviving remanence older than 2700 Ma in this continent and the few supposedly $\approx$ 2700 Ma paleopoles available are now called into question with the advent of new radiometric and paleomagnetic data. A complete review of this topic, including a discussion about the need for a re-definition of the late Archean-early Proterozoic APWP for North America, is given in chapter 4. The results in chapters 4 and 5 are the contribution of this thesis to the Precambrian paleomagnetic data base, for the late Archean and early Proterozoic of North America. These chapters are devoted to a paleomagnetic and rock magnetic study of the Red Lake greenstone belt.

1.3 Thermochemical overprints in Precambrian units of the Superior Province

Paleomagnetic studies of natural test-cases involving an evaluation of the regional effects of hydrothermal alteration plus a characterization of associated TCRMs are rarely found in the literature. In fact, traditional paleomagnetism, namely the analysis of the directions and blocking temperatures of remanent magnetizations, has only occasionally been applied to the study of altered rocks and ore deposits in order to estimate the timing and temperature of ore mineralization (e.g. Geissman et al, 1980; Hagstrum and Johnson, 1986; Ueno and Tonouchi, 1987). Magnetic properties such as low field susceptibility and saturation isothermal remanent magnetization (SIRM) have also only rarely been used as indicators of the degree of rock alteration and in mapping out or delineating reheated and altered regions (e.g. Criss and Champion, 1984; Lapointe et al, 1986). In this thesis, two kinds
of TCRMs are evaluated using paleomagnetic and rock magnetic information from the hydrothermally altered units in the Red Lake greenstone belt, and from the supposedly Keweenawan remagnetization of the Archean Shawmere anorthosite in the KSZ.

The paleomagnetic and rock magnetic studies of the TCRM associated with oxidation and hydration of magnetic iron oxides by hydrothermal fluids in the highly altered units of the Red Lake greenstone belt, have a two-fold motivation: first, to discriminate it from the primary 2700 Ma old thermal magnetic remanence (TRM) found in the unaltered granitic batholiths, and secondly to constrain, by paleomagnetic evidence, the timing and average temperature of gold mineralization in this region. Chapter 5 is devoted to a characterization of both Red Lake magnetic remanences. Such a characterization is based on a study of the magnetic properties of the unaltered and altered rocks plus petrographic evidence from thin section analyses of opaque minerals, using transmitted and reflected light microscopy.

Chapters 6 and 7 deal with what seems to be a completely different type of chemical remagnetization involving the growth and crystallization of magnetite in the Shawmere anorthosite. Chapter 6 describes a paleomagnetic study carried out in the four alkaline complexes intruding the Chapleau block and aimed at isolating the same B component previously reported for the Shawmere anorthosite. Data from additional sampling sites in the western, northeastern and central parts of the Shawmere anorthosite are also reported.

Finally a characterization of this TCRM and a mapping of the extent of hydrothermal alteration in the Shawmere anorthosite is attempted by using granulometric analyses. Chapter 7 describes these results and the correlation between grain sizes and degree of alteration observed in thin sections and/or, on a macroscopic scale, between grain sizes and sample locations with respect to different foci of hydrothermal alteration in the Chapleau block. A modified Stephenson test (Stephenson et al, 1986), namely a comparison of the anisotropy of magnetic susceptibility with that of thermal or anhysteretic remanences, is used for this purpose, demonstrating the suitability of this test over traditional methods in granulometric studies of natural samples.
CHAPTER 2

GEOLOGY

2.1 The Superior Province

The Superior Province, in the Canadian Shield, is the nucleus of the North American continental craton (figure 2.1). It is a remnant of an early Precambrian craton with radiometric ages between ≈2700 and 2500 Ma about which younger rocks are distributed. The rocks of the Superior Province are in unconformable contact with Aphebian rocks of the Churchill Province and the Phanerozoic sedimentary cover of the Hudson Bay platform on the north, and in fault or metamorphic contact with the Grenville and the Southern Provinces on the southeast.

The most important characteristics of this Province, which is the largest contiguous area of Precambrian Shield rocks that have been tectonically quiescent since the end of the Archean (2500 Ma ago), have been summarized by Goodwin (1972). He has reported common features such as: predominance of crystalline rocks (migmatites and plutons) relative to supracrustal rocks; low to medium metamorphic grade for deformed supracrustal sequences represented mainly by volcanic and sedimentary rocks; complex and varied structural styles such as steep isoclinal folds and wrench faulting; prevailing east and north-east trending structures; numerous metavolcanic assemblages (greenstone belts) with associated rich mineral deposits for which the province is famous; bimodal metamorphic patterns featuring juxtaposed belts with prevailing greenschist and amphibolite facies respectively and the presence of granulite complexes.

Stockwell (1969) has divided the Superior Province into 13 subprovinces with distinctive tectonic characteristics. Recognizable subdivisions of Archean supracrustal and crystalline rocks constitute eight of these subprovinces; four others are areas of Proterozoic cover rocks; and one, the Kapuskasing structural zone (KSZ) represents a metamorphic faulted complex, probably of late Archean to middle Proterozoic age.
2.2 Red Lake Greenstone Belt

The geology of the Red Lake Greenstone Belt, located in the Uchi subprovince of the northwestern Superior Province (figure 2.1), has been summarized by Corfu and Andrews (1987). This greenstone belt comprises three main supracrustal volcanic units: the lower, the middle and the upper sequences. The lower sequence dominates the eastern and western parts of the belt and consists of tholeiitic basalts and basaltic komatiites with minor interbedded units of felsic pyroclastics, felsic flows and chemical and clastic sediments. The middle sequence consists of mafic and felsic pyroclastic volcanic rocks. Finally the upper sequence is itself subdivided into earlier tholeiitic and later calc-alkaline phases. All these supracrustal sequences are metamorphosed to greenschist facies and highly altered and deformed by hydrothermal activity and shearing stress. Their ages encompass a long period (≈270 Ma) that goes from early (2992 Ma) to late (2733 Ma) Archean times.
Large granitoid bodies surrounding the supracrustal sequences represent the latest intermittent events that took place in the region (Corfu and Andrews, 1987). Their ages encompass a shorter interval of time (≈30 Ma) between 2731 and 2699 Ma. These granitoid bodies are medium to coarse grained rocks of variable mineralogical composition. They are believed to have triggered a series of events in the older supracrustal sequences, characterized by contact metamorphism, alteration, shearing, deformation and gold mineralization. Moreover, there are pronounced similarities in the patterns and ages of these late events which suggest that they are related to each other, and all of them in turn, to a single episode of great magnitude that seems to be granitic plutonism. In fact, relationships observed between metamorphic and alteration mineral assemblages lead to the conclusion that contact thermal metamorphism and hydrothermal alteration occurred as one and the same process. Moreover, mineralogical evidence also confirms that shear deformation was active at that time (Andrews et al., 1986).

Two generations of hydrothermal fluids were responsible for alteration: carbonatized metamorphic fluids derived from dehydration of supracrustal rocks ahead of the rising granite diapirs and with background gold values and late magmatic fluids evolving from the batholiths themselves, representing an H₂O-dominated regime in which most of the gold precipitation took place (Andrews et al., 1986).

Deformation zones, which are 1-3 km wide and 30-50 km long shear and mylonite belts, seem to have been caused by a bulk simple shear regime that extended through early brittle-ductile, ductile and late brittle stages, also related to batholith intrusions. These deformation zones focused the bulk of hydrothermal fluid flow through the crust, resulting in regional scale, intense alteration and gold deposition. Hence the close association of these zones to major gold producing zones in the belt (figure 4.1).

Combined U/Pb and "Ar/"Ar data from zircons, sphenes, hornblendes, biotites and muscovites from Hamell Lake and Trout Lake granites and some supracrustal rocks taken from the gold mines allow a preliminary reconstruction of the geological history of the Red Lake greenstone belt. U/Pb data (Corfu and Andrews, 1987) indicate that the volcanism that gave rise to the three supracrustal sequences spanned at least 270 Ma, between 3000 and 2730 Ma, followed by granite plutonism. Gold mineralization has been also roughly bracketed by the age of several pre- and post-ore felsic
and mafic intrusive rocks between 2720 and 2700 Ma (Andrews et al., 1986; Corfu and Andrews, 1987). \(^{40}\text{Ar}^{39}\text{Ar}\) cooling curves for the granites reveal a rapid initial cooling after intrusion around 2700 Ma at rates between 40 and 25°C/Ma (figure 4.14, McMaster, 1987). This rapid cooling seems to have slowed down after \(\approx\)2640 Ma when gold mineralization was probably initiated, according to a biotite \(^{40}\text{Ar}^{39}\text{Ar}\) date from the metamorphic aureole surrounding an ore lens (McMaster, 1987). Recent \(^{40}\text{Ar}^{39}\text{Ar}\) data for single grains of hornblende extracted from a granidiorite of the Trout Lake batholith seem to indicate a post-orogenic thermal pulse occurring at about 2655 Ma ago which was possibly related to gold mineralization in the Red Lake greenstone belt (Wright and York, 1990). Finally, the tail of the Red Lake cooling curve extends from \(\approx\)2640 Ma to \(\approx\)2570 Ma, defining a cooling rate of \(=\)0.5°C/Ma (Wright, 1989), which has been derived from the slightly different \(^{40}\text{Ar}^{39}\text{Ar}\) ages for different grain sizes of biotite in a sample from the Killala Baird batholith.

Combining isotopic data with structural and petrographic results, Corfu and Andrews (1987) distinguish three phases through which granitic plutonism and its consequential effects on the supracrustal units evolved. The first phase is related to plutonism in the northern batholiths around 2730 Ma (Little Vermillion and Hamell Lake batholiths). The second phase around 2720-2710 Ma is responsible for much of the alteration, deformation and metamorphism (Trout Lake intrusion). Finally the concluding phase around 2705-2700 Ma is associated with the Killala Baird and Howey diorite intrusions in the central part of the belt and the Trout Lake marginal phase.

For the paleomagnetic study of chapter 4 the formations sampled were the largely unaltered Hamell Lake (sites HL), Killala Baird (sites KB), Little Vermillion (sites VB) and Trout Lake (sites TL) batholiths; plus the Howey diorite (sites HD), the Dome stock (sites DS) and two quartz-rich felsic dikes (DML and DMQ), a lamprophyre dike (DMD) and a quartz muscovite-rich rhyolitic andesite (DMD), from the Dickenson Mine (DM). HD, DS and DM have been hydrothermally altered in the same event that caused gold mineralization in the supracrustal units of the belt (figure 4.1).

2.3 Shawmere anorthosite and Kapuskasing alkaline complexes

Kapuskasing Structural Zone

The Kapuskasing Structural Zone (KSZ) in north-central Ontario is a 400-km long, NNE trending
belt of dense, high grade gneissic rocks, cutting across the E-W grain of greenschist and amphibolite-grade rocks of the Archean Superior Province, from the late Proterozoic margin of Lake Superior in the south to the Hudson Bay lowlands, where it is buried under Phanerozoic cover. To explain the gravity signature and WNW gradational decrease in metamorphic grade, Percival and Card (1983) proposed that the southern part of the KSZ represents an oblique cross section through the upper two thirds of the Archean crust, uplifted along a listric fault whose surface expression is the Ivanhoe Lake cataclastic zone (ILCZ) (figures 6.1 & 6.2). High grade rocks of the KSZ are juxtaposed with greenschist facies rocks of the Abitibi Subprovince across the ILCZ, whereas the western boundary of the KSZ with the Wawa subprovince is gradational, implying premetamorphic continuity.

The late Archean Kenoran orogeny marked the end of widespread folding, intrusion and metamorphism in the Superior Province. Following sedimentation and volcanism in the Abitibi and Michipicoten greenstone belts between 2750 and 2700 Ma (e.g., Nunes and Jensen, 1980), major deformation of the Wawa and Abitibi subprovinces is bracketed by ages of the youngest volcanism (2700 Ma) and the intrusion of large syntectonic plutons (2680 Ma) (Percival and Sage, 1984). However there is evidence of continued activity in the KSZ after that time. Mafic gneiss and paragneiss samples near the ILCZ have given U/Pb zircon ages of 2650-2630 Ma (Percival and Krogh, 1983), but these ages probably record cooling to about 700°C and the blocking of Pb diffusion in zircons rather than a second metamorphic event.

Recent ⁴⁰Ar/³⁹Ar data (Lopez-Martinez and York, 1990) suggest a long period of differential uplift and subsequent tilting of the KSZ spanning the period from ≈2570 to 2300 Ma ago. In addition, a period of activity from 1850 to 1650 Ma, perhaps related to events in the Trans-Hudson orogen to the north, has been proposed by Percival and Sage (1984) as the likely time of the main uplift. Finally, late Proterozoic ⁴⁰Ar/³⁹Ar ages from minerals with low Ar blocking temperatures (Farrar and Archibald, 1985; Hanes, 1985; Lopez-Martinez and York, 1990) suggest a mild reactivation at 1100-1000 Ma.

Shawmere anorthosite

The lowermost pre-2765 Ma megalayer of the KSZ cross-section adjacent to the ILCZ comprises: paragneisses, mafic gneisses and the Shawmere anorthosite complex (Percival and Krogh, 1983). This megalayer is characterized by a high metamorphic grade (upper amphibolite to granulite facies). It
could be a consequence of early burial of the whole structure under a volcanic pile and of the late intrusion of tonalite sheets that represent the main lithological units of the upper crustal layers.

The Shawmere anorthosite consists of a detached southern mass (5x15 km) of coarse gabbroic anorthosite and a 15x50 km main body with various lithological and textural units (figures 6.1 & 6.2). These units are a border zone of migmatitic garnetiferous amphibolite, a banded zone of anorthosite, gabbro, garnet-rich and ultramafic rocks, an anorthosite zone with minor gabbro and a zone of coarse grained gabbroic anorthosite with minor anorthosite, anorthositic gabbro, gabbro and metagabbro (Percival and Card, 1983).

The Shawmere anorthosite was probably intruded into a succession of older mafic gneiss and paragneiss prior to 2765 Ma. This stratified intrusive body could be the result of differentiation, at depths of no more than 20 km, of tholeiitic magmas, which elsewhere erupted at the surface. The minimum age of 2765 Ma for this intrusion is based on a U/Pb zircon date (Percival and Krogh, 1983) from a foliated garnetiferous tonalite within the Shawmere anorthosite main body whose genetic relationship to the complex is not clearly understood.

For the paleomagnetic study of chapter 6, sites were taken from three locations in the anorthosite main body: in its northernmost end along the shore of Little Lemoine Lake (sites LLL1-5), in its central part along a lumber road about 20 km southwest of Little Lemoine Lake (SH6-8, 39-42) and in its southernmost end along the previously sampled Shawmere River traverse (Costanzo-Alvarez and Dunlop, 1988) augmented now by new sites SH1-5 (figures 6.1 & 6.2).

Alkaline complexes and carbonatite intrusions in the Chapleau block

Alkaline complexes and associated carbonatites are rather common in the Superior Province and they together represent one of the oldest and largest areas of alkaline magmatism yet documented. These alkaline complexes are mainly Proterozoic, unmetamorphosed circular bodies. Associated carbonatites are relatively cold intrusions (683 to 450°C, Heinrich, 1966) and geochemical evidence reveals that these intrusions were rapidly emplaced (low contamination with country rock trace elements; Bell et al, 1982; Bell et al, 1987) during three main episodes of incipient rifting and alkaline intrusion, around 600, 1100 and 1700 Ma (Gittins et al, 1967: whole rock K/Ar). The same geochemical evidence reveals that they probably originated in the subcontinental upper mantle (>70
A number of these alkaline complexes and associated 1 to 2 km diameter carbonatite plugs occur along a 170 km-long belt in the KSZ (figures 6.1 & 6.2). Specifically in the Chapleau block (southernmost KSZ) four of these alkaline complexes can be distinguished: the Nemegosenda intrusion with ages of 1036 and 988 Ma (K/Ar on nepheline, Gittins et al, 1967); 1015 Ma (Rb/Sr WR, Bell et al, 1982) or 1107 Ma (U/Pb on zircon, Heaman et al. 1988); the Shenango complex with ages from 1045 (Rb/Sr WR, Bell et al, 1982) to 1076 and 1082 Ma (K/Ar on biotite, Bell et al, unpublished data reported by Thurston et al, 1977); the Lackner Lake complex with ages of 1090-1095 Ma (K/Ar and Rb/Sr WR, Gittins et al, 1967 and Bell et al, 1982 respectively); and the Borden Township magnetic anomaly with ages between 1810 Ma (Rb/Sr WR) and 1870-1890 Ma (U/Pb, Pb/Pb) (Bell et al., 1987).

A line connecting these four bodies would run almost parallel to the ILCZ (figure 6.2). Gittins et al. (1967) have pointed out that the Kapuskasing belt could have been the locus of carbonatite magmatism for about 750 Ma and Bell et al (1982, 1987) have indicated that alkaline magmatism in the Superior Province seems to be controlled by large-scale structural features such as the KSZ. In fact, the control of the emplacement of intraplate alkaline magmatism related to post-continental fragmentation by zones of weakness as the KSZ has been well documented (Sykes, 1978). Thus it seems reasonable that the same zone of weakness could also act as a major vehicle in channelling hydrothermal activity that accompanied the emplacement of the alkaline bodies.

The ages for the KSZ alkaline complexes suggest a causal relationship with Keweenawan rifting in the nearby Lake Superior area (immediately southwest of the KSZ). This suggested causal relationship is not the one proposed by Burke and Dewey (1973) who explained the Kapuskasing belt as a failed arm of the Keweenawan rift system. Instead, these alkaline intrusions would be a reflection of Keweenawan rifting in the KSZ, favored by an existing zone of weakness.

The Nemegosenda complex is located about 20 km northeast of Chapleau around Lake Nemegosenda. The geology of this complex has been described by Parsons (1961) and Thurston et al (1977). It consists of a nucleus of alkaline syenite surrounded by a contact zone of brecciated syenitic rocks. Brecciation, alteration and recrystallization increase outwards to a metasomatic aureole. Country rocks are Archean gneisses of the KSZ which in the metasomatic aureole itself
show two fenitization zones. The inner zone is characterized by dehydration and reduction with abundant magnetite. The outer zone has been extensively hydrated and oxidized. This zone is also highly foliated and rich in hematite. In addition, a few minor late mafic dikes, porphyry dikes, carbonatite dikes and carbonatite veins occur in and adjacent to the complex.

In order to characterize different petrological phases in the Nemegosenda complex using their magnetic signatures, Symons and Garber (1974) carried out a paleomagnetic study of 17 sites within the core of the complex and in its metasomatic aureole. Although this original goal was not achieved due to remanence instability and resultant scatter between site mean directions, an overall mean paleomagnetic component: D=305°, I=46° was reported as a primary remanence. Its corresponding pole position of 43°N, 178°W is concordant with poles from the apex of the Logan loop (middle Proterozoic apparent polar wander path for North America) with an age range of 1100-1000 Ma. This paleomagnetic evidence also indicates that the KSZ and the complex itself have not been subjected to significant post-emplacement tectonic deformation. Unfortunately, scatter and instability of the presumed primary Nemegosenda remanence, probably a consequence of not only the problems related to the magnetic carriers in the rocks sampled but also to the sampling of different lithologies with slightly different ages, make Symons and Garber’s interpretation inconclusive.

For the paleomagnetic study of chapter 6, a total of 6 sites with an average of 5 samples per site were taken as follows: Site NE-1, NE-2 and NE-6: alkalic syenite, Site NE-3: carbonatite at the nucleus of the complex, NE-4: fenitized gneiss, NE-5: syenitic breccia (figure 6.3a).

The Lackner Lake alkaline complex is located about 25 km southeast of Chapleau and adjacent to the ILCZ. Its geology has been described by Hodder (1961), Parsons (1961) and Thurston et al (1977). The nucleus of the complex is almost circular with a diameter of approximately 5.5 km, comprising mainly coarse-grained nepheline syenite that has intruded Archean granulite gneisses of the KSZ. Between the core and the periphery of the complex, nepheline syenite alternates with concentric bands and partial rings of foliated malignite-ijolite, calcic carbonatite and ijolite breccia which dip at 40 to 65° towards the centre. Fenitization occurs in the country rock along the contact with the outer edge of the complex. Also, carbonatite and apatite-magnetite veins plus occasional dikes which are not exposed, cut the nepheline syenite. As in the case of Nemegosenda, there is no evidence for major post-intrusion metamorphism or tectonism, with the exception of minor late faults on the south and east sides of the complex.
A paleomagnetic study of the Lackner Lake alkaline complex has been carried out by Symons (1989) in order to isolate a primary paleomagnetic component and to check for evidence of any post-intrusive tectonic motion in the KSZ. A mean direction of remanence of D=305°, I=64° with a corresponding paleopole at 54°N, 157°W has been interpreted as a paleomagnetic component dating from the time of emplacement of the complex at 1108 Ma and also indicating no post-intrusion tilting of the KSZ. However the proximity of this direction of remanence to the direction of the present Earth's field in the region, along with the low coercivities and blocking temperatures that this supposedly primary remanence exhibits during AF and thermal demagnetizations, argue against Symons' interpretation.

For the paleomagnetic study of chapter 6, only two sites were taken in the Lackner Lake complex because of the poor exposure. Site 54 was sampled in a foliated ijolitic malignite and syenitic unit and site 53 was taken from an outcrop of nepheline syenite (figure 6.3b).

The Shenango River intrusive complex is an elliptical body located in Sherlock and Shenango townships, approximately 30 km northwest of Foleyet and intruding mafic and metasedimentary gneisses and foliated dioritic plutonic rocks of the northeastern end of the Chapleau block (KSZ) (figures 6.1 & 6.2). The complex comprises a monzonitic core with some arcuate mafic hornfels units and a peripheral unit of syenodiorite and diorite on the east side. These various units seem to be comagmatic and grade gradually into each other. In contrast with the other alkaline complexes in the Chapleau block, the Shenango complex does not show characteristic units of a carbonatite-alkalic suite and seems to be an alkali-poor silica-saturated series rather than one of significant undersaturation and alkali enrichment. Moreover, no evidence for fenitization has been found in the country rocks surrounding the complex.

The results reported in chapter 6 for the Shenango complex represent the first paleomagnetic work ever done on this body. Samples were taken from the northern end of the Shenango intrusion on the line of the Canadian National Railway that connects Foleyet to Elsas and along the shore of Shiners Lake. This part of the Shenango intrusion is characterized by medium to coarse-grained, massive and fresh grey diorite with accessory magnetite. Some sites were also taken from the country rock, a KSZ mafic gneiss, intruded by the diorite unit (figure 6.4a).
The Borden complex is located within Borden township, approximately 21 km northeast of Chapleau and about 3 km west of highway 101. It is marked by a prominent circular magnetic anomaly with a diameter of approximately 1.6 km corresponding to a carbonatite body that intrudes the gneissic tonalites of the KSZ. There are no outcrops for this complex and the only direct evidence of its lithologies is given by exploration trenches and mining drill holes. Sage (1983) distinguishes two main lithological units in the Borden complex: sovite with more than 50% of calcite and silico-carbonatite containing more than 50% of oxide as magnetite or silicate minerals such as amphibole, biotite-phlogopite and olivine. These two lithological groups alternate with variably fenitized gneissic rocks characterized by the presence of sodic pyroxene, sodic amphibole, biotite and carbonate. No paleomagnetic work has ever been done in this complex. For this study, two sites were collected in the country rock that overlies the magnetic anomaly (figure 6.4b).
CHAPTER 3

SAMPLING, MEASUREMENTS AND ANALYSIS

3.1 Sampling

For the paleomagnetic studies of the Red Lake Greenstone Belt and the Shawmere anorthosite and alkaline complexes in the Kapuskasing Structural Zone (KSZ), (chapters 4 and 6 respectively) an average of five samples per site were collected. Detailed accounts of the number of sites per unit and the lithologies sampled for each study are given in chapters 2, 4 and 6. Samples were either drilled directly from the outcrops with a portable drill fed by a continuous flow of cooling water or taken as hand samples and oriented by sun and magnetic (Brunton) compass with an orienting platform.

Extensive glacial erosion and deposition in northern Ontario have resulted in generally poor exposures of flat and isolated outcrops. Field work in the Red Lake greenstone belt was conducted during the fall of 1986. The initial detailed sampling on which this paleomagnetic study is based covers as much as can be covered in this area. Sampling was guided and assisted by Maurice Lavigne and Brian Atkinson, resident geologists for the Ontario Geological Survey (OGS) in Red Lake, who planned a comprehensive 3 weeks' sampling schedule of the region.

Most of the Red Lake batholiths are unreachable by land, hence flights in a Beaver aircraft were necessary in order to gain access to Hammel, Little Vermillion and Trout Lakes. A motor boat was used to reach sampling sites in these lakes, thus covering most of the outcrops on the shorelines. On the other hand, the Dome stock, Howey diorite and Killala Baird batholith are easily accessible by land. The Killala Baird batholith was sampled at all the outcrops available on a lumber road that transects it, including two sites, KBE and KBF, close to and within the Flat Lake Howey Bay deformation zone (figure 4.1).

A one-hour visit to the Dickenson Mine in Balmertown was arranged in order to sample directly
in the gold ore. Hand samples were taken at levels 23 and 30 (=2000 m underground). However since mining activities had to be shut down during the visit, the time available was very limited. This time constraint limited the sampling to one sample per site and samples had to be oriented by magnetic compass.

A first reconnaissance field trip to the Kapuskasing Structural Zone was conducted during the summer of 1986. Besides an assessment of the logistic problems of access to the Shenango and Nemegosenda alkaline complexes, sampling of the few rock exposures available for the Lackner Lake carbonatite and Borden Township gneissic tonalites, sites 49 and 66 in the Nemegosenda carbonatite contact zone, and some extra sampling on the Shawmere River traverse (southwestern end of the Shawmere anorthosite main body; see Costanzo-Alvarez and Dunlop, 1988) were performed as well.

Follow-up work was conducted in three more field trips during the fall of 1987 and the summer and fall of 1988 to the central and northern end of the Shawmere anorthosite main body and the Nemegosenda and Shenango alkaline complexes. Flights in small float planes to Nemegosenda and Little Lemoine Lakes were required to gain access to the Nemegosenda carbonatite and some anorthosite sites in the northeastern end of the Shawmere anorthosite main body, otherwise unreachable by lumber roads. A motor boat was used to reach sampling sites cropping out along the shorelines of these lakes. These sampling sites represent most of the outcrops available for the Nemegosenda carbonatite and Little Lemoine Lake.

The Shenango alkaline complex was sampled during two field seasons (fall 1987 and summer 1988). The only accessible part of this body is its northern end (Shiners Lake area) where it is cut by a Canadian National Railway line that connects the villages of Foleyet and Elsas. Sampling was constrained by this line and included sites from both a syenodiorite that belongs to the complex itself plus some sites on the contact between the syenodiorite and older Kapuskasing amphibolites.

3.2 Paleomagnetic analyses

At least two cylindrical specimens, 2.5 cm in diameter and 2.2 cm high, were cut from each of the drill cores or drilled from each hand sample in the laboratory. Stepwise alternating field (AF) demagnetization to 100 mT and thermal demagnetization, usually to 600°C, were carried out in
magnetic shields with standard commercial demagnetizers: a Schonstedt GSD-1 AF demagnetizer and a Schonstedt TSD-1 furnace with an internal field < 5 nT.

AF demagnetizations were carried out in steps of 1 to 2 mT up to 10 mT and in 5 to 10 mT increments from 10 mT up to 100 mT. These demagnetizations were performed in six successive orthogonal orientations to avoid any systematic magnetization caused by imperfect external field cancellation. In the case of thermal demagnetizations, temperature increments were usually 50°C, but a 20°C increment was used between 500 and 600°C. Samples were heated for an hour at each temperature step and cooled in a zero field shield.

Magnetic moments of thermally demagnetized specimens from the Shawmre anorthosite and the alkaline complexes in the KSZ were measured with a Schonstedt spinner magnetometer. A modified Digico spinner magnetometer with a sensitivity of = 0.025 mA/m was used in measuring the magnetic moments of the rest of the samples. Both magnetometers are connected to IBM-compatible microcomputers programmed for direct display of the measurements and subsequent processing of this data in order to obtain intensity and direction of remanence in both laboratory and field coordinates.

Directions of remanence for 21 samples from the Nemegosenda and Shenango carbonatites were determined at the paleomagnetic laboratories of the Geological Survey of Finland in Espoo by Dr. Lauri J. Pesonen. For these measurements, a Schonstedt GSD-5 AF demagnetizer with tumbler and a mu-metal shielded coil-spinner magnetometer (internal field < 40 nT and sensitivity of = 0.2 mA/m) built at the Geological Survey of Finland and described by Mertanen et al (1987) was used.

The characteristic (highest coercivity $H_c$ or laboratory unblocking temperature $T_{un}$) NRM component or ChRM of each specimen was revealed as a stable end point direction on stereographic projections. Minimum dispersion of directions over a demagnetization interval in which NRM intensity decayed significantly was required in defining the stable end point, but in most cases components were well defined by linear trajectories on orthogonal vector projections (Zijderveld, 1967). These linear trajectories were tested by a principal component analysis FORTRAN program (Kirschvink, 1980) and were accepted only if a segment including at least three consecutive points (excluding the origin) had an angular uncertainty less than 10°. Final site means were calculated using the directions of remanence of independent samples within a site.
In some cases, different Precambrian directions of remanence were isolated from independent samples from a single site. Most of the samples show a single high coercivity or unblocking temperature ($T_{ub}$) magnetization partially overprinted by a recent viscous component. There are very few examples where two Precambrian components of different ages can be obtained from the same sample. Examples regarding this problem are described and discussed for particular samples in chapter 6.

Figure 3.1  A characteristic difference in intensity decay spectra upon thermal demagnetization of two samples from site TLC (trout lake batholith) suggests preferential magnetic carriers for RLN and RLR. Sample TLC-1-2, with a directional swing towards the RLN direction, has very low unblocking temperatures ($T_{ub}$'s), and shows no evidence for single domain magnetite. On the other hand, sample TLC-4-2 with a swing towards the RLR direction shows much higher $T_{ub}$'s and single domain magnetite seems to be the dominant magnetic phase.
For many sites, specially those in the Red Lake granitic batholiths and the alkaline complexes of the Kapuskasing study, only one or two Precambrian magnetizations were included in some of the site averages. This is because the characteristic magnetic mineralogy of granites and carbonatites is usually dominated by fractions of multidomain magnetite rather than single domain ones. Such multidomain dominance favours in most cases a complete overprinting of the Precambrian components by a present Earth’s field viscous remanence. Heterogeneities of magnetic mineralogies between samples from a single site thus dictate that only few of these samples would preserve their ancient remanences whereas a recent viscous overprint would be the only magnetization present in the rest of them. Figure 3.1 illustrates this situation for a particular example of contrasting differences in intensity decay spectra for two samples from the same site TLC in the Trout Lake granitic batholith (Red Lake greenstone belt). Sample TLC-1-2 with a steep down direction of remanence that seems to tend towards the RLN direction (chapter 4), has very low T_CBN’s, and shows no evidence for single domain magnetite. On the other hand, in sample TLC-4-2, with a shallow up direction of remanence that seems to tend towards the RLR direction (chapter 4), the T_CBN’s are higher and single domain magnetite seems to be the dominant magnetic phase.

3.3 Petrographic analyses

Polished thin sections were examined at magnifications up to 400X in transmitted light using a polarizing microscope (Nikon Labophot) with a fully automatic exposure control and camera attached (Nikon HFX-II). For reflected light photomicrographs of the Red Lake samples, a Vickers Instruments polarizing microscope was used. Magnifications in this case ranged up to 320X. Exposure control of the attached camera was completely manual.

3.4 Magnetic properties measurements

Thermomagnetic curves were measured for some of the Red Lake samples (figure 4.2) using a recording Curie balance with a near-saturating field of 300-500 mT and a heating-cooling rate of 10-20°C/min. In addition, a routine determination of initial volume susceptibility \( k_v \) values was carried out on all the Red Lake and Kapuskasing samples using an AC Bartington bridge with a peak field of \( \approx 0.1 \) mT.
A storage test was carried out for a group of those samples showing univectorial Red Lake components (normal and reversed). They were first demagnetized to AF peak fields of 100 mT. Then the magnetic remanence left after demagnetization was measured. The axes of the demagnetized cylindrical samples were aligned along the direction of the present Earth’s magnetic field (=0.06 mT) and left in that position, at room temperature, for a period of three weeks. Afterwards the viscous remanent magnetization (VRM) acquired was measured and compared to the pre-experiment direction of remanence. Stepwise AF demagnetization was performed on these samples in order to determine the median destructive field for the VRM overprint.

For the saturation isothermal remanent magnetization (SIRM) tests reported in chapters 5 and 7, samples were initially AF demagnetized in a field of 100 mT. They were then progressively magnetized along their cylindrical axes to 800 mT using a large electromagnet. The samples were finally stepwise AF demagnetized to 100 mT and their remanence intensities measured after each step.

In order to measure the values of saturation magnetization $M_s$, saturation isothermal remanence $M_{rs}$, and coercive force $H_c$, complete hysteresis loops were obtained at room temperature over a range of applied fields between -600 and 600 mT using a Foner-type vibrating sample magnetometer (Princeton Applied Research Model 150). To determine the remanence coercivities $H_k$ at room temperature, these samples were firstly saturated at 800 mT along their cylindrical axes using a large electromagnet. With the same electromagnet, they were then DC stepwise magnetized in the opposite sense. Values for $H_k$ were determined by finding the interpolated value of the DC field corresponding to zero remanence from the experimental linear relationship obtained between remanent magnetization and DC field.

3.5 Stephenson Test

Granulometric analyses of some of the Shawmere anorthosite samples were carried out using a modified Stephenson test (Stephenson et al. 1986: chapter 7). This test consists of comparing the shape and the orientation of TRM (or anhysteretic remanent magnetization (ARM)) and susceptibility ellipsoids.

Susceptibility anisotropy ellipsoids were determined for unheated and heated samples (700°C)
using an inductance bridge (Sapphire Instruments SI-2 system) with an applied field of 0.1 mT and a sensitivity of \( \approx 30 \) mA/m-mT. Measurements were taken along six different orientations (X, Y, Z, XY, XZ, YZ) and were analysed using the program AMSSTAT developed by Dr. G.W. Pearce which gives the eigenvalues and eigenvectors referred to the sample system of coordinates: X-axis along the strike line, Y-axis perpendicular to the strike line and Z-axis along the cylindrical axis.

TRM anisotropy ellipsoids were obtained by heating each sample three times, for one hour each time, to 700°C and cooling in fields of either 0.06 or 0.16 mT using a Schonstedt TSD-1 furnace. In the first heating, the field was applied along the X-axis and after cooling the X, Y and Z components of TRM were measured in the same modified Digico spinner magnetometer used for the paleomagnetic analyses. In the second and third heatings, the field was applied along the Y and Z-axes respectively. Thus the nine values of the non-diagonalized tensor associated with the TRM susceptibility ellipsoid of anisotropy were obtained referred to the system of coordinates of the sample:

\[
\begin{align*}
M_{XX} & \quad M_{XY} & \quad M_{XZ} \quad \text{Field along X-axis} \\
M_{YX} & \quad M_{YY} & \quad M_{YZ} \quad \text{Field along Y-axis} \\
M_{ZX} & \quad M_{ZY} & \quad M_{ZZ} \quad \text{Field along Z-axis}
\end{align*}
\]

From these nine values, six independent coefficients were obtained, i.e. \( M_{XX} \), \( M_{YY} \), \( M_{ZZ} \), \( (M_{XY}+M_{YX})/2 \), \( (M_{XZ}+M_{ZX})/2 \) and \( (M_{YZ}+M_{ZY})/2 \), (In theory \( M_{xy}=M_{yx} \), etc. but to allow for experimental error, an average value was taken).

ARM anisotropy ellipsoids were obtained by using a peak AC demagnetizing field of 100 mT and a DC field of either 0.06 or 0.16 mT. As in the case of the TRM ellipsoids, the DC field was applied along the X, Y and Z-axes of the sample's system of coordinates and in each case the X, Y and Z components of remanence were measured in a Digico spinner magnetometer. Again, six independent coefficients were obtained from the nine experimental values of the non-diagonalized tensor associated with the ARM susceptibility ellipsoid of anisotropy.

For the TRMs or ARMs induced along each of the three orthogonal axes of the samples analysed, a stepwise AF demagnetization in increments of \( \approx 20 \) mT up to 100 mT was performed and the elements of the tensors associated with the TRM and ARM susceptibility anisotropy ellipsoids were
measured after each demagnetization step in order to observe changes in orientation and shape of the TRM and ARM anisotropy ellipsoids with AF demagnetization.

The TRM and ARM tensors were diagonalized using the FORTRAN subroutine JACOBI from the Numerical Recipes by Press et al. (1989). This subroutine computes all eigenvalues and eigenvectors of a real symmetric matrix of size $N \times N$ using Jacobi's diagonalization method. Given the eigenvalues and eigenvectors as an output from JACOBI, the subroutine EIGSRT, from the same Numerical Recipes, sorts the eigenvalues into descending order and rearranges the columns of the eigenvectors correspondingly. TRM and ARM eigenvectors, as in the case of the susceptibility eigenvectors, are referred to the sample system of coordinates.

In order to monitor changes of magnetic mineralogies after three heatings to 700°C in those samples where TRM ellipsoids were induced, SIRM acquisition and AF demagnetization curves were determined before and after heating, following the procedure indicated above for the SIRM tests.
CHAPTER 4

PALEOMAGNETISM OF ARCHEAN FORMATIONS FROM THE RED LAKE GREENSTONE BELT, NORTHWESTERN ONTARIO: A NEW DEFINITION FOR THE ARCHEAN APPARENT POLAR WANDER PATH OF LAURENTIA

4.1 Introduction

The Red Lake greenstone belt, in the Uchi subprovince of the Superior Province of the Canadian Shield, has been, since 1930, one of the major gold-producing regions in Canada. Fourteen mines working in a 880 km² area have produced an average of 42 tonnes of gold so far.

In the last seven years the Ontario Geological Survey (OGS) has focused the multidisciplinary efforts of Earth Science researchers to gain some knowledge about the processes that gave rise to the alteration and metamorphism of the Archean supracrustal sequences in the belt, and about the spatial and temporal relationships of such processes to gold mineralization.

Extensive U/Pb and \(^{40}\)Ar/\(^{39}\)Ar dating of the greenstone belt itself, gold deposits and the surrounding batholiths, along with structural studies, have allowed a re-interpretation of the local geology and a good mapping of the region, accomplishing part of the original goals of the OGS and yielding a solid framework for further, more detailed research.

Three main reasons make the Red Lake greenstone belt specially suited for a paleomagnetic study. First, the high quality of U/Pb and \(^{40}\)Ar/\(^{39}\)Ar radiometric data in the batholiths, with their evidence for an event of initial regional cooling at an average rate of \(\approx 30^\circ\text{C/Ma}\) about 2700 Ma ago, increases the possibility of finding a clearcut univectorial Precambrian paleomagnetic component without disturbing secondary younger overprints. Moreover, the availability of preliminary isotopically determined cooling curves would allow the direct age calibration of this primary thermal magnetic
remanence.

Secondly, with a paleomagnetic study, there is the possibility of determining with a single method both spatial and temporal information regarding alteration, metamorphism, deformation and gold mineralization in the supracrustal units.

Finally there is also the possibility of obtaining a paleomagnetic pole for the poorly documented 2700-2600 Ma interval of the North American apparent polar wander path (APWP), which would represent one of the oldest $^{40}\text{Ar}^{39}\text{Ar}$ dated paleopoles for this continent.

4.2 Paleomagnetic results

A total of 201 independently oriented samples, were taken at 38 sites in the Hamell Lake (HL: 5 sites, 28 samples), Killala Baird (KB: 6 sites, 32 samples), Little Vermillion (VB: 7 sites, 41 samples) and Trout Lake (TL: 6 sites, 36 samples) batholiths, which lie outside deformation zones (figure 4.1), and in the Howey diorite (HD: 4 sites, 24 samples), Dome Stock (DS: 6 sites, 36 samples), and the Dickenson Mine (4 sites, 4 samples) in or near the deformation zones (figure 4.1).

Thermomagnetic curves (figure 4.2) were measured in air for representative samples from the Little Vermillion batholith (VB-site A), the Dome Stock (DS-site D) and the Killala Baird batholith (KB-site F). All these samples show nearly pure magnetite with Curie points around 580°C. These magnetites are also stable against oxidation upon heating in air, as evidenced by the near reversibility of the $M_s$ vs. temperature curves.

Three main groups of remanent magnetizations, which were called RLN, RLR and RLG (Red Lake: Normal, Reversed and Gold respectively), were isolated by alternating field (AF) and thermal demagnetization (figure 4.3). Unit mean and final mean directions for these components are plotted in figure 4.3 and listed in tables 4.4-4.6. Site means are listed in tables 4.1-4.3 for all the units and components.

Histograms of median destructive fields (MDFs) for these three components are shown in figure 4.4. They provide evidence for distinct MDFs for each component. RLN has a peak in MDF's at \( \approx 10 \text{ mT} \). The RLR and RLG histograms, on the other hand, show that these remanences are
Figure 4.1 Sketch map of the major geological units in the Red Lake greenstone belt showing sampling sites in the almost unaltered batholiths and altered supracrustal units and deformation zones.
Figure 4.2. Thermomagnetic curves for representative samples from the Little Vermillion batholith (VB-site A), the Dome Stock (DS-site D) and the Killala Baird batholith (KB-site F). All these samples have nearly pure magnetite with Curie points near 580°C.
Figure 4.3  Equal area stereographic projections of unit mean RLN, RLR and RLG directions for the
different units of the Red Lake greystone belt together with final means and circles of 95% confidence. The
present Earth's field (PEF) direction is also indicated.
Figure 4.4a, b, c  Normalized histograms of median destructive fields (MDFs) for the three Red Lake components. RLN (4.4a) has a peak MDF of ~10 mT. RLR and RLG histograms (4.4b & 4.4c), on the other hand, show that these remanences are magnetically harder, with characteristic destructive fields ranging up to 100 mT and peaks around 10, 30 and 100 mT for RLR, and 40 and 70 mT for RLG.
<table>
<thead>
<tr>
<th>SITE</th>
<th>Decl. (°)</th>
<th>Incl. (°)</th>
<th>N</th>
<th>σ_95 (°)</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDA</td>
<td>358</td>
<td>84</td>
<td>6</td>
<td>13</td>
<td>20</td>
</tr>
<tr>
<td>HDB</td>
<td>351</td>
<td>82</td>
<td>6</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>HDC</td>
<td>19</td>
<td>84</td>
<td>6</td>
<td>11</td>
<td>27</td>
</tr>
<tr>
<td>HD</td>
<td>322</td>
<td>82</td>
<td>6</td>
<td>13</td>
<td>20</td>
</tr>
<tr>
<td>HD LN</td>
<td>351</td>
<td>84</td>
<td>4</td>
<td>3</td>
<td>708</td>
</tr>
<tr>
<td>RSA</td>
<td>58</td>
<td>85</td>
<td>6</td>
<td>19</td>
<td>9</td>
</tr>
<tr>
<td>RSB</td>
<td>70</td>
<td>64</td>
<td>4</td>
<td>24</td>
<td>9</td>
</tr>
<tr>
<td>RSC</td>
<td>49</td>
<td>46</td>
<td>5</td>
<td>11</td>
<td>33</td>
</tr>
<tr>
<td>RSD</td>
<td>335</td>
<td>72</td>
<td>5</td>
<td>29</td>
<td>5</td>
</tr>
<tr>
<td>RSE</td>
<td>241</td>
<td>67</td>
<td>6</td>
<td>21</td>
<td>8</td>
</tr>
<tr>
<td>RSK</td>
<td>234</td>
<td>81</td>
<td>6</td>
<td>14</td>
<td>17</td>
</tr>
<tr>
<td>RL</td>
<td>359</td>
<td>81</td>
<td>6</td>
<td>17</td>
<td>11</td>
</tr>
<tr>
<td>HLA</td>
<td>238</td>
<td>76</td>
<td>4</td>
<td>17</td>
<td>16</td>
</tr>
<tr>
<td>HLB</td>
<td>341</td>
<td>70</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>HLC</td>
<td>331</td>
<td>53</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>HLD</td>
<td>57</td>
<td>48</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>HEL</td>
<td>317</td>
<td>67</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>HL LN</td>
<td>348</td>
<td>70</td>
<td>5</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>VBA</td>
<td>357</td>
<td>59</td>
<td>6</td>
<td>18</td>
<td>11</td>
</tr>
<tr>
<td>VBB</td>
<td>302</td>
<td>76</td>
<td>7</td>
<td>26</td>
<td>7</td>
</tr>
<tr>
<td>VBC</td>
<td>293</td>
<td>79</td>
<td>5</td>
<td>14</td>
<td>19</td>
</tr>
<tr>
<td>VBD</td>
<td>0</td>
<td>68</td>
<td>4</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>VBE</td>
<td>4</td>
<td>76</td>
<td>6</td>
<td>21</td>
<td>7</td>
</tr>
<tr>
<td>VBF</td>
<td>305</td>
<td>60</td>
<td>5</td>
<td>27</td>
<td>6</td>
</tr>
<tr>
<td>VBG</td>
<td>73</td>
<td>63</td>
<td>4</td>
<td>30</td>
<td>6</td>
</tr>
<tr>
<td>VB LN</td>
<td>348</td>
<td>74</td>
<td>7</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>KBA</td>
<td>323</td>
<td>77</td>
<td>6</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>KBB</td>
<td>354</td>
<td>79</td>
<td>6</td>
<td>19</td>
<td>9</td>
</tr>
<tr>
<td>KBC</td>
<td>26</td>
<td>79</td>
<td>4</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>KBD</td>
<td>312</td>
<td>79</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>KBE</td>
<td>15</td>
<td>48</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>KBF</td>
<td>85</td>
<td>74</td>
<td>5</td>
<td>24</td>
<td>7</td>
</tr>
<tr>
<td>KB LN</td>
<td>85</td>
<td>76</td>
<td>6</td>
<td>12</td>
<td>23</td>
</tr>
<tr>
<td>SITE</td>
<td>Decl. (°)</td>
<td>Incl. (°)</td>
<td>N</td>
<td>α_{95} (°)</td>
<td>k</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>-----------</td>
<td>----</td>
<td>------------</td>
<td>----</td>
</tr>
<tr>
<td>TLA</td>
<td>301</td>
<td>69</td>
<td>5</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>TLB</td>
<td>350</td>
<td>65</td>
<td>4</td>
<td>30</td>
<td>6</td>
</tr>
<tr>
<td>TLC</td>
<td>198</td>
<td>64</td>
<td>6</td>
<td>28</td>
<td>4</td>
</tr>
<tr>
<td>TLD</td>
<td>18</td>
<td>82</td>
<td>5</td>
<td>21</td>
<td>9</td>
</tr>
<tr>
<td>TLE</td>
<td>135</td>
<td>86</td>
<td>5</td>
<td>13</td>
<td>24</td>
</tr>
<tr>
<td>TLF</td>
<td>34</td>
<td>80</td>
<td>4</td>
<td>13</td>
<td>29</td>
</tr>
<tr>
<td>TL RLN</td>
<td>321</td>
<td>85</td>
<td>6</td>
<td>13</td>
<td>19</td>
</tr>
</tbody>
</table>

**TABLE 4.2**

**SITE AND UNIT MEANS COMPONENT RLR**

<table>
<thead>
<tr>
<th>SITE</th>
<th>Decl. (°)</th>
<th>Incl. (°)</th>
<th>N</th>
<th>α_{95} (°)</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLA</td>
<td>143</td>
<td>-66</td>
<td>2</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>TLB</td>
<td>96</td>
<td>-45</td>
<td>2</td>
<td>-</td>
<td>210</td>
</tr>
<tr>
<td>TL RLR</td>
<td>112</td>
<td>-58</td>
<td>2</td>
<td>-</td>
<td>12</td>
</tr>
<tr>
<td>VBA</td>
<td>141</td>
<td>-63</td>
<td>6</td>
<td>7</td>
<td>60</td>
</tr>
<tr>
<td>VBB</td>
<td>225</td>
<td>-49</td>
<td>4</td>
<td>11</td>
<td>45</td>
</tr>
<tr>
<td>VBD</td>
<td>195</td>
<td>-65</td>
<td>2</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>VBF</td>
<td>223</td>
<td>-53</td>
<td>2</td>
<td>-</td>
<td>19</td>
</tr>
<tr>
<td>VBG</td>
<td>231</td>
<td>-80</td>
<td>2</td>
<td>-</td>
<td>14</td>
</tr>
<tr>
<td>VB RL R</td>
<td>205</td>
<td>-66</td>
<td>5</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>KBC</td>
<td>142</td>
<td>-75</td>
<td>2</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>KBD</td>
<td>212</td>
<td>-60</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>KBF</td>
<td>211</td>
<td>-78</td>
<td>3</td>
<td>24</td>
<td>11</td>
</tr>
<tr>
<td>KBE</td>
<td>288</td>
<td>-72</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>KB RL R</td>
<td>215</td>
<td>-77</td>
<td>4</td>
<td>15</td>
<td>22</td>
</tr>
<tr>
<td>HLA</td>
<td>67</td>
<td>-64</td>
<td>3</td>
<td>29</td>
<td>8</td>
</tr>
<tr>
<td>HLB</td>
<td>220</td>
<td>-65</td>
<td>5</td>
<td>22</td>
<td>8</td>
</tr>
<tr>
<td>HLC</td>
<td>179</td>
<td>-60</td>
<td>3</td>
<td>22</td>
<td>10</td>
</tr>
<tr>
<td>HLE</td>
<td>76</td>
<td>-63</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HL RL R</td>
<td>132</td>
<td>-77</td>
<td>4</td>
<td>24</td>
<td>9</td>
</tr>
<tr>
<td>SITE</td>
<td>Decl. ($)</td>
<td>Incl. ($)</td>
<td>N</td>
<td>$\alpha_{ST}$ ($)</td>
<td>k</td>
</tr>
<tr>
<td>----------</td>
<td>-----------</td>
<td>-----------</td>
<td>----</td>
<td>-------------------</td>
<td>----</td>
</tr>
<tr>
<td>HDA</td>
<td>204</td>
<td>-61</td>
<td>4</td>
<td>15</td>
<td>21</td>
</tr>
<tr>
<td>HDC</td>
<td>169</td>
<td>-54</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HD RLG</td>
<td>185</td>
<td>-59</td>
<td>2</td>
<td>-</td>
<td>34</td>
</tr>
<tr>
<td>DSA</td>
<td>184</td>
<td>-40</td>
<td>3</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>DSC</td>
<td>202</td>
<td>-51</td>
<td>6</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>DSE</td>
<td>124</td>
<td>-70</td>
<td>2</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>DS RLG</td>
<td>180</td>
<td>-57</td>
<td>3</td>
<td>24</td>
<td>11</td>
</tr>
<tr>
<td>DMC</td>
<td>251</td>
<td>-59</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>DMD</td>
<td>158</td>
<td>-19</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>DML</td>
<td>219</td>
<td>-58</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>DMQ</td>
<td>121</td>
<td>-45</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>DM RLG</td>
<td>176</td>
<td>-56</td>
<td>4</td>
<td>34</td>
<td>4</td>
</tr>
</tbody>
</table>
magnetically harder with characteristic destructive fields ranging up to 100 mT and peaks around 10, 30 and 100 mT for RLR, and 40 and 70 mT for RLG. More detailed information about the nature and stability of RLN, RLR and RLG remanences will now be given separately for each component.

**Component RLN Results**

RLN is the dominant natural remanent magnetization (NRM) in all the granite batholiths (HL, VB, KB, TL), the Dome Stock (DS), and the Howey diorite (HD). Averaging unit means for these six units gives a grand mean RLN direction: \(D=352^\circ, I=79^\circ\) (\(\alpha_{95}=4^\circ, k=165, N=6\) units, (34 sites)) (Tables 4.1 and 4.4).

Figure 4.5 shows three examples of AF demagnetization of component RLN in selected specimens from the VB, HL and KB batholiths. These samples often have a directionally fairly stable, apparently univectorial RLN NRM. Coercivities below 20 mT seem to be associated with multidomain magnetite to judge by the initial exponential decay of the remanence upon AF demagnetization. In samples KBB-2-1 and VBE-1-3 a small percentage of the initial remanence has a slow AF decay concentrated above 20 mT, probably carried by single domain magnetite.

**Component RLR and RLG Results**

Components RLR and RLG, with southerly directions of remanence and similar inclinations, seem to be the reversed equivalent of component RLN in the same units HL, VB, KB, TL, DS and DM. Their mean directions of remanence are: \(D=191^\circ, I=-76^\circ\) (\(\alpha_{95}=13^\circ, k=41, N=3\) units, 11 sites) for RLR and \(D=180^\circ, I=-58^\circ\) (\(\alpha_{95}=3^\circ, k=902, N=3\) units, 9 sites) for RLG (Tables 4.2, 4.3, 4.5 and 4.6). Although these components are similar in their directions and MDFs, there is paleomagnetic, rock magnetic and petrological evidence that suggests they have to be treated as independent magnetizations (section 4.3 and chapter 5).

Figures 4.6 - 4.8 illustrate, for individual samples, the contrasting petrographic and magnetic features that characterize and distinguish component RLR from RLG. A more detailed study on the magnetic petrology of the Red Lake samples follows in chapter 5.
Figure 4.5 Three examples of typical univectorial component RLN NRM for selected specimens from the VB, HL and KB batholiths. Orthogonal vector and equal area stereographic projections of magnetization vectors in the course of AF demagnetization and their corresponding total intensity decay curves are shown.
Figure 4.6a shows a cross-polarized transmitted light photomicrograph of fresh euhedral magnetite crystals in a sample from the Little Vermillion batholith. Accompanying stereographic and orthogonal vector projections (figures 4.6b and c) plus an intensity decay curve (4.6d) for sample VBB-6-2 suggest that its RLR-like remanence is magnetically strong (=630 mA/m) and probably carried by fine-grained magnetite.

Figure 4.7 corresponds to a sample from site KBF in the Killala Baird batholith just on the Flat Lake-Howey Bay deformation zone (see figure 4.1). Paleomagnetic hybrid characteristics between components RLR and RLG would be expected for this sample. The transmitted light plane-polarized photomicrograph of figures 4.7a shows a hematite crystal with typical reddish internal reflections. Some evidence for deformation and alteration (biotite crystals probably associated with the hematite) can be also observed. However, alteration does not seem to reach the level of complete obliteration of original mineralogies and is probably deuteric. Orthogonal vector projections and intensity decay spectra of figures 4.7c and d (sample KBF-2-1-1) reveal that most of the remanence in this sample is carried by hematite judging from the high unblocking temperatures over 600°C. Intensity of its high unblocking temperature magnetization (>800°C) is $\approx$180 mA/m. Neither stereographic or orthogonal projections of figures 4.7c indicate the expected RLR + RLG hybrid behaviour. Moreover, the direction of remanence isolated in this sample seems to be closer to the RLR-like direction of remanence isolated in sample VBB-6-2 (figure 4.6) than to RLG.

The appearance of opaque minerals observed in the cross-polarized transmitted light photomicrograph of figure 4.8a for the highly hydrothermally altered Dome stock contrasts with that of the Little Vermillion and Killala Baird batholiths. This photomicrograph evidences the intense alteration and complete obliteration of the original mineralogy of this sample, showing anhedral opaque minerals in a background of dusty altered feldspars and chloritized micas. Stereographic and orthogonal projections in figures 4.8b and c and the intensity decay spectrum of figure 4.8d (sample DSC-5-4-1) reveal that the magnetic remanence carried by this sample is quite stable in direction and its intensity decays steadily with AF demagnetization at coercivities >2 mT. Intensity of its high coercivity magnetization is $\approx$ 3 mA/m.
Figure 4.6a, b, c, d Characterization of component RLR in a sample from the Little Vermillion batholith (VBB-6-2). In 4.6a, a cross-polarized transmitted light photomicrograph shows very fresh and cubic opaque minerals in biotite. In 4.6b and c, stereographic and orthogonal projections of magnetization vectors in the course of thermal demagnetization, showing a swing towards a high unblocking temperature RLR-like direction of remanence. In 4.6d the corresponding total intensity decay curve for this sample is also shown.
Figure 4.7a, b, c, d  Characterization of component RLR in a sample from the supposedly 'hybrid' site KBF (KBF-2-1-1) in the Killala Barnd boulders, on the Flat-Lake Howey Bay deformation zone. In 4.8a, a plane-polarized transmitted light photomicrograph shows a hematite crystal with typical reddish internal reflections. Some evidence of deformation and alteration (biotite crystals probably associated with the hematite) can be observed. However alteration does not reach the extreme of complete obliteration of original mineralogies. In 4.7b and c equal area stereographic and orthogonal vector projections of magnetization vectors in the course of thermal demagnetization showing a swing towards a high unlocking temperatures RLR-like direction of remanence. In 4.7d the corresponding total intensity decay curve for this sample is also shown.
Figure 4.8a, b, c, d Characterization of component RLG in a sample from the Dome stock (DSC-541). In 4.8a, a cross-polarized transmitted light photomicrograph shows anhedral opaque minerals in a background of dusty altered feldspars and chloritized micas. For this sample, intense alteration has completely obliterated silicates and opaque minerals, contrasting with the freshness of the batholith samples. In 4.8b and c, equal area stereographic and orthogonal vector projections of magnetization vectors in the course of AF demagnetization showing a swing towards a high coercivity RLG-like direction of remanence. In 4.9d the corresponding total intensity decay curve for this sample is also shown with an initial low intensity noisy plateau that starts to decay steadily at coercivities of ≈ 2 mT.
All these properties indicate that hematite is the main carrier of remanence for this sample. However, contrary to sample KBF-2-1-1, and judging from the low intensity of magnetization and the petrographic characteristics observed in thin section, the hematite in sample DSC-5-4-1 must be a secondary by-product of hydrothermally altered primary magnetite.

Figure 4.9 shows examples of NRM directions and final RLR directions for some individual samples from the batholiths studied. Component RLR has been isolated in each case using principal component analyses and stable end points. Also, three vector diagrams and their corresponding demagnetization curves are shown for samples HLC-5-2, KBF-3-1-1 and VBB-3-1. These examples show that component RLR is not only a high coercivity but also has a high unblocking temperature remanence (500 to 650°C).

Figure 4.10 illustrates an interesting example of RLR magnetization (AF demagnetized) for site VBA (Little Vermillion batholith), where demagnetization circles (equal area net) converge towards a well constrained RLR direction that seems to reside in high coercivities (about 100 mT).

Figure 4.11 shows examples of NRM directions, demagnetization trajectories and the final mean RLG direction for some individual samples from the Howey diorite, the Dome Stock and Dickenson Mine. Paleomagnetic data from Dickenson Mine are considerably scattered. However they are included in the final RLG mean to reinforce the conclusions obtained from the better defined data from Dome Stock and Howey diorite. Dickenson Mine’s RLG-like directions of remanence have been isolated from samples in or adjacent to the ore, and hence the significance of being included in the final mean. They represent the most direct evidence for the presence of a remanence associated with gold mineralization in the Red Lake greenstone belt.
Figure 4.9 Examples of NRM directions and final RLR directions for some individual samples from the batholiths studied. Also orthogonal vector projections (stars and squares: horizontal and vertical projections respectively) for samples HLC-5-2, KBF-3-1-1 and VBB-3-1, plus their corresponding demagnetization curves are shown. These examples show that component RLR is typically not only a high coercivity but also a high blocking temperature remanence (500 to 650°C).
Figure 4.10 Equal area stereographic projection showing AF demagnetization data for site VBA (Little Vermillion Batholith), where demagnetization circles converge towards a well constrained RLR direction that seems to reside in high coercivities (about 100 mT).
Figure 4.11  Examples of NRM directions and final RLG directions for some individual samples from the Howey diorite, the Dome Stock and Dickenson Mine.
TABLE 4.4

COMPONENT RLN UNIT MEAN DIRECTIONS AND VGP
AFTER AF DEMAGNETIZATION

<table>
<thead>
<tr>
<th>UNIT</th>
<th>DEC (°)</th>
<th>INC (°)</th>
<th>N sites</th>
<th>$\alpha_{eq}$ (°)</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD</td>
<td>351</td>
<td>84</td>
<td>4</td>
<td>3</td>
<td>708</td>
</tr>
<tr>
<td>HL</td>
<td>347</td>
<td>70</td>
<td>5</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>VB</td>
<td>348</td>
<td>74</td>
<td>7</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>KB</td>
<td>9.9</td>
<td>76</td>
<td>6</td>
<td>12</td>
<td>23</td>
</tr>
<tr>
<td>TL</td>
<td>321</td>
<td>84</td>
<td>6</td>
<td>13</td>
<td>19</td>
</tr>
<tr>
<td>DS</td>
<td>359</td>
<td>81</td>
<td>6</td>
<td>17</td>
<td>11</td>
</tr>
<tr>
<td>MEAN</td>
<td>352</td>
<td>79</td>
<td>6</td>
<td>4</td>
<td>165</td>
</tr>
</tbody>
</table>

Paleopole 104°W 73°N dp=8° dm=8°

4.3 Discussion

Component RLN

The paleomagnetic pole RLN corresponding to the mean RLN direction falls at 104°W, 73°N (dp=8°, dm=8°), among the probably primary paleopoles for the Kawashe Lake gabbro (normal and reversed), the Dobie Lake Batholith (reversed), the Kawashe Lake Stock (normal and reversed) and the Graniteboss Lake Stock (reversed) in the Meens Lake-Dempster Lake greenstone belt (Hale and Lloyd, 1989), and the primary paleopole for the Otto Stock (normal and reversed) in the Abitibi belt (Pullaiah and Irving, 1975; Buchan et al, 1990) (figure 4.12a). U-Pb zircon ages for all these units range between 2747-2700 Ma (Corfu and Stott, 1989; Corfu et al, 1990). However the low characteristic destructive field of RLN (=10 mT) and its proximity to the direction of the present Earth’s field (PEF) in the Red Lake area (D=5°, I=80°) argue against a Precambrian age for this component.
Figure 4.12a, b Late Archean and early Proterozoic APWP for North America. In 4.12a the redefined APWP includes the 2700 Ma old RLR (this study), the 2600 Ma old primary paleopole OS for the Otto Stock in the Abitibi belt (Pullan and Irving, 1975; Buclan et al., 1990; Corfu et al., 1990; the also primary and = 2700 Ma old paleopoles DR, KGR, KS and GB corresponding to the Duble Lake batholith, the Kawase Lake gabbro, the Kawase Lake Stock and the Grandchamp Lake Stock respectively, all intrusives in the Meen Lake-Döppen Lake greenstone belt (Hale and Lloyd, 1989); the approximately 2580 Ma old Shelley Lake granite (SL1), RLG (this study) and the 2450 Ma old Matchewan dike sub-paleopoles. Also included: RLG (PEP) and Trout Lake (TL) corresponding paleopoles. Open and closed circles are reversed and normal components. Ovals of 95% confidence are indicated for all the poles with the exception of TL and OS. In 4.12b a previous version of the Late Archean and early Proterozoic APWP for North America. The various primary and secondary paleopoles of this curve are: KK, DS, MD, Kamiskotia complex, Dundolled sill, and Matchewan diabase, Ontario (Irving and Naldrett, 1977); OR Ghost Range intrusive complex, Ontario (Geissman et al., 1982); AB, MD2, Abitibi basin primary and Matchewan diabase, Ontario (Schuch and Dunlop, 1981); SMD, MMG, AMG, MMS, SMG, AMG, MMS, primary and secondary magnetizations of Algoman banded iron formations from the Sherman Mine, Moore Mountain Mine, and Adams Mine, Ontario (Symons and Suppavong, 1983; also quoted by Seguin et al., 1983); WB, Wabigoon gabbro, Ontario (Dunlop, 1983a); SK, Stéphanie volcanics, Ontario (Ridler and Foster, 1981); KS, Kinojevis volcanics, Ontario (Geissman et al., 1983); PMa, PMa (ovestran by SL1), reversed and normal polarities, Poodah Lake alkaline complex, Ontario (Dunlop, 1983); SW, SW2, Stillwater complex, Montana, after correction for Laramide tilting (Bergh, 1970; Geissman and Mogk, 1980); CS, Chibougamau sills, Quebec (Ueno and Irving, 1976); SL1, Shelley granite, Ontario, type 1 remanence, Ontario (Dunlop, 1984a); BL1, Burchell Lake granite, Ontario (Dunlop, 1984b); ND, AL, Halleybury diorite and Algoman granite, Quebec (Leedam and Symons, 1976). The Racine and Shawmere A paleopoles (Kapuskasing, Archean), before and after tilt corrections are also shown (Costa and Alvaro and Dunlop, 1988).
In order to test the hypothesis that many of the RLN remanences are geologically recent VRMs, a storage test was carried out on a group of samples from the different batholiths that had univectorial RLN remanences. Figure 4.13 summarizes the results for this storage test in two of these samples, from the Hamell Lake and the Little Vermillion batholiths. In this figure, the VRM acquired in a period of three weeks is compared to the pre-storage direction of remanence after complete AF demagnetization of the NRM. Coercivity spectra for the NRM and VRMs are also compared. Both samples show a strong tendency to acquire VRM.

Destructive fields of less than 20 mT achieve a complete demagnetization of the VRMs in all the samples for which the storage test was performed, except for VBC-4-2. In this sample, the VRM seems to reside partly in the small fraction of single-domain magnetite or hematite evidenced by the "hard tail" in the AF demagnetization curve. This test confirms that RLN, in these samples at least, is a young viscous overprint.

The three weeks period used in this storage test proves to be a good approximation to a real geological situation of VRM acquisition since it can be demonstrated that the interval of time in which the VRM is acquired does not seem to affect considerably the median destructive field at which such a VRM is demagnetized. In fact, from the equation that describes relaxation time of an assemblage of magnetic grains with equal shape and volume in an external field $H_0$ (Néel, 1955):

$$\ln \frac{\tau}{\tau_0} = \frac{VM_{50}H_{ko}}{2kT_0}$$

where

- $\tau$ is relaxation time
- $\tau_0$ is the atomic reorganization time = $10^{10}$ s
- $M_{50}$ is spontaneous magnetization at room temperature
- $V$ is the volume of the magnetite grains
- $T_0$ is the room temperature
- $k$ is the Boltzman constant
- $H_{ko}$ is the microscopic coercive force at room temperature,

it can be found, assuming $V = 300$ Å and $M_{50} = 500$ emu/cm$^3$, that:
\( H_{ko} = 15 \text{ mT for } \tau = 10 \text{ s and } \ln \frac{\tau}{\tau_0} = 25 \)

\( H_{ko} = 23 \text{ mT for } \tau = 3 \text{ weeks and } \ln \frac{\tau}{\tau_0} = 38 \)

\( H_{ko} = 33 \text{ mT for } \tau = 700000 \text{ year (Brunhes epoch) and } \ln \frac{\tau}{\tau_0} = 54. \)

The fact that the characteristic magnetic phase for these granitic samples seems to be multidomain magnetite explains why soft RLN is the most commonly found paleomagnetic component for Red Lake (chapter 5). There are some exceptions in which RLN shows unusually high median destructive fields (=65 mT), but in order to avoid any possibility of misinterpretations, every sample showing a RLN-like direction of remanence was considered to be a PEF-overprinted sample.

**TABLE 4.5**

**COMPONENT RLR UNIT MEAN DIRECTIONS AND VGP AFTER AF DEMAGNETIZATION**

<table>
<thead>
<tr>
<th>UNIT</th>
<th>DEC (°)</th>
<th>INC (°)</th>
<th>N sites</th>
<th>( \alpha_{95} ) (°)</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>HL</td>
<td>132</td>
<td>-77</td>
<td>4</td>
<td>24</td>
<td>8</td>
</tr>
<tr>
<td>VB</td>
<td>205</td>
<td>-66</td>
<td>5</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>KB</td>
<td>215</td>
<td>-77</td>
<td>4</td>
<td>15</td>
<td>22</td>
</tr>
<tr>
<td>MEAN</td>
<td>191</td>
<td>-76</td>
<td>3 units</td>
<td>13</td>
<td>41</td>
</tr>
<tr>
<td>TL</td>
<td>112</td>
<td>-58</td>
<td>2</td>
<td>-</td>
<td>12</td>
</tr>
</tbody>
</table>

Paleopole (TL is not included)

<table>
<thead>
<tr>
<th>Paleopole</th>
<th>73°W</th>
<th>76°N</th>
<th>dp=22°</th>
<th>dm=24°</th>
</tr>
</thead>
</table>

Paleopole TL

<table>
<thead>
<tr>
<th>Paleopole TL</th>
<th>171°W</th>
<th>42°N</th>
<th>dp=31°</th>
<th>dm=42°</th>
</tr>
</thead>
</table>

Component RLR: Hamell Lake, Little Vermillion and Killala Baird Batholiths

The paleomagnetic pole corresponding to the mean RLR direction where only VB, KB and HL
Figure 4.13 Summary of results of a storage test performed on two samples from the Hamell Lake and Little Vermillion batholiths carrying component RLN. The VRM acquired in a period of three weeks at room temperature along the direction of the PEF is compared to the pre-storage direction of remanence after complete AF demagnetization of the NRM. Coercivity spectra for the NRM's and VRM's are also compared.
unit means have been taken into account in calculating the final average, falls at 73°W, 76°N (dp=22, dm=24), close to RLN and among the ≈2740-2700 Ma paleopoles for the Otto Stock and the Meens Lake-Dempster Lake greenstone belt intrusives (Hale and Lloyd, 1989; Pullaiah and Irving, 1975; Buchan et al, 1990, Corfu and Stott, 1989; Corfu et al, 1990) (figure 4.12a).

Relatively high MDFs for RLR (peaks at = 30 and 100 mT, figure 4.4b and c) make more promising the hypothesis that this component has survived from Precambrian times. Its sporadic occurrence when compared to RLN reflects the preference of this component for residing in high coercivity and high unblocking temperature magnetic phases, which are relatively rare in these granites.

Provided that RLR is a primary thermal remanent magnetization (TRM) acquired when intrusion of the granitoid batholiths took place, then it is possible to place this component in the framework of the 40Ar/39Ar and U/Pb preliminary cooling curves obtained for the Red Lake region (McMaster, 1987; Wright, 1989), which predict a relatively rapid initial regional cooling at ≈2700 Ma at a rate between 40 and 25°C/Ma (McMaster, 1987) (figure 4.14a).

As can be observed in figure 4.14a, an age of 2700 Ma for RLR implies that it was acquired at temperatures of ≈550°C. This result agrees with the median magnetic unblocking temperatures obtained for this component which are close to the Curie point of magnetite, namely 580°C. A detailed study of the magnetic petrology of the Red Lake samples is described in chapter 5 in order to demonstrate that RLR is indeed a TRM acquired during the initial cooling of the batholiths that intruded the supracrustal sequences in the Red Lake region, thus justifying the age calibration of component RLR using the 40Ar/39Ar cooling curves.

The inferred age of ≈2700 Ma for this component leads to some interesting considerations. First, component RLR would represent the oldest 40Ar/39Ar age-calibrated paleopole for North America, and secondly, the position of this paleopole on a segment of the APWP far away from the group of paleopoles with ages nominally around 2700 Ma, would redefine the sense of the late Archean-early Proterozoic APWP for North America in the opposite direction (figure 4.12a) to that previously accepted (figure 4.12b). A more detailed discussion on this re-defined Late Archean - Early Proterozoic APWP follows at the end of this chapter.
Figure 4.14a, b Preliminary $^{40}\text{Ar}/^{39}\text{Ar}$ cooling curves obtained for the Red Lake region (McMaster, 1987; Wright, 1989), which record a relatively rapid initial regional cooling at $\approx 2700$ Ma at a rate between 40 and 25$^\circ$C/Ma (McMaster, 1987: 4.14a), followed by a slow cooling ($\approx 0.5^\circ$C/Ma) "tail" that extends to approximately 2570 Ma (Wright, 1989: 4.14b). The $a$ values correspond to different grain sizes of biotite. According to these curves, component RLR, if primary, would represent a remanence acquired 2700 Ma ago during emplacement of the Red Lake batholiths at a temperature of about 540$^\circ$C. On the other hand, the TCRM component RLG was probably acquired at temperatures as low as 260$^\circ$C approximately 2580 Ma ago.
Component RLR: Trout Lake batholith

The virtual geomagnetic pole (VGP) corresponding to the steep up component found in the Trout Lake batholith lies far away from any known segment of the Precambrian APWP of North America at 171°W, 42°N (dm=42°, dp=31°) (figure 4.12a).

The Trout Lake RLR-like component shows high Tm’s and coercivities within the same range as its RLR counterparts in the rest of the batholiths and may represent a rotated RLR. A major counterclockwise rotation (≈79°) of this batholith around an almost vertical axis, postdating RLR acquisition and probably related to the last period of shearing and intense deformation of the supracrustal sequences of the Red Lake greenstone belt, could explain the directional results for Trout Lake. However, there is no concrete geological evidence that supports such an hypothesis. There is no paleomagnetic evidence to suggest that the other batholiths were significantly affected by similar rotations. On the other hand, it is difficult to believe that secular variation of the Precambrian Earth’s magnetic field about an average paleopole or apparent polar wander could be completely responsible for paleolatitude deviations as high as 30°, as apparently recorded by TL’s RLR-like VGP.

Combined structural, petrographic and isotopic data relate the intrusion of the Trout Lake batholith to at least two well defined tectonic phases in the geological history of the belt (Corfu and Andrews, 1987). A phase taking place at ≈2720-2710 Ma and responsible for much of the alteration, deformation and metamorphism in the eastern and northwestern sections of the belt, is directly related to the formation of the bulk of the Trout Lake batholith (Corfu and Andrews, 1987). The marginal part of this batholith could have been formed during a concluding tectonic phase that occurred at ≈2705-2700 Ma and was also associated with the emplacement and crystallization of the Killala Baird batholith (Corfu and Andrews, 1987).

Noble (1989) has pointed out, on the basis of his recently reported U/Pb data for the Trout Lake batholith, that the bulk of this intrusive body was the result of different tonalitic intrusions starting at ≈2838 Ma and spanning a period of ≈32 Ma. Renewed granitic activity took place ≈107 Ma later at ≈2699 Ma (U/Pb zircon and sphene age, Noble, 1989) with the intrusion of the Walsh Lake phase (western margin of the Trout Lake batholith) from which all the samples used in this
paleomagnetic study come. This phase coincides with the cessation of plutonic activity in the Red Lake belt.

Although the geological history of the Trout Lake batholith spans a long period of intermittent igneous activity (=140 Ma), the history of the Walsh Lake phase seems to be rather simple in the light of the U/Pb data. However, recent \(^{40}\text{Ar}^{39}\text{Ar}\) analyses of small and intermediate-sized hornblende grains of a granodiorite from the Walsh Lake phase (Wright and York, 1990) have revealed the occurrence of a post-orogenic thermal pulse that took place about 2655 Ma ago. Providing that such a thermal pulse was restricted only to the Walsh Lake phase, then it could be a reasonable explanation for the anomalous position observed for the Trout Lake RLR-like corresponding paleopole.

**Component RLG: Dome Stock, Howey diorite and Dickenson Mine**

Unlike the other units studied, the Dome Stock, Howey Diorite and the Dickenson mine are located in the central region of the Red Lake belt where the bulk of contact metamorphism, shearing stress, deformation and intense hydrothermal alteration are concentrated. The corresponding paleopole for their characteristic RLG magnetization falls at 85°E, 77°N (dp=3°, dm=4°) (table 4.6 and figure 4.12a).

In addition, the central region of the Red Lake belt is transected by local shear zones which host the gold producing deposits (Corfu and Andrews, 1987). One of these deformation zones, the Flat Lake-Howey Bay (figure 4.1), is especially important since it significantly affected the 2718 Ma Dome Stock and ceased by the time of the Howey diorite dike intrusion =2699 Ma ago. The shearing of this deformation zone also seems to have been active during thermal metamorphism related to the nearby Killala Baird batholith (Andrews et al, 1986; Corfu and Andrews, 1987).

Thus, component RLG could be a magnetic overprint acquired during activity on the Flat Lake-Howey Bay deformation zone and the intrusion of HD. If this is the case, then this component should be included in the final average of 2700 Ma old component RLR. However, the proximity of the RLG paleopole to the well dated group of =2580 Ma paleopoles, especially that from the Shelley Lake granite (Dunlop, 1984a) and the tight grouping of the RLG directions of remanence, whose final average \(\alpha_9\) confidence circle does not overlap with its RLR counterpart, do not seem to be fortuitous consequences of the secular variation of the Earth's magnetic field. In fact, detailed
petrographic and rock magnetic analyses for samples carrying either RLR or RLG components (chapter 5) suggest that they should be considered as independent magnetizations.

If RLG is a chemical or thermochemical remanence associated with hydrothermal alteration in the central region of the Red Lake belt, then it seems quite sensible to assign to this component an age lower than 2700 Ma (figure 4.14a). Thus, component RLG could date either from the time of the 2655 Ma post-orogenic thermal pulse recently reported by Wright and York (1990), or from the latest stages of hydrothermal alteration in the belt corresponding to the <2600 Ma tail of the Red Lake cooling curve (Wright, 1989). The first possibility seems less likely since an age of ~2655 Ma for RLG would imply an unusually high (=6.5 cm/yr) drift velocity for Laurentia between 2700 and 2655 Ma.

Although it is possible to have the same paleopole location at different times, the simplest explanation of the coincidence of the RLG and SL1 (Shelley Lake granite primary remanence) paleopoles is that they represent the same time of magnetizing, namely 2580 Ma (Dunlop, 1984a; Berger and York, 1979). If this is the case, then a temperature of about 260°C for the thermochemical acquisition of RLG could be "read" from the "tail" of the Red Lake cooling curve (figure 4.14b; Wright, 1989). Such a temperature agrees with the thermal conditions under which low-grade regional metamorphism occurs, accompanied by intense chloritization of the biotites, as tested in the analysis of thin sections (chapter 5).

**TABLE 4.6**

**COMPONENT RLG UNIT MEAN DIRECTIONS AND VGP AFTER AF DEMAGNETIZATION**

<table>
<thead>
<tr>
<th>UNIT</th>
<th>DEC (°)</th>
<th>INC (°)</th>
<th>N sites</th>
<th>α_{95} (°)</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD</td>
<td>185</td>
<td>-59</td>
<td>2</td>
<td>-</td>
<td>34</td>
</tr>
<tr>
<td>DS</td>
<td>180</td>
<td>-57</td>
<td>3</td>
<td>24</td>
<td>11</td>
</tr>
<tr>
<td>DM</td>
<td>176</td>
<td>-56</td>
<td>4</td>
<td>34</td>
<td>4</td>
</tr>
<tr>
<td>MEAN</td>
<td>180</td>
<td>-58</td>
<td>3 units</td>
<td>3</td>
<td>902</td>
</tr>
</tbody>
</table>

Paleopole | 85°E 77°N dp=3° dm=4°
Late Archean - Early Proterozoic Apparent Polar Path of Laurentia

As indicated before, RLR and RLG paleopoles suggest a re-definition of the late Archean - early Proterozoic APWP for Laurentia (figure 4.12a). The problem of a re-definition of this path has been addressed only in the last two years.

U/Pb data on baddeleyite (ZrO\textsubscript{2}) and zircon (Heaman, 1988) and U-Th-Pb data on whole rocks (Smith and Farquhar, 1988) for Matachewan-Hearst dike swarms have given ages of 2454 and 2480 Ma respectively, thus casting serious doubts on the previously accepted direction of the Precambrian APWP of Laurentia. Much of the presently accepted characterization of the late Archean and early Proterozoic APWP has been based on the pivotal MD paleopole (Irving and Naldrett, 1977; Schutts and Dunlop, 1981; Ernst and Halls, 1984; Halls and Shaw, 1988) which derives from the primary TRM for these dikes, with a Rb/Sr age of 2690 +/- 91 Ma (Gates and Hurley, 1973). These new U/Pb Matachewan ages would imply a complete change in the direction of the APWP, namely aging from Asia to North America and going through the North Pole (figure 4.12a) instead of in the opposite sense as currently accepted (figure 4.12b). Also, paleopoles corresponding to the probably primary magnetic remanences of the Kawashe Lake gabbro (normal and reversed), Dobie Lake Batholith (reversed), Kawashe Lake Stock (normal and reversed) and Graniteboss Lake Stock (upwards), located in the Meens Lake-Dempster Lake greenstone belt (northwestern Superior province) and with U-Pb zircon ages ranging between 2747-2720 Ma (Corfu and Stott, 1989), have been recently reported by Hale and Lloyd (1989) (figure 4.12a). None of these paleopoles is consistent with the Archean APWP of Laurentia as it is conventionally drawn; however, they lie close to the RLR paleopole. Moreover, a positive baked contact test for the remanence of a Matachewan dike that intrudes the Otto stock (Abitibi belt, Superior Province) has proved that the steep down magnetization carried by the stock, which resembles closely, but with opposite polarity, the RLR direction of remanence, must be significantly older than the dike itself (Buchan et al, 1990). In fact, a very recent U/Pb zircon age for the stock (Corfu et al., in press) reveals that this remanence, probably primary and once believed to be = 2114 Ma (Rb/Sr, Bell and Blenkinsop, 1976), should be rather = 2680 Ma. In order to explain these results, the conventional APWP (figure 4.12b) that decreases in age from the Matachewan paleopoles to the Otto stock paleopole has to be reversed, younghost from the Otto stock to the Matachewan paleopole.
Consequently, the group of paleopoles that was believed to represent the Archean segment of the path, southeast of the paleopole MD, is now controversial. Most of these paleopoles have been indirectly dated using U/Pb and Rb/Sr ages for samples from locations that differ from the ones where the paleomagnetic studies were performed, and probably the NRM's are not even primary after all. Problems inherent to the differences between magnetic and isotope diffusion temperatures, slow cooling, retrograde metamorphism and chemical alteration have not been taken into account in most cases when radiometric ages were assigned to these paleopoles. Also it is not known to what extent these supposed late Archean paleopoles represent the entire Canadian Shield or just the history of the individual craton from which most of the data come.

There is also the problem that some of these "Archean" paleopoles are based on very scanty data. With the exception of paleopole KK (Irving and Naldrett, 1977) for the Kamiskotia gabbro, which has been considered an unbaked remanence older than Matachewan primary remanence after a positive contact test performed on a Matachewan dike intruding the gabbro (but with no evidence for a hybrid zone of progressive swing from MD-like direction towards KK-like direction in the contact aureole), the Archean ages assigned to the other paleopoles seem to be arguable or at least poorly justified. In fact, there is evidence for a magnetic overprint of Keweenawan age in some units within or surrounding the Abitibi belt (Geissman et al., 1982; Costanzo-Alvarez and Dunlop, 1988) that resembles in direction the remanences from which these supposedly Archean paleopoles are derived. This Keweenawan remanence seems to have also overprinted Matachewan dikes in the Wawa subprovince in northcentral Ontario (H.C. Halls, personal communication). Hence a similar direction of remanence recently isolated by Vandall and Symons (1989) in the northern and eastern external granitic terrane in the Michipicoten Belt and the Baldhead river quartz monzonite may be also been a Keweenawan overprint. Vandall and Symons, however, have interpreted this direction of remanence as a late Archean magnetization in an attempt at reconciling the previously accepted early Precambrian APWP of Laurentia with the new ages for the Matachewan dikes. An alternative explanation to the position of these supposedly 2700-2600 Ma old paleopoles (figure 4.12b) has been suggested by Hale (1985) who points out that, since all these remanences were acquired at low latitudes, track 6 could be also explained by a rotation of Laurentia, or local block rotations, around a vertical axis.

The important conclusion that can be drawn from this discussion is that the small interval of the
early Proterozoic APWP for North America that connects the $=2580$ Ma group of paleopoles (including Shelley Lake 1 and Kapuskasing rotated paleopoles) and the $=2450$ Ma MD paleopoles, can be regarded as a reliably age-calibrated interval of the Precambrian path (figure 4.12a). In such a framework, paleopole RLR would extend this segment of the path back into the late Archean (2700 Ma) together with the $=2700$ Ma old paleopoles for the Otto Stock (OS) in the Abitibi belt (Pullaiah and Irving, 1975; Buchan et al, 1990; Corfu et al, 1990) and some intrusive bodies (KS, GB, KGR and DB) in the Meens Lake-Dempster Lake greenstone belt, northwestern Ontario (Hale and Lloyd, 1989) (figure 4.12a).

The position of the western Superior Province at the different periods during the closing of the Archean and beginning of the Proterozoic can now be estimated from this redefined APWP. Using the method of Irving (1964, p. 186) and a reference point situated at the centre of the western Superior Province, just north of Lake Nipigon close to the village of Armstrong (52°N, 88.5°W), three different positions of the Superior Province are calculated for the period between 2700-2450 Ma. These paleogeographic positions, along with the amount of rotation with respect to the present position of the Superior Province and the drift velocities in °/Ma, are shown in table 4.7 and figure 4.15.

### TABLE 4.7

**DRIFT HISTORY OF THE SUPERIOR PROVINCE**

<table>
<thead>
<tr>
<th>AGE (Ma)</th>
<th>Plat. (°)</th>
<th>Plon. (°)</th>
<th>$\lambda_r$ (°)</th>
<th>$\phi$ (°)</th>
<th>$d\lambda_r/dt$ (°/Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2700</td>
<td>76N</td>
<td>73W</td>
<td>65</td>
<td>-9</td>
<td></td>
</tr>
<tr>
<td>2580</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SL1</td>
<td>78N</td>
<td>66E</td>
<td>41</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>RLG</td>
<td>77N</td>
<td>85E</td>
<td>39</td>
<td>-2</td>
<td>0.21</td>
</tr>
<tr>
<td>2450</td>
<td>45.5N</td>
<td>65E</td>
<td>10</td>
<td>-17</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Coordinates for the reference locality: 88.5°W, 52°N

$\lambda_r$ = Reference paleolatitude

$\phi$ = amount of rotation with respect to the present orientation of the western Superior Province.

$d\lambda_r/dt$ = corresponding drift velocity between two periods.
Figure 4.15  The position of the western Superior Province at different times at the close of the Archean and the beginning of the Proterozoic. These positions are derived from the redefined APWP for North America (figure 4.12a) and using the method of Irving (1964, p.186) with a reference point situated at the centre of the western Superior Province, just north of Lake Nipigon close to the village of Armstrong (52°N, 88.5°W).
Using a mean radius of the Earth of $6.371 \times 10^6$ m, the drift velocities are recalculated as:

2.3 cm/yr for the period between 2700-2580 Ma

2.6 cm/yr for the period between 2580-2450 Ma

These velocities are compatible with average Precambrian drift velocities of $\approx 2$ cm/yr calculated for other continents such as Fennoscandia (Pesonen et al, 1989) but are in contrast with early estimates based on the old definition of the APWP, which required rates of latitude change for Laurentia in the Precambrian of $\approx 4.5$ cm/yr, over twice as great as in the Phanerozoic ($\approx 1-1.5$ cm/yr) (Irving, 1979).

4.4 Conclusions

Judging from the high coercivities ($\geq 30$ mT) and laboratory unblocking temperatures ($>500^\circ$C) of RLR, along with the pristine appearance of the euhedral opaque crystals examined in thin sections, it is believed that this component is a primary TRM acquired at about 2700 Ma when initial regional cooling of the primary magmas that gave rise to the Hamell Lake, Killala Baird and Little Vermillion batholiths took place, as predicted by preliminary hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ and zircon and sphene U/Pb ages (McMaster, 1987; Corfu & Andrews, 1987).

On the other hand, a high coercivity ($\geq 40$ mT) and unblocking temperature ($\geq 500^\circ$C) component RLG was isolated in samples from the Dome Stock, the Howey diorite and the Dickenson Mine, which are in the deformation zones and are gold-bearing. This component is believed to be an early Proterozoic chemical or thermochemical remanence acquired during the latest stages of regional hydrothermal alteration ($\approx 2580$ Ma) and gold mineralization. A temperature of acquisition for this component is suggested to be about $260^\circ$C from the "tail" of the $^{40}\text{Ar}/^{39}\text{Ar}$ cooling curve for Red Lake as modified by Wright (1989).

The paleopoles for RLR (2700 Ma) and RLG (2650 Ma) follow a sequence in the northern hemisphere that also includes paleopoles for the Shelley Lake granite (2580 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende and biotite) and the Matachewan/Hearst dikes (2450 Ma, U/Pb zircon and baddeleyite, 2480 Ma U/Pb isochron). This sense of motion on the late Archean-early Proterozoic APWP for Laurentia is
opposite to that previously accepted, but is supported by new paleomagnetic results of other workers.

This redefined late Archean-early Proterozoic APWP for Laurentia also suggests a rate of paleolatitudinal change of \( \approx 2.5 \, \text{cm/yr} \), which is less than previous estimates of \( \approx 4-5 \, \text{cm/yr} \) (Irving, 1979) for Laurentia but agrees with those calculated for other Precambrian cratons such as Fennoscandia (Pesonen et al, 1989) at about the same period.
CHAPTER 5

MAGNETIC PETROLOGY OF THE RED LAKE SAMPLES

5.1 Introduction

The main conclusions of chapter 4 were based on the assumption that, in spite of directional similarities between components RLR and RLG, the former is a thermal magnetic remanence (TRM) dating from the time of initial rapid cooling of the Red Lake belt (=2700 Ma), whereas the latter is a chemical or thermochemical magnetization associated with the final stages of hydrothermal alteration in the region that ended with gold mineralization (=2580 Ma). A way for discriminating between the nature and origins of these two components is necessary in order to test this hypothesis.

A first characterization of components RLN, RLR and RLG is described in chapter 4, using the information given by NRM intensity decay curves, storage tests and histograms of median destructive fields (MDFs) (figure 4.4). From these analyses it was concluded that RLN was, in most cases, a soft component residing in low-coercivity and low-unblocking-temperature magnetite (probably a PEF overprint), in contrast with the higher-coercivity and higher-unblocking-temperature components RLR and RLG. Unfortunately it was not possible to establish, on the same grounds, a clearcut distinction between components RLR and RLG, which have overlapping MDF histograms and similar steep up directions of remanence. Moreover, it was also impossible to test the TRM nature of RLR and the CRM nature of RLG.

There is no straightforward way of proving whether a paleomagnetic component is purely a TRM, a CRM, or a combination of both. A positive contact test certainly suggests a primary thermal nature of the NRM in an intrusive rock. However the Red Lake units do not always show clear contacts, and in some instances, for example, the large batholiths of the Red Lake belt, the few clear contacts exposed are within the highly altered supracrustal units, whose primary remanences have been completely obliterated by later overprints.
A positive Thellier test (Thellier and Thellier, 1959), in which NRM and laboratory TRM are compared in companion heating steps that span the whole range of unblocking temperatures, is an alternative way of testing for the thermal nature of a paleomagnetic component. However, this kind of test is extremely laborious, and furthermore there is no guarantee of successful results in multicomponent or very weakly magnetized samples (L.J. Pesonen, personal communication) such as RLR samples overprinted by RLN, or weakly magnetized RLG samples.

An alternative approach to the problem of distinguishing between chemical and thermal remanences in multicomponent NRMs is by looking at the shapes and kinks of Zijderveld plots (McClelland-Brown, 1982) to determine whether or not the components' unblocking-temperature spectra overlap. However, in most cases this method proves ambiguous, especially in very old samples whose remanences are noisy and consequently whose different components in a Zijderveld plot are not well resolved. Furthermore, by this approach only the overprints can be diagnosed.

A detailed but qualitative magnetic characterization of the Red Lake samples is described in this chapter in order to establish a correlation between magnetic petrology and the different magnetic components. The goal of this study was to gain more insight into the nature and origin of components RLR and RLG.

5.2 Magnetic characterization of the Red Lake samples

A rock magnetic study was conducted on typical single component samples carrying RLN, RLR and/or RLG from both unaltered and altered units of the Red Lake Belt. In a first attempt to characterize the magnetic mineralogies of altered and unaltered samples initial volume susceptibility ($k_v$) was measured on an AC bridge for about 200 specimens. The Königsberger $Q_v$ ratio, $Q_v = M_{nrm}/k_v H$ for $H=0.6$ Oe, was calculated for each sample. Results are plotted in figure 5.1 in the form of an NRM vs. $k_v$ diagram. $Q_v$ values can be read off with reference to the labelled diagonal lines of constant $Q_v$. The samples have broad ranges of both $k_v$ and NRM, spanning more than three orders of magnitude. However there is a clear tendency of these data to group with susceptibilities in the range of 100 to 1000 x $10^4$ emu/cm$^3$, NRMs between 10 and 100 x $10^4$ emu/cm$^3$, and $Q_v$ values between 0.10 and 10. More than 50% of the collection shows multidomain
Figure 5.1 $M_{\text{REOM}}$ vs. $k_v \times 0.6$ diagram for about 200 samples from all the units studied in the Red Lake greenstone belt. Initial volume susceptibility ($k_v$) has been measured using an AC bridge. The Köhler'sberger $Q_v$ ratio $Q_v = M_{\text{REOM}}/k_v H$ for $H = 0.6$ Oe, was calculated for each sample. $Q_v$ values can be read off with reference to the labelled diagonal lines of constant $Q_v$. 
magnetite characteristics, namely low $Q_\alpha$ values (<1) and high susceptibilities. However a considerable number of samples from the altered Dome Stock and the apparently fresh Trout Lake batholith have, along with their low NRM$s$ and $Q_\alpha$ values, low susceptibilities as well. This trend, which can be attributed to the presence of hematite or to a low magnetite concentration, is observed in only a few samples from the altered Howey diorite. Samples with $Q_\alpha$ values higher than 1 and NRMs ranging from 1 to $1000 \times 10^4$ (stable single or pseudo-single domain magnetite behaviour) are probably the ones that carry most of the primary Precambrian remanences. However, a dominant multidomain magnetite fraction seems to account for susceptibility in all samples, hence the shift of the data towards a restricted range of high $k_\alpha$ values. Felsic intrusives like the Red Lake granites generally owe their remanences to discrete MD opaques, as indicated by their usually soft viscous magnetization. In fact, in most cases the constituent potassium and sodium feldspars of granitic rocks do not contain magnetic inclusions responsible for the intense and hard NRM’s observed in mafic and intermediate intrusives (e.g. Dunlop, 1983b; Dunlop et al, 1984).

Acquisition curves for saturation isothermal remanent magnetization (SIRM) and the corresponding AF demagnetization spectra were obtained for some representative samples from the altered and unaltered units, carrying components RLN, RLR or RLG. These curves are shown in figures 5.2 to 5.3. Samples from the non-altered zone (Red Lake granites) carrying component RLN (figure 5.2a and b) show a general tendency for a rapid initial acquisition of the remanence and an exponential decay of the SIRM upon AF demagnetization. The same behaviour is observed in RLN samples from the altered zone (DS and HD, figure 5.2 c and d) and is indicative of a predominantly multidomain magnetite fraction, apparently independent of the rock type, with which component RLN seems to be associated.

From the analysis of initial susceptibilities and $Q_\alpha$ values, multidomain magnetite fractions seem to be present in all samples. Hence even those specimens that retain Precambrian remanences (components RLR and RLG) show, in most cases, the typical multidomain behaviour of rapid acquisition of a saturation remanence and an exponentially decaying AF demagnetization spectrum (figure 5.3 a-f). This behaviour does not discriminate between samples from the altered and non-altered units, perhaps because multidomain magnetite is less prone to alteration than fine-grained magnetite. The ability of these samples to retain Precambrian components is probably due to the presence of a small fraction of single-domain magnetite or hematite, completely undetected by the analysis of the SIRM acquisition and AF demagnetization curves.
Figure 5.2a, b, c, d  Saturation isothermal remanent magnetization (SIRM) acquisition curves (5.2a & 5.2c) and the corresponding AF demagnetization spectra (5.2b & 5.2d) for samples carrying component RLN from both the non-altered (5.2a & 5.2b) and altered supracrustal units (5.2c & 5.2d).
Figure 5.3a, b, c, d, e, f: Saturation isothermal remanent magnetization (SIRM) acquisition curves (5.3a, 5.3c & 5.3e) and the corresponding AF demagnetization spectra (5.3b, 5.3d & 5.3f) for samples carrying components RLR and RLG from both the non-altered (5.3a & 5.3b) and altered supracrustal units (5.3c & 5.3d) including Dickenson Mines samples (5.3e & 5.3f).
A few RLR and RLG samples show slow continuing remanence acquisition that does not reach saturation at 100 mT, and have a hard response to AF demagnetization. These are typical indicators of dominant fractions of pseudo-single-domain or single-domain magnetite and/or hematite. Examples like these are completely absent in all the RLN samples analysed.

Analyses of initial susceptibilities, Königsberger ratios, SIRM acquisition curves and SIRM AF demagnetization spectra provide some general information about the nature of the magnetic mineralogies of the Red Lake samples, but they do not seem to be sensitive in characterizing either different rock units or Precambrian components RLR and RLG. It is clear from these rock magnetic analyses and the discussion of chapter 4 that RLN can be properly characterized as a viscous component that resides mainly in multidomain magnetite fractions of both altered and non-altered samples.

In general, component RLG is weaker (i.e. less intense) than RLR. Such a weakness could be a symptom of its inferred chemical nature. The orthogonal vector projections of figures 5.4-5.8 show examples of these differences of intensities for some characteristic samples from both the unaltered batholiths (RLR, figures 5.4-5.6) and the altered units (RLG, figures 5.7-5.8). A careful graphical calculation of these intensities of magnetization has been carried out using these vector projections. In those cases where the spectrum of coercivity or unblocking temperatures of a secondary soft magnetization partially overlaps that of either RLR or RLG, the linear segments corresponding to each component are extrapolated over the hybrid range of coercivities (or unblocking temperatures). The lengths of the projections for RLR or RLG on the orthogonal planes have been measured from the intersection of these extrapolated lines to the origin (Dunlop, 1979).

These analyses reveal that the intensity of the high coercivity and unblocking temperature RLR magnetization ranges from approximately 40 to 4500 mA/m for samples from the Little Vermillion (figure 5.4), Hamell Lake (figure 5.5) and Killala Baird (figure 5.6) batholiths, whereas the intensity of RLG ranges from values as low as 3 mA/m up to approximately 300 mA/m for samples from the Howey diorite (figure 5.7), Dome Stock (figure 5.8a) and Dickenson Mine (figure 5.8b). Thus the whole range of intensities for RLG seems to be at least one order of magnitude lower than that for RLR.
Figure 5.4a, b Orthogonal vector projections of magnetization in the course of AF (5.4a) and thermal (5.4b) demagnetization for two samples from sites VBA and VBB in the Little Vermillion batholith.

Calculated intensities for component RLR are ≈4460 mA/m for VBB-4-2 and ≈120 mA/m for VBA-5-3.
Figure 5.5a, b Orthogonal vector projections of magnetization in the course of AF demagnetization for two samples from sites HLB (5.5a) and HLC (5.5b) in the Hamell Lake basalt. In 5.5b the spectrum of coercivities of a secondary soft magnetization partially overlaps that of RLR; the linear segments corresponding to each component have been extrapolated over the hybrid range. The lengths of the projections for RLR on the orthogonal planes have been measured from the intersection of these extrapolated lines to the origin (Dunlop, 1979). Calculated intensities for component RLR are ~430 mA/m for HLC-5-1 and ~125 mA/m for HLC-5-3.
Figure 5.6a, b  Orthogonal vector projections of magnetization in the course of AF demagnetization for a sample from site KBD in the Killala Baird batholith. Calculated intensity for the RLR-like component in this sample is \( \approx 40 \, \text{mA/m} \).
Figure 5.7a, b: Orthogonal vector projections of magnetization in the course of AF demagnetization for two samples from sites DSD (5.7a) and DSC (5.7b) in the Dome Stock. In both samples the spectrum of coercivity of a secondary soft magnetization partially overlaps that of RLG; the linear segments corresponding to each component have been extrapolated over the hybrid range. The length of the vertical projection of RLG has been measured in 5.7a from the intersection of these extrapolated lines to the origin (Dunlop, 1979), in the horizontal projection no distinction between both components can be observed therefore RLG length is measured from the intersection value derived from the vertical projection. In 5.7b a maximum length of the RLG is measured from the furthest hybrid point to the origin. Calculated intensities for component RLG are $290 \text{ mA/m}$ for DSD-4-1 and $3 \text{ mA/m}$ for DSC-2-3-1.
Figure 5.8a, b Orthogonal vector projections of magnetization in the course of AF demagnetization for two samples from sites HDA (5.8a) and DMD (5.8b) in the Howey dome and Dickensson Mnt. For sample HDA-4-2 component RLG, although stable in direction, underwent apparent fluctuations as a result of its low intensity. As a rough estimate, RLG intensities must be <100 mA/m for this sample. In the case of sample DMD (5.8b), on the other hand, calculated intensity for the RLG-like component is ~290 mA/m.
5.3 Analysis of thin sections

Thin section analyses under transmitted and reflected light reveal petrological differences between batholith samples (VB, HL, KB and TL) and samples from the altered zones (HD, DS and DM). The most striking feature of the batholith samples is their freshness. Opaque minerals are in general euhedral and pristine, probably primary phases dating from the time of initial cooling of the original magma that gave rise to these large granitoid bodies. There is almost no evidence of alteration or metamorphism in spite of their age.

There is also evidence for the presence of hematite in these batholiths. However, the freshness of the samples precludes the possibility that this hematite could be a late, low-temperature by-product of alteration. As in the case of the magnetites, they also probably date from the time of initial cooling of the original magma since oxidation of magnetite to hematite usually takes place during initial cooling of an igneous rock, at temperatures of 600 to 1000°C (Carmichael, 1982). Biotites associated with euhedral opaque minerals may also have formed deuteronally. In some instances hematite shows lens-like inclusions of ilmenite lamellae. It is believed that the oxidation of magnetite to hematite plus ilmenite inclusions took place soon after emplacement of these batholiths since the average cooling rate of \(-30°C/Ma\) (McMaster, 1987) was slow enough to allow for all these processes to reach completion, leading to the formation of hematite during cooling. Some of the hematite could also have crystallized from the original magma, as commonly occurs in acidic magmas that are poor in ferrous ions (Deer et al, 1982).

In contrast to the batholith samples, thin sections for the altered units (Dome Stock and Howey diorite), carrying component RLG and located in the central part of the Red Lake belt where the bulk of metamorphism, deformation and hydrothermal alteration occurred, show high alteration and almost complete obliteration of original mineralogies.

The following figures summarize the magnetic petrology of the Red Lake samples showing examples of the most characteristic cases observed throughout the whole collection. Photomicrographs in figures 5.9-5.13 show examples of pristine magnetic mineralogies for VB, TL and HL batholith samples. Photomicrographs in figures 5.14-5.16 show examples of hematite in samples from
VB, HJ, and KB. Finally figures 5.17 and 5.18 show photomicrographs of altered samples from the Dome Stock (DS) and Howey diorite (HD).
Figure 5.9a, b  Reflected light photomicrographs of fresh euhedral magnetite crystals are shown in figures 5.9a and b. These pictures come from a thin section from site VBA in the Little Vermillion batholith.
Figure 5.10a, b, c A transmitted light plane-polarized photomicrograph for a sample from the Hammell Lake batholith (site HLB), shows a cluster of probably primary opaque minerals in quartz (5.10a). A higher magnification reflected light photomicrograph of the same image in figure 5.10b reveals euhedral magnetite or titanomagnetite crystals. Another euhedral titanomagnetite crystal from the same sample is shown in figure 5.10c.
Figure 5.11a, b  Figures 5.11a and b (transmitted light cross-polarized photomicrographs) show a rim of opaque minerals sandwiched between a nucleus of amphibole and an external ring of biotites in a sample from the Hammell Lake batholith (site HLB). The photomicrograph of figure 5.11b is an enlargement of some of those opaque minerals.
Figure 5.12a, b Transmitted light cross-polarized photomicrographs, for a sample from site HLC in the Hamell Lake batholith, show plagioclase with ghost lines of impurities recording different stages of its growth. A smaller euhedral opaque crystal (probably magnetite), enlarged in figure 5.12b, has also been trapped within the crystal of plagioclase.
Figure 5.13a, b For a sample from the Trout Lake batholith (Walsh Lake phase), two transmitted light cross-polarized photomicrographs (figures 5.13a and b) show the association of euhedral and anhedral opaque minerals with biotites. The freshness observed in the rest of the minerals in this sample leads to the conclusion that both biotites and opaque minerals, if not primary, are probably the products of slight alteration almost coeval with the initial cooling of the batholith.
Figure 5.14a, b Evidence for hematite in the almost unaltered batholith samples is seen in the photomicrographs of figures 5.14 - 5.16 for the Little Vermillion, the Killala Baird and Hamel Lake batholiths.

For the Little Vermillion batholith (site VBB), an anhedral crystal of hematite shows lens-like exsolution bodies of ilmenite under reflected light (figure 5.14a). Primary ilanomagnetite oxidation to hematite with ilmenite exsolution probably occurred during initial cooling of the magma, since no evidence for major metamorphism of these batholiths has been revealed by thin section analyses or radiometric data.

The high magnification (x320) photomicrograph of figure 5.14b is an inset of the needle-shaped marginal inclusion of the same hematite grain shown in figure 5.14a. It shows more clearly the characteristic brightness that makes hematite recognizable under reflected light.
Figure 5.15 Hematite crystals seen in a transmitted light plane-polarized photomicrograph. This example comes from the Killala Baird batholith (site KBF). Hematite has grown between quartz grains and along their boundaries.
Figure 5.16a, b  This figure shows, for a sample from the Hamell Lake batholith, a similar situation to that for the Killala Baird sample of figure 5.15. Figure 5.16a is a transmitted light cross-polarized photomicrograph of a hematite crystal sandwiched between two quartz crystals and also growing along their boundaries.

Figure 5.16b shows an enlargement (x320) of 5.16a (reflected light). Reddish internal reflections cause the bright white appearance that normally characterizes hematite under reflected light to fade out completely.
Figure 5.17 The appearance of opaque minerals observed in the photomicrographs of thin sections from the highly hydrothermally altered Howey diorite and Dome stock contrasts with that of minerals in the unaltered granitoid bodies. For these samples, intense alteration is observed in silicates and opaque minerals, the latter being in most cases anhedral secondary by-products of primary magnetic phases.

For a sample from the Dome stock this figure shows a cross-polarized transmitted light photomicrograph of anhedral opaque minerals in a background of dusty altered feldspars and chloritized micas.
Figure 5.18a, b, c  For two samples from the Howey diorite, the reflected light photomicrographs of figure 5.18 (a, b and c) reveal skeletal textures of original ilmenite exsolution lamellae in a titanomagnetite. The residual magnetite has altered to rutile. The ilmenite, although keeping its original lamellar texture, has altered to hematite. An enlargement of these lamellar hematites (x320) is shown in figure 5.18c.
5.4 Conclusions

A study of magnetic properties and thin section analyses of opaque mineralogies has been carried out on the Red Lake samples. The study was aimed at characterizing the three different components isolated in the palaeomagnetic study of the previous chapter, and thus testing the original hypothesis about their natures, origins and relative ages, since traditional methods for distinguishing between TRMs and CRMs seem to be unsuitable for these samples.

Analyses of initial susceptibilities, Königsberger ratios, SIRM acquisition curves and SIRM AF demagnetization spectra provide some general information about the nature of the magnetic mineralogies of the Red Lake samples, such as the characteristic multidomain magnetite fraction that seems to occur in almost all the units and the evident presence of hematite and/or single-domain magnetite in some of the RLR and RLG samples. However these analyses do not seem to be very sensitive in distinguishing among different magnetic petrologies for samples carrying different palaeomagnetic components.

In general, intensities of RLR magnetization seem to be higher than their RLG counterparts. This contrast in intensities could be a symptom of RLG chemical origin. The information derived from the analyses of magnetic properties is supplemented by the analysis of the opaque minerals in thin section.

In summary, component RLN is a soft, viscous and probably recent overprint that resides in the dominant multidomain magnetite fraction (judging mainly from its low MDF and from the results of the storage tests described in chapter 4). This component occurs in samples from both altered and unaltered units.

RLR is the hardest and strongest component, judging from its MDFs and median intensity. These magnetic properties suggest fine grained magnetite as the main RLR carrier. This, in turn, suggests that RLR is the oldest surviving palaeomagnetic component for the Red Lake Belt. The freshness observed in the thin sections for the RLR samples, including the generally euhehdral opaque minerals, supports the idea that RLR was acquired soon after the intrusion of the Red Lake batholiths during
their relatively rapid cooling. Component RLR occurs only in the almost unaltered samples from the Little Vermillion, Killala Baird, Hamell Lake and Trout Lake batholiths.

Component RLG shows a directional similarity to RLR but is different at the 95% confidence level. It occurs only in the highly altered units from the central part of the Red Lake Belt, namely the Dome Stock, the Howey diorite, and samples from the Dickenson Mine. It is probably a chemical or thermochemical overprint acquired during the late alteration of the supracrustal units at temperatures of about 260°C. Its chemical or thermochemical nature is suggested by high MDFs and low median intensity of magnetization. Analyses of thin sections show high alteration of opaque minerals and silicates for all the RLG samples, contrasting dramatically with their RLR counterparts.
CHAPTER 6

KEWEENAWAN-AGE MAGNETIZATIONS OF ALKALINE COMPLEXES AND REMAGNETIZATION OF THE SHAWMERE ANORTHOSITE, KAPUSKASING STRUCTURAL ZONE.

6.1 Introduction

Figure 6.1 (Costanzo-Alvarez and Dunlop, 1988) shows previous paleomagnetic sampling sites from traverses across the Shawmere anorthosite and Racine Lake tonalitic gneisses in the southern lobe of the Kapuskasing Structural Zone (KSZ). Sampling and measurements during the past three years have concentrated on new sites in the central and northern parts of the Shawmere anorthosite main body and on sites in the Shenango, Nemegosenda, Borden and Lackner Lake alkaline complexes (figures 6.2, 6.3 & 6.4).

Previous paleomagnetic work (Costanzo-Alvarez & Dunlop, 1988) on samples from the Shawmere and Racine traverses (Figure 6.1) isolated a late Archean magnetization (Component A) with NE declination and intermediate downward inclination. The distinctly different directions of this A magnetization in the Shawmere and Racine areas, were interpreted to be due to differing crustal tilts on the east and west sides of the KSZ. Untilting of 30° and 15° respectively about the strike of the KSZ restored the Shawmere and Racine paleomagnetic poles to the late Archean apparent polar wander path (APWP) around 2550 Ma. Initial uplift, without tilting, to intermediate crustal levels and temperatures must have occurred at this time, blocking the A magnetization. Final upthrusting and tilting occurred later. Alternatively, the two A magnetizations may differ in age (Lopez-Martinez and York, 1990).

In addition to component A, Shawmere anorthosite samples carry an easterly declination, steep to intermediate up inclination secondary magnetization (B component) which is similar to approximately 1100-Ma-old reverse Keweenawan magnetizations defining the apex of the “Logan Loop” of the North American APWP. There is however some controversy regarding the nature, origin and age of this second component in the Shawmere anorthosite. Symons et al (1988) have interpreted it as a TRM
Figure 6.1 Sketch map of the major geological units in the southern (Chapleau) block of the KSZ showing previous paleomagnetic sampling sites from traverses across the Shawmere anorthosite and Racine Lake tonalitic gneisses (after Costanzo Alvarez & Dunlop, 1988).
Figure 6.2 Sketch map of the alkaline complexes and the Shawmere anorthosite in the Chapleau block. New sampling sites in the anorthosite and the alkaline complexes are shown along with the previous sites for the Shawmere River traverse from Costanzo-Alvarez and Dunlop (1988). The hypothetical carbonatite trend that connects the alkaline complexes in the area (Skenango, Nemegosenda, Borden and Lackner Lake) and some other zones of weakness (the II.CZ and other faults) that could act as paths for channeling the extensive hydrothermal circulation that probably accompanied the Keweenawan-age alkaline magmatism in the KSZ, are also indicated.
Figure 6.4a, b  Geological map of the Shenango alkaline complex (6.4a) and magnetic anomaly map of the Borden Township (6.4b) complex in the Chapeau block (KS2). The geological map is after Thurston et al (1977) with the sampling sites for this study indicated.
dating from the time of uplift and consequent cooling of the KSZ at 1950 Ma. On the other hand Costanzo-Alvarez and Dunlop (1988) suggest that this component could be a thermochemical overprint related to alkaline intrusions in the KSZ around 1100-1000 Ma, and in a more general fashion to Keweenawan rifting and volcanism, about the same time, in the nearby Lake Superior area. Such an argument is based on the proximity of the B paleopole to the Keweenawan (1100 Ma) section of the North American Precambrian APWP, on the fact that the B component seems to be more prominent at Shawmere anorthosite sites close to the Nemegosenda carbonatite intrusion, and also to the presence of 1200-1000 Ma K/Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ feldspar ages in the Chapleau block (Farrar and Archibald, 1985; Lopez-Martinez and York, 1990).

As a test for this second hypothesis, this chapter describes a palaeomagnetic study carried out in the four Keweenawan-age alkaline complexes (Shenango River, Nemegosenda, Lackner Lake and Borden anomaly) intruding the Chapleau block (southeastern lobe of the KSZ). Such a study is aimed at isolating the same B component previously reported for the Shawmere anorthosite. In addition, the results of new sampling sites in the western, northeastern and central parts of the Shawmere anorthosite are also reported.

6.2 Results for the Shenango Alkaline Complex

Component B1, with a B-like direction of remanence, was isolated in samples from sites in the northeastern lobe of the Shenango complex. A total of 9 sites with an average of 6 samples per site were studied (figures 6.2 and 6.4a). One or two specimens of each sample were AF demagnetized, usually in 12 steps to 100 mT.

For approximately 20 representative samples, twin specimens were thermally demagnetized in steps to 680°C (or until the magnetization became unmeasurable). In addition, directions of remanence for the Shenango intrusion were also determined by AF demagnetizations in 12 samples analysed at the palaeomagnetic laboratories of the Geological Survey of Finland in Espoo by Dr. Lauri J. Pesonen. These results are labeled as "Espoo" (E) results.

The B1 remanence is bipolar (figures 6.5) and the reversed (R) and normal (N) remanences are almost
180° reversed. Keweenawan rocks of this age (=1100 Ma), on the other hand, have well-documented asymmetrical reversals (Halls and Pesonen, 1982). Component B1 (R and N) mean directions are given in table 6.1 along with AF site means, thermal means (TH) and "Espoo" means (E). In those sites where "Espoo" and thermal means were available, they were given independent statistical weights in the calculation of the final site averages. B1R (figure 6.5) was found in 31 samples (9 sites) having median destructive fields of \( = 60 \) mT and B1N in 33 samples (7 sites) having median destructive fields in the range of 7.5 - 10 mT and also about 60 mT.

Figure 6.6 shows individual examples of superimposed B1N and B1R magnetizations in samples from sites SHE-6 and 1. In one case, the B1R remanence has coercivities in the 4-50 mT range and is accompanied by a small but very hard B1N component that is barely affected by 80 mT demagnetizations (SHE-6). In the other case, the B1N remanence is soft (0-30 mT) and B1R has coercivities of 30-80 mT (SHE-1). The B1R magnetization has an initial intensity of 35-40 mA/m in either case. It is B1N that has great contrasts in intensity and coercivity, being sometimes a small component carried by hematite and sometimes a large remanence carried by soft multidomain magnetite.

Country rock samples from sites SHE-5, SHE-6 (figure 6.6a and 6.7a) and SHE-7, near the contact with the Shenango intrusion, have stable, quite well-grouped B1N magnetizations, probably carried by hematite, overprinted by softer B1R components. Unfortunately a full baked contact test on similar lithologies sampled far from the contact was not possible because of limited access. The rocks near the contact have retained no discernible pre-B1 primary remanence.

Figure 6.7 shows some examples (stereographic and orthogonal projections) of individual specimens from sites SHE-6 (country rock) and SHE-8, carrying components B1N (figure 6.7a) and B1R (figure 6.7b and c). In samples SHE-8-3-2-1 and SHE-6-2-1 component B1R underlies an initial steep positive remanence with low coercivities, probably a recent viscous overprint (figure 6.7b and c). B1R has high coercivities (30 to > 100 mT) in these samples and is the only stable magnetization present.

Figures 6.8 and 6.9 illustrate the typical AF and thermal demagnetization response of those Shenango samples which have characteristic bimodal (coexistence of multidomain (MD) and single-domain (SD) magnetite fractions) coercivity (\( H_c \)) and unblocking temperature (\( T_{ub} \)) spectra.
### TABLE 6.1

SHENANGO RIVER ALKALINE COMPLEX COMPONENTS B1R AND B1N

<table>
<thead>
<tr>
<th>SITE</th>
<th>Decl. (°)</th>
<th>Incl. (°)</th>
<th>N</th>
<th>$\alpha_{95}$ (°)</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHE1 (AF)</td>
<td>120</td>
<td>-58</td>
<td>2</td>
<td>-</td>
<td>27</td>
</tr>
<tr>
<td>SHE1 (E)</td>
<td>117</td>
<td>-59</td>
<td>2</td>
<td>-</td>
<td>79</td>
</tr>
<tr>
<td>SHE1</td>
<td>119</td>
<td>-59</td>
<td>2</td>
<td>-</td>
<td>3800</td>
</tr>
<tr>
<td>SHE2 (TH)</td>
<td>124</td>
<td>-46</td>
<td>6</td>
<td>19</td>
<td>14</td>
</tr>
<tr>
<td>SHE2 (AF)</td>
<td>133</td>
<td>-37</td>
<td>5</td>
<td>10</td>
<td>36</td>
</tr>
<tr>
<td>SHE2 (E)</td>
<td>146</td>
<td>-31</td>
<td>3</td>
<td>28</td>
<td>8</td>
</tr>
<tr>
<td>SHE2</td>
<td>135</td>
<td>-38</td>
<td>3</td>
<td>12</td>
<td>49</td>
</tr>
<tr>
<td>SHE3</td>
<td>77</td>
<td>-65</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SHE4 (TH)</td>
<td>91</td>
<td>-54</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SHE4 (AF)</td>
<td>86</td>
<td>-44</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SHE4 (E)</td>
<td>162</td>
<td>-40</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SHE4</td>
<td>114</td>
<td>-52</td>
<td>3</td>
<td>30</td>
<td>7</td>
</tr>
<tr>
<td>SHE5</td>
<td>123</td>
<td>-42</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SHE6</td>
<td>125</td>
<td>-29</td>
<td>2</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>SHE7</td>
<td>108</td>
<td>-24</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SHE8</td>
<td>121</td>
<td>-33</td>
<td>3</td>
<td>16</td>
<td>25</td>
</tr>
<tr>
<td>SHE9</td>
<td>51</td>
<td>-51</td>
<td>2</td>
<td>23</td>
<td>18</td>
</tr>
<tr>
<td>B1R</td>
<td>112</td>
<td>-46</td>
<td>9</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>SITE</td>
<td>Decl. (°)</td>
<td>Incl. (°)</td>
<td>N</td>
<td>$\alpha_{26}$ (°)</td>
<td>k</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>-----------</td>
<td>----</td>
<td>------------------</td>
<td>----</td>
</tr>
<tr>
<td>SHE1 (TH)</td>
<td>282</td>
<td>46</td>
<td>4</td>
<td>27</td>
<td>7</td>
</tr>
<tr>
<td>SHE1 (E)</td>
<td>279</td>
<td>54</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SHE1</td>
<td>281</td>
<td>50</td>
<td>2</td>
<td>-</td>
<td>194</td>
</tr>
<tr>
<td>SHE2 (TH)</td>
<td>327</td>
<td>50</td>
<td>4</td>
<td>13</td>
<td>20</td>
</tr>
<tr>
<td>SHE2 (AF)</td>
<td>328</td>
<td>67</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SHE2 (E)</td>
<td>2</td>
<td>59</td>
<td>2</td>
<td>-</td>
<td>3094</td>
</tr>
<tr>
<td>SHE2</td>
<td>339</td>
<td>60</td>
<td>3</td>
<td>14</td>
<td>36</td>
</tr>
<tr>
<td>SHE3 (AF)</td>
<td>312</td>
<td>34</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SHE3 (E)</td>
<td>301</td>
<td>34</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SHE3</td>
<td>307</td>
<td>34</td>
<td>2</td>
<td>-</td>
<td>159</td>
</tr>
<tr>
<td>SHE4 (TH)</td>
<td>338</td>
<td>52</td>
<td>2</td>
<td>-</td>
<td>22</td>
</tr>
<tr>
<td>SHE4 (AF)</td>
<td>314</td>
<td>50</td>
<td>3</td>
<td>32</td>
<td>16</td>
</tr>
<tr>
<td>SHE4 (E)</td>
<td>298</td>
<td>39</td>
<td>2</td>
<td>-</td>
<td>33</td>
</tr>
<tr>
<td>SHE4</td>
<td>315</td>
<td>48</td>
<td>3</td>
<td>15</td>
<td>29</td>
</tr>
<tr>
<td>SHE5</td>
<td>298</td>
<td>55</td>
<td>4</td>
<td>15</td>
<td>159</td>
</tr>
<tr>
<td>SHE6</td>
<td>285</td>
<td>45</td>
<td>6</td>
<td>7</td>
<td>75</td>
</tr>
<tr>
<td>SHE9</td>
<td>313</td>
<td>57</td>
<td>2</td>
<td>-</td>
<td>135</td>
</tr>
<tr>
<td>B1N</td>
<td>304</td>
<td>51</td>
<td>7</td>
<td>10</td>
<td>31</td>
</tr>
</tbody>
</table>
Figures 6.5 Equal area stereographic projection of site mean B1N and B1R directions for the Shenango River alkaline complex, together with the unit means (diamonds) and circles of 95% confidence.
Figure 6.6a, b  Equal area stereographic and orthogonal vector projections in the course of AF demagnetization for individual samples from sites SHE-6 and SHE-1 showing superimposed B1N and B1R magnetizations. In 6.6a, the B1R remanence has coercivities in the 4-50 mT range and is accompanied by a small but very hard B1N component that is barely affected by 80 mT demagnetization (SHE-6).
Figure 6.7a, b, c Components B1N (6.7a) and B1R (6.7b and c) characteristic directions of remanence for individual samples SHE-6-1-1-1 (6.7a), SHE-8-3-2-1 (6.7b) and SHE-6-1-1-1 (6.7b) from the Shenango River alkaline complex (NRM to stable end points). Stereographic and orthogonal vector projections are shown for each sample in the course of AF demagnetization. High coercivity B1R in SHE-8-3-2-1 and SHE-6-2-1 (6.7b and c) is overprinted by a low coercivity PEF.
For samples SHE-6-1 and SHE-8-2 (figure 6.8) the single-domain fractions dominate over the multidomain ones, with high coercivity tails carrying more than 50% of the initial NRM and surviving peak demagnetization fields of 80 and 100 mT. Thermal demagnetizations of these tails reveals single-domain magnetite as the main carrier of remanence for sample SHE-8-2, which has a narrow interval of $T_{UB}$'s around 580°C (figure 6.8d). Sample SHE-6-1 shows a lower mean $T_{UB}$ around 350°C (figure 6.8b) probably caused by the presence of Ti impurities in most of the high coercivity magnetites or pyrrhotite.

The initial sharp exponential decay of the AF demagnetization curves for samples SHE-2-1 and SHE-4-2 (figure 6.9) reveals a multidomain magnetite fraction as their dominant carrier of remanence. The single-domain tail for sample SHE-2-1 demagnetizes over a wide range of $T_{UB}$'s, with a final and dramatic drop around 550°C (Curie point of magnetite) and evidence for a minor remaining hematite fraction (figure 6.9b). Sample SHE-4-2 thermal demagnetization also reveals a wide range of $T_{UB}$'s with a progressive NRM decay that finishes at 580°C (figure 6.9d).

6.3 Results for the Nemegosenda Carbonatite

Component B1 (N and R) was also isolated in samples from the Nemegosenda carbonatite. A total of 6 sites in the carbonatite itself, plus two sites in the baked contact zone (mafic gneisses 49 and 66), with an average of 6 samples per site were studied, following the same AF and thermal demagnetization procedures used for the Shenango samples (figures 6.2 and 6.3a). Its mean directions are given in table 6.2 along with AF site means, thermal means (TH) and "Espoo" means (E). Site and final means are plotted in the equal area stereonet of figure 6.10.

The B1R component was found in only 5 samples and has median destructive fields of $= 6$-10 mT. This is the first time that reversed B1 magnetizations have been found in Nemegosenda samples. Symons and Garber's (1974) early paleopole was based on normal-polarity results only.

Component B1N was commoner than B1R in the Nemegosenda intrusion. It was found in 18 samples (6 sites) with median destructive fields of 10-60 mT and median $T_{UB}$'s of $= 540$-$567^\circ$C. Figure 6.11 shows two examples (stereographic and orthogonal projections) of individual specimens from sites NE-6
Figure 6.8a, b, c, d  Intensity decay curves during AF and thermal demagnetization for samples SHE-6-1 and SHE-6-2 showing characteristic bimodal coercivity ($H_c$) and unblocking temperature ($T_{ub}$) spectra. Thermal demagnetization of high coercivity tails carrying more than 50% of the initial NRM reveals single-domain magnetite as the main carrier of remanence for sample SHE-8-2, which has a narrow interval of $T_{ub}$'s around 580°C (6.8d). Sample SHE-6-1 shows a lower mean $T_{ub}$ around 350°C, (6.8b) probably caused by the presence of titanium impurities in most of the high coercivity magnetites or pyrrhotite.
Intensity decay curves during AF and thermal demagnetization for samples SHE-2-1 and SHE-4-2, showing an initial sharp exponential decay characteristic of a dominant multidomain magnetic fraction. The single-domain tail for sample SHE-2-1 demagnetizes over a wide range of $T_{un}$'s with a final and dramatic drop around 580°C evidencing a minor remaining hematite fraction (6.9b). Sample SHE-4-2 thermal demagnetization also reveals a wide range of $T_{un}$'s with a progressive NRM decay that dies out completely at 580°C (6.9d).
### TABLE 6.2

**NEMEGOSENDA CARBONATITE B1R AND B1N COMPONENTS**

<table>
<thead>
<tr>
<th>SITE</th>
<th>Decl. (°)</th>
<th>Incl. (°)</th>
<th>N</th>
<th>α₉₅ (°)</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE1 (E)</td>
<td>135</td>
<td>-78</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NE3</td>
<td>137</td>
<td>-57</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NE4</td>
<td>119</td>
<td>-26</td>
<td>2</td>
<td>-</td>
<td>204</td>
</tr>
<tr>
<td>66</td>
<td>112</td>
<td>-65</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B1R</td>
<td>124</td>
<td>-57</td>
<td>4</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>NE1 (AF)</td>
<td>325</td>
<td>40</td>
<td>3</td>
<td>19</td>
<td>18</td>
</tr>
<tr>
<td>NE1 (E)</td>
<td>335</td>
<td>41</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NE1</td>
<td>330</td>
<td>41</td>
<td>2</td>
<td>-</td>
<td>221</td>
</tr>
<tr>
<td>NE2</td>
<td>271</td>
<td>66</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NE3 (TH)</td>
<td>250</td>
<td>48</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NE3 (AF)</td>
<td>281</td>
<td>42</td>
<td>3</td>
<td>29</td>
<td>8</td>
</tr>
<tr>
<td>NE3</td>
<td>266</td>
<td>46</td>
<td>2</td>
<td>-</td>
<td>25</td>
</tr>
<tr>
<td>NE5</td>
<td>330</td>
<td>49</td>
<td>3</td>
<td>14</td>
<td>24</td>
</tr>
<tr>
<td>NE6 (TH)</td>
<td>315</td>
<td>37</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NE6 (AF)</td>
<td>331</td>
<td>43</td>
<td>3</td>
<td>21</td>
<td>15</td>
</tr>
<tr>
<td>NE6 (E)</td>
<td>314</td>
<td>55</td>
<td>2</td>
<td>-</td>
<td>700</td>
</tr>
<tr>
<td>NE6</td>
<td>320</td>
<td>45</td>
<td>3</td>
<td>11</td>
<td>50</td>
</tr>
<tr>
<td>49</td>
<td>340</td>
<td>54</td>
<td>3</td>
<td>16</td>
<td>25</td>
</tr>
<tr>
<td>66</td>
<td>310</td>
<td>59</td>
<td>3</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>Contact (49+66)</td>
<td>326</td>
<td>57</td>
<td>2</td>
<td>-</td>
<td>45</td>
</tr>
<tr>
<td>B1N</td>
<td>310</td>
<td>54</td>
<td>6</td>
<td>14</td>
<td>16</td>
</tr>
</tbody>
</table>
Nemegosenda carbonatite site & final means

Figures 6.10 Equal area stereographic projection of site mean B1N and R directions for the Nemegosenda carbonatite, together with the unit means (diamonds) and circles of 95% confidence.
and NE-4, carrying components B1N (figure 6.11a) and B1R (figure 6.11b).

A baked contact test was carried out on mafic gneisses at site 49, approximately 1 km (< 1/2 intrusion width) from the contact (figure 6.2) and on gneisses of similar lithology at site 29 (figure 6.1), many kilometres from the Nemegosenda metamorphic aureole. Examples of results from the two sites are given in figure 6.12. Samples from site 29 have univectorial A magnetizations (Archean Kapuskasing component, Costanzo-Alvarez & Dunlop, 1988) that decay linearly toward the origin of the Zijderveld vector plots on both AF and thermal demagnetizations (figure 6.12c). 80% of the unblocking temperatures are between 500 and 550°C. Sample 49-4 from site 49 was first AF demagnetized in 20 steps to 100 mT and then thermally demagnetized in 20 further steps to 670°C (figure 6.12a). Throughout the AF demagnetization, only an A magnetization was demagnetized. Its coercivity characteristics were identical to those of A magnetizations at site 29. On thermal demagnetization of 49-4 a small B1N magnetization with NW declination and intermediate to steep positive inclination was isolated above the magnetite Curie temperature of 580°C (figure 6.12a and b). Thus gneisses in the metamorphic aureole have had their pre-intrusion (late Archean, in fact) A magnetizations overprinted by the B1N magnetization at the time the Nemegosenda was intruded, whereas gneisses outside the metamorphic aureole retain only the A magnetization. This positive contact test suggests that B1N is the primary remanence of the Nemegosenda intrusion. However, this is not a conventional baked contact test, in which the overprinting of the country rock is thermal and removed at lower temperatures than the primary remanence. The hematite that carries the B1N overprint at site 49 must be secondary, since it is not in evidence at site 29. The site 49 overprint is therefore probably a chemical remanence, and the hydrothermal alteration that produced it could conceivably have accompanied a second rather than the first phase of intrusion.

Figures 6.13 and 6.14 illustrate the typical AF and thermal demagnetization response of the Nemegosenda samples. Once more, evidence for bimodality of the magnetic carriers (MD and SD magnetite) is observed in the rapid initial AF decay of the NRM intensities followed by a hard tail of high coercivities and unblocking temperatures (figures 6.13a, 6.13b and 6.14a, 6.14c). However, unlike the Shenango samples, Nemegosenda soft multidomain fractions seem to be more dominant than single-domain ones, particularly in samples like NE-4-6 and NE-4-5 (figures 6.13c and 6.13d) where no single-
domain fraction is observed after AF demagnetization is completed up to 100 mT. Thermal demagnetizations reveal in most cases (with the exception of sample NE-6-5, figure 6.14d) a rather progressive decay of intensities over the whole range of $T_{UB}$'s (figures 6.13e, 6.13f and 6.14b) that dies out almost completely around 580°C (Curie point of magnetite).

Thus, the Nemegosenda and Shenango alkaline complexes show similar magnetic mineralogies characterized by bimodality, probably in both mineralogy and grain sizes, and wide ranges of coercivities and unblocking temperatures. However, Nemegosenda samples proved to be in general softer than their Shenango counterparts, as a result of a prominent multidomain magnetite fraction.

6.4 Results for the Borden anomaly and the Lackner Lake carbonatite

Data for these two intrusions are rather scanty and thus no major conclusions can be drawn from them. However, some of the results obtained can be used to reinforce the conclusions obtained from the better defined data from Shenango and Nemegosenda alkaline complexes and the Shawmere anorthosite. The scarcity of data for the Borden and Lackner Lake bodies is a result of the poor exposures. In the case of Borden there is no exposure at all of the carbonatite itself and all the results come from the country rock overlying the anomaly which was presumably heated and overprinted by the intrusion of the carbonatite pipe (figures 6.3b and 6.4b).

Table 6.3 along with figure 6.15 show $B1$ mean directions of remanence for both Borden and Lackner samples. The Lackner Lake $BIR$ component is not completely 180° reversed to $B1N$. Note that Keweenawan asymmetric reversals are well documented (Halls and Pesonen, 1982). However the $B1R$ and $B1N$ asymmetry observed in the Lackner Lake samples could be a result of the scarcity and consequent scatter of the data, and thus the poor definition of mean directions.

6.5 Component B2 Results

The shallow $B2$ (N and R) remanences are found only occasionally and at specific sites (table 6.4). In order to improve their statistical resolution, the final means for $B2$ (N and R) were calculated using
Figure 6.11a, b, Components B1N (6.11a) and B1R (6.11b) characteristic directions of remanence for individual samples NE-6-1-1-1 (6.11a) and NE-4-6-2 (6.11b) from the Nemegosenda Lake alkaline complex (NRM to stable end points). Stereographic and orthogonal vector projections are shown for each sample in the course of AP demagnetization.
Figure 6.12a, b, c Results for a baked contact test carried out on mafic gneisses at site 49, approximately 1 km from the western contact of the Nemeosenda carbonatite, and on gneisses of similar lithology at site 29 many kilometres from the metamorphic aureole. In 6.12a are shown stereographic and orthogonal vector projections plus intensity decay curves for sample 49-4. This sample was first AF demagnetized in 20 steps to 100 mT and then thermally demagnetized in 20 further steps to 670 °C. Throughout the AF cleaning, only an A magnetization was demagnetized. On thermal cleaning a small B1N magnetization was isolated above 580 °C. Thus gneisses in the metamorphic aureole have had their late Archean A magnetizations overprinted by the B1N magnetizations at the time the Nemeosenda was intruded. The stereographic projection of 6.12b shows sample mean directions with their corresponding T95's for components A and B1N isolated at site 49. The B1 overprint is probably a CRM carried by secondary hematite, since it is removed at higher temperatures than the primary remanence A. Gneisses outside the metamorphic aureole from site 29 (6.12c) retain only the A magnetization with univectorial A magnetizations that decay linearly toward the origin of the Zijderveld vector plots on both AF and thermal cleaning.
Figure 6.13a, b, c, d, e, f  Intensity decay curves during AF and thermal demagnetization for different Nemegeonda samples, showing bimodality of the magnetic carriers in the rapid initial AF decay of the NRM intensities followed by a hard tail of high coercivities and blocking temperatures (6.13a, 6.13b). Thermal demagnetizations reveal a rather progressive decay of intensities over the whole range of $T_{cm}$'s (6.13c & 6.13d) that dies out almost completely around 580°C. Nemegeonda soft multidomain fractions seem to be more dominant than single-domain ones, particularly in samples like NE-4-6 and NE-4-5 (6.13c & 6.13d) where no single-domain fraction is observed after AF demagnetization is completed up to 100 mT.
Figure 6.14a, b, c, d  Intensity decay curves during AF and thermal demagnetization for two Nemegosenda samples, showing bimodality of the magnetic carriers in the initial AF decay of the NRM intensities followed by a hard tail of high coercivities and blocking temperatures. Thermal demagnetization for the high coercivity tail of sample NE-1-1 reveals a rather progressive decay of intensities over the whole range of $T_{ub}$'s (6.14a & 6.14b) that dies out almost completely above 580°C.
<table>
<thead>
<tr>
<th>SITE</th>
<th>Decl. (°)</th>
<th>Incl. (°)</th>
<th>N</th>
<th>$\alpha_{95}$ (°)</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lackner</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>53</td>
<td>96</td>
<td>-39</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>54</td>
<td>120</td>
<td>-29</td>
<td>2</td>
<td>-</td>
<td>12</td>
</tr>
<tr>
<td>B1R</td>
<td>109</td>
<td>-35</td>
<td>2</td>
<td>-</td>
<td>27</td>
</tr>
<tr>
<td>54 (B1N)</td>
<td>313</td>
<td>50</td>
<td>4</td>
<td>22</td>
<td>10</td>
</tr>
<tr>
<td>Borden</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>301</td>
<td>52</td>
<td>3</td>
<td>11</td>
<td>56</td>
</tr>
<tr>
<td>68</td>
<td>313</td>
<td>49</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B1N</td>
<td>307</td>
<td>51</td>
<td>2</td>
<td>-</td>
<td>211</td>
</tr>
</tbody>
</table>
Figure 6.15a, b  Equal area stereographic projection of site mean B1N and B1R direction of remanence for Lackner Lake (6.15a) and Borden Lake (6.15b) alkaline complexes, together with the unit means (diamonds) and circles of 95% confidence.
the available B2 data from all the intrusions studied (table 6.8). Even so, the circles of 95% confidence for the B2R and B2N grand means are 2-3 times larger than those of the B1 components (figure 6.16).

All the complexes have at least a few examples of B2 components, but they are not found in all the Shawmere anorthosite samples. Median destructive fields of these components are \(\approx 30\text{-}40\text{ mT}\) for both B2N and B2R in Shenango, Nemegosenda and the Shawmere anorthosites. For the few samples of the Borden anomaly and Lackner Lake carbonatite showing these components, median destructive fields are much lower, ranging between \(\approx 2\) and \(8\text{ mT}\).

Examples of component B2 (N and R) for individual specimens in sites NE-3 (Nemegosenda), SHE-4 (Shenango), 68 (Borden) and 53 and 54 (Lackner) are shown in figures 6.17 and 6.18 (stereographic and orthogonal projections). In most of these examples B2 seems to be a stable remanence overprinted by a softer and steeper viscous component whose coercivity spectra overlaps considerably that of B2. Hence the possibility that B2 is either an hybrid transition between a steep down (probably a PEF or B1N) and a steep up (probably B1R) direction of remanence, or a CRM acquired in a direction intermediate between B1R and B1N at the time when the magnetic field that induced component B1 reversed its polarity.

### 6.6 Results for the Shawmere Anorthosite

B1R-like directions of remanence seem to be also characteristic magnetizations of the Shawmere anorthosite samples. However as illustrated in figure 6.19, a stereographic projection of all the site means, including those reported by Costanzo-Alvarez and Dunlop (1988), clearly evidences a non-Fisherian distribution of these directions, with streaking between a steep up direction and a shallower one. Streaking of apparently stable end points has long been recognized as an indicator of the superposition of two magnetizations (Irving, 1964). The virtual geomagnetic poles (VGP's) corresponding to these directions are also non-Fisherian in their distribution.

In the Shawmere anorthosite, components with steeper inclinations seem to have higher coercivities \((= 60\text{-}80\text{ mT})\) than their shallower counterparts \((= 30\text{ mT})\) which resemble the B1R direction of
<table>
<thead>
<tr>
<th>SITE</th>
<th>Decl. (°)</th>
<th>Incl. (°)</th>
<th>N</th>
<th>α_{95} (°)</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHE3</td>
<td>312</td>
<td>12</td>
<td>2</td>
<td>-</td>
<td>45</td>
</tr>
<tr>
<td>SHE4 (TH)</td>
<td>236</td>
<td>-2</td>
<td>2</td>
<td>-</td>
<td>11</td>
</tr>
<tr>
<td>SHE4 (AF)</td>
<td>273</td>
<td>13</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SHE4</td>
<td>254</td>
<td>6</td>
<td>2</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>SHE7</td>
<td>208</td>
<td>-3</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SHE9</td>
<td>266</td>
<td>-16</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Shenango B2R</td>
<td>260</td>
<td>0</td>
<td>4</td>
<td>37</td>
<td>4</td>
</tr>
<tr>
<td>SHE2 (AF)</td>
<td>88</td>
<td>-12</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SHE2 (E)</td>
<td>83</td>
<td>-13</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SHE2</td>
<td>86</td>
<td>-13</td>
<td>2</td>
<td>-</td>
<td>529</td>
</tr>
<tr>
<td>SHE4</td>
<td>127</td>
<td>10</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SHE8</td>
<td>76</td>
<td>-12</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Shenango B2N</td>
<td>96</td>
<td>-5</td>
<td>3</td>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td>NE1 (TH)</td>
<td>304</td>
<td>7</td>
<td>2</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>NE1 (AF)</td>
<td>243</td>
<td>-3</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NE1 (E)</td>
<td>277</td>
<td>-9</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NE1</td>
<td>275</td>
<td>-2</td>
<td>3</td>
<td>31</td>
<td>7</td>
</tr>
<tr>
<td>NE3 (TH)</td>
<td>304</td>
<td>5</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NE3 (AF)</td>
<td>302</td>
<td>-2</td>
<td>3</td>
<td>10</td>
<td>68</td>
</tr>
<tr>
<td>NE3</td>
<td>303</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>212</td>
</tr>
<tr>
<td>Nemegosenda B2R</td>
<td>289</td>
<td>0</td>
<td>2</td>
<td>-</td>
<td>17</td>
</tr>
<tr>
<td>SITE</td>
<td>Decl. (°)</td>
<td>Incl. (°)</td>
<td>N</td>
<td>$\alpha_{45}$ (°)</td>
<td>k</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
<td>-----------</td>
<td>----</td>
<td>-------------------</td>
<td>----</td>
</tr>
<tr>
<td>NE1</td>
<td>37</td>
<td>-3</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>NE5</td>
<td>59</td>
<td>-6</td>
<td>2</td>
<td>-</td>
<td>101</td>
</tr>
<tr>
<td>Numegen-</td>
<td>48</td>
<td>-5</td>
<td>2</td>
<td>-</td>
<td>27</td>
</tr>
<tr>
<td>senda B2N</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>55 Borden</td>
<td>270</td>
<td>14</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>68 Borden</td>
<td>281</td>
<td>-2</td>
<td>2</td>
<td>-</td>
<td>121</td>
</tr>
<tr>
<td>Borden B2R</td>
<td>276</td>
<td>6</td>
<td>2</td>
<td>-</td>
<td>35</td>
</tr>
<tr>
<td>53 Lackner</td>
<td>44</td>
<td>-2</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>B2N</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>54 Lackner</td>
<td>257</td>
<td>-14</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>B2R</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>106</td>
<td>10</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>90</td>
<td>-14</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>55</td>
<td>-11</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>SH6</td>
<td>120</td>
<td>0</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>SH8</td>
<td>12</td>
<td>-3</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>LLL3</td>
<td>61</td>
<td>-1</td>
<td>2</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>LLL5</td>
<td>127</td>
<td>15</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Shawmere B2N</td>
<td>83</td>
<td>-1</td>
<td>7</td>
<td>27</td>
<td>4</td>
</tr>
<tr>
<td>39 (TH)</td>
<td>339</td>
<td>-24</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>39 (AF)</td>
<td>274</td>
<td>9</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>305</td>
<td>-9</td>
<td>2</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>LLL3</td>
<td>339</td>
<td>9</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Shawmere B2R</td>
<td>322</td>
<td>0</td>
<td>2</td>
<td>-</td>
<td>9</td>
</tr>
</tbody>
</table>
Figure 6.16a Equal area stereographic projections of B2N and B2R overall means averaging all the site means. Circles of 95% confidence are shown for each overall mean.
Figure 6.17a, b, c, d Component B2R characteristic directions of remanence for individual samples SHE-4-4-1 (6.17a), NE-3-2-2 (6.17b), 68-2-3-3 (6.17c) and 54-8-3-1 (6.17d) from the Shenango River, Nemegosenda Lake, Borden anomaly and Lackner Lake alkaline complexes respectively (NRM to stable end points). Stereographic and orthogonal vector projections are shown for each sample in the course of AF demagnetization. In some cases like that for sample NE-3-2-2 (6.17a), coercivity spectrum of B2R partially overlaps that of a soft viscous overprint.
Figure 6.18a, b, c Components B2N characteristic directions of remanence for individual samples SHE-4-5-2 (6.18a), 68-5-2-3 (6.18b) and 53-6-2-1 (6.18c) from the Shenango river, Borden township and Lackner lake alkaline complexes respectively (NRM to stable end points). Stereographic and orthogonal vector projections are shown for each sample in the course of AF demagnetization. In most cases, specially for samples 68-5-2-3 (6.18b) and 53-6-2-1 (6.18c), coercivity spectrum of B2R partially overlaps that of a soft viscous overprint.
remanence isolated for the Shenango and Nemegosenda alkaline complexes. Although the criterion used here to separate these directions of remanence, based exclusively on their median destructive fields, may not be entirely reliable, it does result in a good grouping of two distinguishable paleomagnetic components with non-overlapping 95% confidence circles. Thus site means and final averages are given separately in tables 6.5 and 6.6 and figure 6.20 for the B1R-like direction of remanence and a second component with higher median destructive field and steeper inclination (steep up (SU)).

Costanzo-Alvarez and Dunlop (1988) did not discriminate between these two directions of remanence. The scatter of this component ($\alpha_{95}=17^\circ$, $k=17$) could be explained thus by the mingling of two different unresolved components with similar directions. Discriminating between two paleomagnetic components with similar directions is not an easy task. In the case of the Shawmere anorthosite this problem becomes even more critical since there are no clear examples of bivectorial B1R + SU magnetizations. Figures 6.21a and 6.21b show two individual examples of what seem to be superimposed B1R and SU components in anorthosite specimens SH-6-5-1-2 and SH-7-3.

For SH-6-5-1-2 (figure 6.21a), a linear segment of the orthogonal projection is defined between coercivities of 30-60 mT (B1R (?), $D=82^\circ$, $I=-25^\circ$). In addition a second, slightly different linear segment, is defined between coercivities of 60-100 mT (SU(?), $D=86^\circ$, $I=-41^\circ$). However the presence of a steep down soft component introduces the possibility that the B1R-like direction of remanence is just a hybrid of the viscous PEF and the steep up components, whose coercivity spectra happen to overlap. For sample LLL-4-2-2 (figure 6.21c) a B1R-like direction of remanence ($D=96^\circ$, $I=-31^\circ$) is evidenced by a linear segment on the orthogonal projection between 40-80 mT. This component seems to be a small fraction of the total NRM intensity of this sample, and is overprinted by a softer steep down component that is mainly demagnetized at coercivities of $\approx 10$ mT.

For SH-7-3 (figure 6.21b) there is a minor viscous overprint that seems to demagnetize completely at coercivities lower than 4 mT. In addition, two linear segments between 15-30 mT and 40-100 mT can be distinguished from the orthogonal projection. The first one defines a B1R-like direction of remanence ($D=68^\circ$, $-48^\circ$) whereas the second one defines a SU-like direction ($D=68^\circ$, $I=-66^\circ$).
### TABLE 6.5

**SHAWMERE ANORTHOSTITE BIR COMPONENT**

<table>
<thead>
<tr>
<th>SITE</th>
<th>Decl. (°)</th>
<th>Incl. (°)</th>
<th>N</th>
<th>$\alpha_{95}$ (°)</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>132</td>
<td>-31</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>41</td>
<td>40</td>
<td>-64</td>
<td>2</td>
<td>-</td>
<td>131</td>
</tr>
<tr>
<td>42</td>
<td>110</td>
<td>-62</td>
<td>3</td>
<td>19</td>
<td>14</td>
</tr>
<tr>
<td>SH6</td>
<td>88</td>
<td>-34</td>
<td>5</td>
<td>10</td>
<td>39</td>
</tr>
<tr>
<td>SH7</td>
<td>88</td>
<td>-57</td>
<td>3</td>
<td>17</td>
<td>23</td>
</tr>
<tr>
<td>LLL4</td>
<td>105</td>
<td>-37</td>
<td>4</td>
<td>29</td>
<td>6</td>
</tr>
<tr>
<td>LLL5</td>
<td>17</td>
<td>-64</td>
<td>2</td>
<td>-</td>
<td>36</td>
</tr>
<tr>
<td>B1R</td>
<td>92</td>
<td>-55</td>
<td>7</td>
<td>18</td>
<td>9</td>
</tr>
</tbody>
</table>

### TABLE 6.6

**SHAWMERE ANORTHOSTITE STEEP UP COMPONENT**

<table>
<thead>
<tr>
<th>SITE</th>
<th>Decl. (°)</th>
<th>Incl. (°)</th>
<th>N</th>
<th>$\alpha_{95}$ (°)</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>132</td>
<td>-80</td>
<td>2</td>
<td>-</td>
<td>37</td>
</tr>
<tr>
<td>SH7</td>
<td>67</td>
<td>-76</td>
<td>5</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>LLL1</td>
<td>330</td>
<td>-67</td>
<td>3</td>
<td>11</td>
<td>52</td>
</tr>
<tr>
<td>LLL2</td>
<td>119</td>
<td>-80</td>
<td>4</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>LLL3</td>
<td>63</td>
<td>-66</td>
<td>4</td>
<td>31</td>
<td>5</td>
</tr>
<tr>
<td>LLL4</td>
<td>76</td>
<td>-73</td>
<td>3</td>
<td>16</td>
<td>25</td>
</tr>
<tr>
<td>LLL5</td>
<td>127</td>
<td>-77</td>
<td>4</td>
<td>14</td>
<td>24</td>
</tr>
<tr>
<td>MEAN</td>
<td>73</td>
<td>-80</td>
<td>7</td>
<td>10</td>
<td>31</td>
</tr>
</tbody>
</table>
Figure 6.19  Stereographic projection of BIR-like directions of remanence in samples from the Shawmere anorthosite. Site means for the B component reported by Costanzo-Alvarez and Dunlop (1988) are also included in this figure. The streaking observed between a steep up and a shallower direction which resembles the BIR in the alkaline complexes can be explained either as a consequence of incomplete resolution of two superimposed components with similar directions of remanence, or by PEF contamination and/or by the effects of the magnetic fabric of these rocks on the direction of remanence. The first hypothesis of superimposed components with similar directions of remanence seems to be the most reasonable one to explain such a streaking.
Figure 6.20a, b Equal area stereographic projection of site mean B1R (6.20a), and the steep up direction of remanence (6.20b) for the Shawmere anorthosite, together with the unit means (diamonds) and circles of 95% confidence.
Figure 6.21a, b, c. B1R and steep up characteristic directions of remanence for individual samples SH-6-5-1-2 (6.21a), SH-7-3 (6.21b) and LLL-4-2-2 (6.21c) from the Shawmere anorthosite (NRM to stable end points). Stereographic and orthogonal vector projections are shown for each sample in the course of AF demagnetization. In the orthogonal projections for SH-6-5-1-2 (6.21a) and SH-7-3 (6.21b) there seem to be two B1R-like vectors with slightly different inclinations. The softer one resembles B1R in the Sheanago complex and Nemegosenda carbonatite. The harder one is steeper. For sample LLL-4-2-2 (6.21c) a B1R-like direction of remanence seems to be a small fraction of the total NRM of this sample residing in coercivities higher than 10 mT and overprinted by a soft PEF viscous remanence.
Minor contamination by a PEF viscous overprint is also observed in the individual examples shown in figure 7.22 for anorthosite samples from sites SH-1, LLL-2, LLL-3 and LLL-5 carrying an SU-like direction of remanence, apparently without an overlapping B1R-like component. The fact that, in general, these anorthosite samples do not seem to carry either prominent viscous overprints or more than one high coercivity paleomagnetic component in a single specimen is probably a reflection of their characteristic magnetic mineralogies constrained to narrow ranges of fine-grained magnetite with consequent narrow ranges of coercivity and blocking temperatures. Thus a contaminating effect of the PEF seems to be an unlikely, or at least an incomplete, explanation for the directional streaking observed in figure 7.19.

Figures 6.23 and 6.24 illustrate the typical AF and thermal demagnetization response of these anorthosites. The contrast with their Nenemosenda and Shenango counterparts is obvious at first glance. For samples LLL-2-1, SH-6-6 and LLL-5-8 (figure 6.23a, 6.23c & 6.24a) the AF demagnetization curves are of single-domain form, with an initial plateau, inflected shape and high median destructive fields. Samples LLL-2-3 and SH-7-5 (figure 6.23b and 6.23d) also show single domain characteristics. The initial increase of intensities for these two samples reveals the presence of two components of remanence with antiparallel or almost antiparallel directions. None of these four samples' demagnetization curves shows, however, evident characteristics of bimodal mineralogies and/or grain sizes.

On the other hand, AF and thermal demagnetization curves for samples 40-5 and 39-2 (figures 6.24c, d, e & f) show bimodal characteristics. However single-domain fractions for these samples seem to be narrowly constrained to an almost unique grain size, as evidenced by the discrete TUB's just below 580°C. The presence of a fraction of hematite, probably a secondary oxidation by-product of the fine-grained magnetites, is also observed in the thermal demagnetization curves of the "hard tail" of sample LLL-5-8-1 (figure 6.24b) and for sample 39-3 (figure 6.24f).

Another possible explanation for the directional streaking observed in figure 6.19 could be the effect of the magnetic fabric of these anorthosites on the direction of remanence. Thus, providing there is only one component whose undeflected direction of remanence could be either closer to B1R or to SU, depending on how anisotropic the sample that carries it is, this direction of remanence would appear to
Figure 6.22a, b, c, d  Steep up characteristic direction of remanence for individual samples SH-7-2-2 (6.22a), LLL-2-1-1-1 (6.22b), LLL-3-4-1-1 (6.22c) and LLL-5-8-1 (6.22d) from the Shawmire anorthosite (NRM to stable end points). Stereographic and orthogonal vector projections are shown for each sample in the course of AF demagnetization. The orthogonal projections show that there is a minor PEP overprint in these samples that is completely cleaned at AF peak fields < 10 mT.
Figure 6.23a, b, c, d Intensity decay curves during AF demagnetization for Shawmere anorthosite samples, contrasting with their Nemegosenda and Shenango counterparts. For samples LLL-2-1, SH-6-6 and LLL-5-8 (6.23a, 6.23c & 6.24a) the curves are of single-domain form, with an initial plateau, inflected shape and high median destructive fields. Samples LLL-2-3 and SH-7-5 (6.23b & 6.23d) also show single domain characteristics. The initial increase of intensities for these two samples reveals, however, the presence of two components of remanence with antiparallel directions.
Figure 6.24a, b, c, d, e, f: Intensity decay curves during AF and thermal demagnetization for Shawmere anorthosite samples. Demagnetization curves for samples 40-5 and 39-2 (6.24c, 6.24d, 6.24e & 6.24f) show bimodal characteristics. However single-domain fractions for these samples seem to be narrowly constrained to an almost unique grain size, as evidenced by the discrete $T_n$'s just below 580°C. The presence of a fraction of hematite is observed in the thermal demagnetization curves of the "hard tail" of sample 1.1L-5-8-1 (6.24b) and for sample 39-3 (6.24f).
be steeper or shallower than it really is.

There are two points that argue against such a hypothesis. First, a systematic variation of the inclination should be expected as one approaches more anisotropic regions within the anorthosite (e.g. the border zone of the Shawmure anorthosite, a migmatitic garnetiferous amphibolite). However, the occurrence of components B1R and SU is not clearly related to the location of the samples that carry them having, in some cases, both directions been isolated in different samples within the same site.

Secondly, most of the anorthosite samples analysed in this study are isotropic granulites with large perfectly rounded plagioclase crystals that have grown under a hydrostatic regime of pressure with apparently minor strain involved. The magnetic mineralogies seem to be quite isotropic as well. Table 7.2 in chapter 7 lists the indices of anisotropy (ratios between maximum and minimum eigenvalues of the susceptibility, TRM and ARM ellipsoids) of some of these anorthosites. In most cases, the index values lie below 2.0, which is an indicator of nearly isotropic fine-grained magnetite as the main carrier of stable remanence (Hyodo, 1989).

Unfortunately, a complete test of the hypothesis of superimposed paleomagnetic components with similar directions is not possible without demonstrating that both of them coexist in the same samples. This problem is especially critical here, since unlike Red Lake components RLR and RLG, components B1R and SU occur in the same type of rock without any evident systematic geographic preference. Thus, a characterization of B1R and SU samples on the basis of their locations, magnetic properties of their carriers and/or petrographic characteristics is not possible.

6.7 Summary of results and paleopoles

Component B1

Figure 6.25 summarizes results from the alkaline complexes and the Shawmure anorthosite, showing
overall means for components B1R and B1N with their \( \alpha_{95} \) confidence circles. Corresponding paleopoles for unit and overall means for components B1 and B2 are summarized in tables 6.7 and 6.8 and plotted on the Logan loop (Keweenawan-age) APWP for North America (figure 6.26).

Paleopoles for component B1(N and R) in the Shenango, Nemegosenda and Lackner Lake alkaline complexes, plus the overall averages for components B2 (N \& R), trace out the Logan Loop of the Proterozoic APWP for North America.

B1N and B1R seem to be the oldest remanences for all the intrusions (= 1109-1095 Ma from the APWP). Since Shenango and Nemegosenda B1N and R poles lie closely grouped at the apex of the loop, it is difficult to judge their relative ages from their positions on the APWP. For the Shenango intrusion, median destructive fields and a partial contact test suggest that B1N was the latest remanence acquired, probably a CRM carried by hematite, and B1R was the primary remanence of the alkaline intrusion itself (see section 6.2). The Nemegosenda contact test proved a chemical overprint in the country rock on the direction of B1N which is the most prominent direction of remanence observed in the intrusion itself, but nothing could be concluded about which polarity came first. Component B1R on the other hand is almost absent in Nemegosenda sites (with the exception of site NE-4).

In the case of the Lackner Lake B1N component, figure 6.26 shows that its corresponding paleopole lies close to that for the Nemegosenda B1N remanence, whereas its B1R paleopole lies close to the Shenango B1R paleopole. Component B1 (N \& R) are probably the oldest remanences dating from initial emplacement of the carbonatite body and at = 1100 - 1000 Ma. However it is important to be cautious about the meaning of these results since, as indicated before, B1N and B1R are not well defined in the Lackner Lake body and they can be only used in conjunction with the better defined data from Shenango and Nemegosenda and the Shawmere anorthosite.

It is not clear whether B1N or B1R is older. The paleomagnetic evidence indicates that at least one reversal of the Earth's field, and possibly two reversals, took place during the time component B1 was acquired. The key point is that B1 (N and R) seems to be the oldest remanence of these alkaline complexes having been acquired at around 1100 Ma. In most cases B1 is probably a primary TRM, the exception being the contact rocks overlying the Borden intrusion.
<table>
<thead>
<tr>
<th>UNIT</th>
<th>Component</th>
<th>Long. (°)</th>
<th>Lat. (°)</th>
<th>dp (°)</th>
<th>dm (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHE</td>
<td>B1N</td>
<td>173W</td>
<td>45N</td>
<td>9</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>B1R</td>
<td>169W</td>
<td>34N</td>
<td>11</td>
<td>17</td>
</tr>
<tr>
<td>NEM</td>
<td>B1N</td>
<td>175W</td>
<td>51N</td>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>B1R</td>
<td>166W</td>
<td>49N</td>
<td>21</td>
<td>29</td>
</tr>
<tr>
<td>SHAW</td>
<td>B1R</td>
<td>149W</td>
<td>27N</td>
<td>18</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Steep up</td>
<td>108W</td>
<td>40N</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>All Units</td>
<td>B2N</td>
<td>155W</td>
<td>13S</td>
<td>11</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>B2R</td>
<td>1W</td>
<td>5S</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Lackner</td>
<td>B1N</td>
<td>180E</td>
<td>50N</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>B1R</td>
<td>174W</td>
<td>27N</td>
<td>13</td>
<td>22</td>
</tr>
<tr>
<td>Borden</td>
<td>B1N</td>
<td>176W</td>
<td>47N</td>
<td>6</td>
<td>9</td>
</tr>
</tbody>
</table>
### TABLE 6.8

OVERALL MEAN DIRECTIONS, AVERAGING ALL UNITS, AND THEIR CORRESPONDING PALEOMAGNETIC POLES

<table>
<thead>
<tr>
<th></th>
<th>Decl. (°)</th>
<th>Incl. (°)</th>
<th>α_{eq} (°)</th>
<th>k</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1N</td>
<td>308</td>
<td>52</td>
<td>3</td>
<td>800</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Long. (°)</td>
<td>Lat. (°)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>176W</td>
<td>48N</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>B1R</td>
<td>Decl. (°)</td>
<td>Incl. (°)</td>
<td>α_{eq} (°)</td>
<td>k</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>109</td>
<td>-49</td>
<td>11</td>
<td>40</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Long. (°)</td>
<td>Lat. (°)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>165W</td>
<td>36N</td>
<td>10</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>B2N</td>
<td>Decl. (°)</td>
<td>Incl. (°)</td>
<td>α_{eq} (°)</td>
<td>k</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>68</td>
<td>-4</td>
<td>22</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Long. (°)</td>
<td>Lat. (°)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>155W</td>
<td>13S</td>
<td>11</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>B2R</td>
<td>Decl. (°)</td>
<td>Incl. (°)</td>
<td>α_{eq} (°)</td>
<td>k</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>280</td>
<td>-2</td>
<td>21</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Long. (°)</td>
<td>Lat. (°)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1W</td>
<td>6S</td>
<td>11</td>
<td>21</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6.25  Stereographic projections of B1 (N and R) overall means are plotted (equal area net), averaging all the unit means. Circles of 95% confidence are shown for each mean.
Figure 6.26 Part of the middle Proterozoic APWP for North America (after Dunlop, 1984; Halls and Pesonen, 1982), showing the paleopoles for unit and overall means of components B1N & R and B2N & R of this study. Ovals of confidence are shown for paleopoles from previous studies (dashed) and for those corresponding to the overall means of this study (solid line). The paleopole for the steep up component of the Shawmere anorthosite is shown along with track 5 of the pre-2100 Ma APWP and its overlap with the apex of the Logan loop. Open and solid circles are normal and reversed polarity paleopoles for unit means with SHE: Shenango complex, NE: Nenegosenda carbonatite, Bor: Borden complex, L: Lackner carbonatite and SHAW: Shawmere anorthosite. Open and solid circles with stars are normal and reversed paleopoles for overall means.
Radiometric ages for these alkaline bodies are: 1036-988 Ma (K/Ar on nepheline, Gittins et al, 1967), 1015 (Rb/Sr WR, Bell et al, 1982) or 1107 Ma (U/Pb on zircon) (Heaman et al. 1988) for the Nemegosenda, 1045 (Rb/Sr WR, Bell et al, 1982) to 1076 and 1082 Ma (K/Ar on biotite, Bell et al, unpublished data reported by Thurston et al, 1977) for the Shenango complex, and 1090-1095 Ma ages (K/Ar and Rb/Sr WR, Gittins et al, 1967 and Bell et al, 1982 respectively) for the Lackner Lake intrusion. Despite the variety of dating methods used, these data suggest that either a time of at least 50 Ma elapsed between intrusion and cooling of these intrusions below the lowest unblocking temperature isotherms, or else that different pulses of intrusion may have occurred shortly after the main emplacement of the carbonatites took place. Although it is not possible to completely rule out either of these two possibilities, the first explanation seems less likely, since carbonatite intrusions are characterized by relatively rapid emplacement and cooling (Bell et al, 1982; Bell et al, 1987). The different petrological phases observed in these alkaline complexes (chapter 2) favours the second explanation of an intermittent alkaline magmatism in the region that took place approximately between 1100 and 1000 Ma ago.

Component B2

Component B2 (N and R) directions are averages that include all the intrusions studied. Their corresponding paleopoles resemble in direction, but not in polarity, paleopoles from Keweenawan volcanics in the Logan loop with ages of =1050 Ma.

The wide range of unblocking temperatures and coercivities for the typical bimodal magnetic mineralogies observed in Shenango and Nemegosenda alkaline complexes probably promoted the overprinting of secondary magnetizations during cooling and/or reheating of these intrusions by later pulses of intrusion. This could also be the reason for the scatter and scarcity of B2 data. As expected, component B2 appears even less often in the Shawmere anorthosite samples, which are generally magnetically hard with high (15-100 mT) coercivities and discrete $T_{ub}$'s just below 580°C, the Curie temperature of magnetite.
Borden anomaly components

Borden is the oldest alkaline complex in the Chapleau block with ages between 1810 Ma (Rb/Sr WR) and 1870-1890 Ma (U/Pb, Pb/Pb) (Bell et al, 1987). Only components B1N and B2R were isolated from the few samples available for this intrusion.

It is not possible to compare the median destructive fields of the Borden samples with those from the other alkaline complexes in the Chapleau block since the lithologies sampled are only the overlying gneissic tonalites that were presumably heated and overprinted by the alkaline intrusion and not the intrusion itself. In fact, the variability of the magnetic mineralogies with the type of lithologies would imply a consequent variability in their coercivity spectra and their median destructive fields.

For the Borden tonalites, the B1N paleopole lies close to the rest of the B1N (= 1100 Ma old) paleopoles for the other alkaline complexes. Component B2R has been included in the final calculation of the B2R mean direction for all the intrusions. There is no evidence however for an NRM dating from the time of the Borden intrusion (= 1870-1890 Ma). Therefore it seems reasonable to believe that components B1 and B2 isolated in the Borden tonalites are later overprints acquired during the time of regional hydrothermal alteration in the Chapleau block, induced by the intrusion of the younger Nemegosenda, Lackner and Shenango alkaline complexes.

Shawmere Anorthosite components

Component B1R and a steep up direction of remanence close to B1R but with higher median destructive fields and steeper inclinations have been found in the Shawmere anorthosite besides the occasional occurrence of component B2 (N and R). The corresponding paleopole for the steep up direction of remanence plots around 1150 Ma, in the eastern arm of the Logan loop. That interval overlaps the 2100-2000 Ma segment of track 5 for the APWP of Laurentia, thus introducing a serious ambiguity in the determination of its age of acquisition.
Since this component appears in rocks of both high and low metamorphic grade, contrasting with the Archean A component which is restricted almost exclusively to low-grade lithologies, Symons et al (1988) interpreted similar directions of remanence as components acquired during the main phases of uplift of the Chapleau block at ≈2000 Ma. This age coincides with the age of the segment of track 5 that underlies the 1150 Ma segment of the Logan loop. However there is clear radiometric evidence (K/Ar and 40Ar/39Ar) for a late mild event that occurred between 1200 and 1000 Ma (Farrar and Archibald, 1985; Lopez-Martinez and York, 1990), probably related to Keweenawan alkaline intrusions, that reset low blocking temperature mineral systems such as feldspars. This event could also affect the magnetic phases of the anorthosites. Hence the presence of a paleomagnetic component or components dating from that time in these intrusions is not unexpected.

On the other hand, the B1R paleopole plots between this steep up component and the group of Nemegosenda and Shenango B1N and R palepoles. The B1R and the steep up (SU) components in the Shawmere anorthosite were separated mainly on the basis of their contrasting coercivities. The B1R and SU directions are so similar, however, that a good definition of the direction of either is difficult, because it is never certain that they have been clearly separated. Therefore a clear interpretation of their ages and origins proves difficult as well. However the results for the alkaline complexes, particularly B1R for Shenango and Nemegosenda, provide some indications that there are probably two remanences in the anorthosites.

Independently of whether or not there is indeed a ≈2000 Ma old magnetization coexisting with a similar younger overprint in the Shawmere anorthosite, the original interpretation for the origin of component B still stands: namely, that the anorthosites were thermochemically overprinted by the general warming of, and hydrothermal circulation within, the hypothetical carbonatite trend that runs almost parallel to the Ivanhoe Lake Cataclastic Zone (ILCZ) and connects the four alkaline complexes in the Chapleau block: Lackner Lake, Borden, Nemegosenda Lake and Shenango River.

The idea of proposing such a carbonatite trend comes from the fact that B component is a regional rather than a local overprint in the anorthosites, and therefore the effect of the carbonatite intrusions cannot be restricted to their narrow contact aureoles, but must extend also along major zones of weakness such as the ILCZ and the other faults shown in figure 6.2 for the Chapleau block, which
would act as paths for channelling the extensive hydrothermal circulation that probably accompanied the Keweenawan-age alkaline activity in the KSZ. Moreover, along with the $^{40}$Ar/$^{39}$Ar feldspar radiometric data which support the hypothesis of this regional and late hydrothermal alteration in the Chapleau block, oxygen isotopic disequilibrium for quartz-feldspar and feldspar-biotite pairs in the tonalite rocks also reflect a low temperature retrograde process after crystallization of the tonalites involving a hydrothermal fluid phase on a limited scale (Li et al., 1988).

In order to test in detail the thermochemical remagnetization hypothesis in the anorthosites, a study of their magnetic mineralogies was conducted, trying to recognize different generations of magnetites coexisting in the same samples. This study is described in the next chapter.

6.8 Conclusions

Two components of remanence were isolated from the Shawmere anorthosite and the alkaline complexes that intrude the Chapleau block in the southern lobe of the KSZ (Lackner Lake, Nemegosenda Lake, Borden and Shenango river alkaline complexes). Corresponding paleopoles for the unit means of the directions of remanence, and overall means for those components whose unit means group well, are listed in tables 6.7 and 6.8 and plotted in figure 6.26. 95% ovals of confidence are shown only for overall means.

The northwesterly intermediate down B1N direction of remanence seems to be the oldest paleomagnetic component in most of the intrusions, judging from its median destructive fields, partial contact tests performed for the Shenango and Nemegosenda alkaline complexes, and the position of its paleopoles on the Logan loop. This component probably dates from the time of emplacement of the alkaline complexes at $= 1$100 Ma. B1N is present in all intrusions except the Shawmere anorthosite samples.

B1R is a southeasterly, intermediate up and well-defined direction of remanence that is almost 180° reversed to B1N and probably represents a complete reversal of the Earth's magnetic field that took place soon after the emplacement of the alkaline complexes in the KSZ. This B1R component is also widely found as a thermochemical remanence in the Shawmere anorthosite and in this case is probably
related to hydrothermal circulation along a hypothesized carbonatite trend that runs parallel to the IL CZ along the line that connects the alkaline complexes in the Chapleau block.

A similarly directed component of remanence with steeper inclinations and higher median destructive fields seems to underlie B1R in the anorthosites. If there is indeed an older component underlying the B overprint, such a component would have to have been acquired during the final stages of uplift of the KSZ at ≈2000 Ma for the Chapleau block and 2100 Ma for the Groundhog river block (Symons et al, 1988; Bates and Halls, 1990). In that case the results for the alkaline complexes, especially the B1R component for Shenango and Nemegosenda, would provide a good guide to discriminating between these two overlapping components with similar directions of remanence in the anorthosites, thus improving the quality of their respective final means.

Component B2 (N and R) seems to be a younger overprint. It probably records the cooling of the carbonatite bodies, accompanied by intermittent pulses of intrusion and thermochemical overprints in the Shawmere anorthosite. Such a late and extensive post-intrusion activity in the carbonatites has been well documented from the radiometric and petrological standpoints as well. However B2 (N and R) is, in general, not as well defined as B1(N and R). Typically it is found in few samples per site, with considerable directional scatter.

From the discussion above it can be concluded that an outline of the history of post-uplift activity in the KSZ can be derived from a paleomagnetic study of the Keweenawan-related alkaline bodies that intruded the Chapleau block when the data are combined with ⁴⁰Ar/³⁹Ar measurements on the same or closely related bodies. These combined data suggest that no major tectonism followed final uplift of this block after ≈2000 Ma. However, the effect of alkaline magmatism in the Chapleau block, during Keweenawan rifting in the Lake Superior region (west of the KSZ) was quite extensive. In fact, intense hydrothermal circulation along and within an hypothesized carbonatite trend that followed alkaline magmatism in the KSZ thermochemically overprinted the Shawmere anorthosite on a regional scale.
CHAPTER 7

GRAIN SIZE OF MAGNETITE IN SAMPLES FROM THE SHAWMERE ANORTHOSITE

7.1 Introduction

Results from the previous chapter show that late middle Proterozoic B1 directions of remanence, are found both as secondary overprints in the Shawmere anorthosite, and as primary TRMs in the nearby alkaline complexes. It is therefore logical to hypothesize that B1 components in the Shawmere anorthosite result from general warming and hydrothermal circulation caused by emplacement of the alkaline intrusions.

As a test of this hypothesis, this chapter will examine how mineralogical and magnetic properties of Shawmere anorthosite samples vary with distance from the "carbonatite trend", a line joining the various alkaline intrusions and approximately parallel to the Ivanhoe Lake Cataclastic Zone (ILCZ). This carbonatite trend is taken to be the surface intersection of the incipient rift in which the carbonatite plugs were emplaced and which could be expected to channel hydrothermal fluids at the time of emplacement. A series of mapped faults (figure 6.2) follow the carbonatite trend line.

The growth or crystallization of magnetite could create high laboratory $T_{unf}$s for B NRM$s that would overlap and obscure $T_{unf}$s of earlier magnetizations in the anorthosite. If this hypothesis of growth and crystallization of magnetite in the Shawmere anorthosite, triggered by late carbonatite intrusions, is correct, the best way of assessing such a CRM would be through a careful granulometric study of the magnetic phases in the anorthosite. Thus, some sort of correlation should be expected between grain size and degree of alteration observed in thin sections or, on a macroscopic scale, between grain sizes and sample locations with respect to the hypothetical carbonatite trend. Both these aspects will be examined in this chapter.

The magnetic methods used to evaluate magnetite grain sizes involve: alternating field characteristics of SIRM and TRM, hysteresis properties, and the Stephenson test (comparison of the
characteristics of SIRM and TRM, hysteresis properties, and the Stephenson test (comparison of the shape and the orientation of TRM and susceptibility ellipsoids; Stephenson et al, 1986). This latter test has not been previously used either in natural samples carrying SD and PSD magnetite or in trying to distinguish and decouple magnetite fractions with different grain sizes in bi-modal mixtures.

7.2 Alternating field characteristics and hysteresis properties.

Figure 7.1 shows a simplified Lowrie-Fuller test (Lowrie and Fuller, 1971) for some of the anorthosites of this study. TRM AF demagnetization curves are shown for pilot samples 13, 39, 15 and LLL3 and they are compared to their SIRM (saturation field = 800 mT) counterparts. The TRM for these samples has been induced in an external field of 0.06 mT, with the exception of sample 13, for which an external field of 0.16 mT has been used.

A detailed granulometric analysis based on these curves is not possible. However, some general guidelines can be drawn from this first approach. One of the most evident characteristics observed is that TRM demagnetization curves are less exponential than their SIRM counterparts, in other words, TRM curves seem to be more resistant to AF demagnetization than SIRM ones. From the shape of these curves, it is not clear whether this kind of behaviour is determined by bimodal mixtures of SD and MD magnetite, or by the presence of small MD magnetite with grain sizes close to the upper threshold of PSD behaviour (Bailey and Dunlop, 1983). In any case, low field TRMs would enhance SD or SD-like characteristics, whereas high field SIRM's will enhance MD characteristics in the samples analysed.

Initial volume susceptibility has been measured for about 250 samples from all the KSZ lithologies including the Shawmore anorthosite, using an AC bridge. The Königsberger $Q_a$ ratio $Q_a = NRM/k_s H$ for $H = 0.6$ Oe, was calculated for each sample. Results are plotted in the form of an $M_{IRM}$ vs. $k_s$ diagram in figure 7.2. $Q_a$ values can be read off with reference to the labelled diagonal lines of constant $Q_a$.

All samples have similar broad ranges of both $k_s$ and NRM values spanning three orders of magnitude. Distinctive patterns for different lithologies are not evident, except that anorthosites have uniformly low $k_s$ values, ranging typically from 3-30 x 10$^4$ cgs. However, these samples have widely ranging NRM values, from extremely strong (corresponding usually to paleomagnetically hard and
Figure 7.1a, b, c, d  A simplified Lowrie-Fuller test for some of the Shawmer anorthosites of this study. TRM AF demagnetization curves are shown for samples from sites 13, 39, 15 and LLL3 and they are compared to their SIRM (saturation field = 800 mT) counterparts. The TRM's for samples 30, 15 and LLL3 have been induced at an external field of 0.06 mT, with the exception of sample 13, for which an external field of 0.16 mT has been used.
Figure 7.2 $M_{\text{NRM}}$ vs. $k_v$ diagram for about 250 samples from all the KSZ lithologies including the Shawmere anorthosite. Initial volume susceptibility ($k_v$) has been measured, using an AC bridge. The Königsberger $Q$ ratio $Q_v = M_{\text{NRM}}/k_v H$ for $H = 0.6$ Oe, was calculated for each sample. $Q_v$ values can be read off with reference to the labelled diagonal lines of constant $Q_v$. Anorthosites have uniformly low $k_v$ values, ranging typically from $5-30$ x $10^4$ cgs, but they have widely ranging NRM values.
stable SD-type behaviour) to relatively weak and soft. Soft MD magnetite probably accounts for susceptibility in all samples, with the paleomagnetically strong samples (which have discrete high blocking temperatures and are the basis for most of the deductions about the Shawmere early A and late Proterozoic B magnetizations) owing their favourable remanence properties to elongated SD needles crystallographically oriented in plagioclase.

In addition saturation isothermal remanence ($M_{rs}$), coercive force ($H_c$) and remanence coercivity ($H_r$) were determined for pilot samples 39, 13, 15, LLL3 and LLL5. Table 7.1 summarizes these parameters including the concentrations of magnetite derived from the measured $M_s$ values, the sample weights and the value of $M_s$ for magnetite = 92.3 Am$^2$/kg (25°C). Hysteresis loops and the linear relationships between magnetization versus DC demagnetization field for each of these samples are shown in appendix A. The $H_c$-$H_r$ correlation of figure 7.3a (Dunlop, 1981) gives a rough idea of the ranges of magnetite grain sizes present in each of these samples. According to this figure: pilot sample 39 is in the SD range, LLL5 in the PSD range (=2-14\textmu m), 13 and 15 carry basically MD magnetite fractions and LLL3 is near the threshold MD-SP (=0.05\textmu m). In the $M_{rs}/M_s$-$H_r/H_c$ diagram of figure 7.3b (Dunlop, 1981) the anorthosites of this study plot off the swath that defines the general trend of synthetic and natural samples. However, they define a trend that parallels to the expected one. Such a shift from the actual trend could be due, in part, to the overwhelming paramagnetic fraction overlapping a small concentration of SD or MD magnetite fractions. Pilot samples LLL3 and LLL5 exhibit characteristics corresponding to limiting cases of MD and PSD-SD respectively. The other samples plot in the middle range of PSD with the exception of pilot sample 15 which lies close to the threshold PSD-MD.

**TABLE 7.1**

HYSTERESIS PARAMETERS FOR SHAWMERE ANORTHOSITE SAMPLES

<table>
<thead>
<tr>
<th>Sample</th>
<th>$M_{rs}$ (mA-m$^2$)</th>
<th>$H_c$ (mT)</th>
<th>$M_s$ (mA-m$^2$)</th>
<th>$H_r$ (mT)</th>
<th>$M_{rs}/M_s$</th>
<th>$H_r/H_c$</th>
<th>$[Fe_3O_4]$ x10$^{-4}$ (gm/gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>0.141</td>
<td>25.4</td>
<td>0.466</td>
<td>58.3</td>
<td>0.303</td>
<td>2.295</td>
<td>2.26</td>
</tr>
<tr>
<td>13</td>
<td>0.020</td>
<td>12.2</td>
<td>0.103</td>
<td>51.7</td>
<td>0.194</td>
<td>4.238</td>
<td>0.43</td>
</tr>
<tr>
<td>15</td>
<td>0.006</td>
<td>8.7</td>
<td>0.072</td>
<td>40.3</td>
<td>0.083</td>
<td>4.632</td>
<td>0.30</td>
</tr>
<tr>
<td>LLL3</td>
<td>0.004</td>
<td>3.2</td>
<td>0.03</td>
<td>31.5</td>
<td>0.133</td>
<td>9.844</td>
<td>0.14</td>
</tr>
<tr>
<td>LLL5</td>
<td>0.038</td>
<td>20.2</td>
<td>0.117</td>
<td>63</td>
<td>0.325</td>
<td>3.119</td>
<td>0.45</td>
</tr>
</tbody>
</table>
Figure 7.3a, b \( H_R/H_C \) and \( M_{s}/M_{s} \) domain-structure diagnosis diagrams after Dunlop (1981) with Shawmee anorthosite data. From 7.3a, sample 39 is in the SD range, LLL5 in the PSD range (=2-14µm), 13 and 15 carry basically MD magnetic fractions and LLL3 is in the threshold MD-SP (=0.05µm). From 7.3b, the anorthosites of this study plot quite far off the swath that defines the general trend of synthetic and natural samples. However, they define a trend that goes almost parallel to the expected one.
Complexities derived from n-modal mixtures of magnetite with different grain sizes are not clearly detected or resolved by granulometric analysis using demagnetization spectra and hysteretic properties. It will be shown in the next section that these situations can usually be better handled by using the Stephenson test.

7.3 Anisotropy of Remanence and Susceptibility ("Stephenson Test")

The Stephenson Test

A theoretical relationship between macroscopic susceptibility and TRM ellipsoids of anisotropy has been derived by Stephenson et al (1986) using a simplified model of \(N_o\) identical particles with their individual microscopic anisotropies represented by TRM and susceptibility preferred axes parallel and normal respectively to the axes of their ellipsoids of revolution. Only three possible orientations of these microscopic axes of revolution along the principal axes of the macroscopic ellipsoids of anisotropy (TRM and susceptibility) are considered in the model.

The general relationships on which this test is based are given by:

\[
\begin{align*}
  p_x &= p_o + s q_x \\
  p_y &= p_o + s q_y \\
  p_z &= p_o + s q_z
\end{align*}
\]

where the \(p\)'s and \(q\)'s are the relative lengths of the principal axes of the susceptibility and TRM ellipsoids respectively, normalized to the sum of their principal TRMs or susceptibilities, and \(p_o\) and \(s\) are parameters that depend exclusively on the TRM and susceptibility values along and perpendicular to the easy axes of the individual magnetic grains.

These relationships derive from equating the expressions \(f_i = p_i(\alpha+2)-1/(\alpha-1)\) and \(f_i = q_i(\gamma+2)-1/(\gamma-1)\) (\(i = X, Y\) and \(Z\)) which describe the fractions \(f_x\), \(f_y\) and \(f_z\) of the \(N_o\) particles (whose easy axes are aligned with the principal axes \(X, Y\) and \(Z\) of the sample) in terms of the
relative lengths \( p \) and \( q \), and the ratios \( \alpha = k / k_o \) and \( \gamma = M / M_r \). The parameters \( k \) and \( m \) are susceptibility and remanent magnetization respectively for each of these \( N_o \) particles, with the subscripts \( p \) and \( n \) indicating parallel or normal to their axes of rotational symmetry. Thus it would be expected that \( p = (\gamma-\alpha)/(\alpha+2)(\gamma-1) \) and \( s = 1-3p \), which represent the intercept and slope of the linear relationships between macroscopic parameters, would yield some information about the characteristics of the individual magnetic grains.

In multidomain magnetite, the expression for TRM (M) acquired in a weak field, is given by Stacey (1963) as: \( M = H / N(1+Nk_{in}) \), where I is the ratio of the spontaneous magnetization at the blocking temperature to that at room temperature; \( N \) the demagnetizing factor and \( k_{in} \) the intrinsic susceptibility. Therefore \( \gamma = N_o(1+N_k k_{in})/N_p(1+N_k k_{in}) \) where, as before, \( n \) and \( p \) subscripts refer to normal and parallel to the axes of rotational symmetry of the particle. On the other hand, the apparent susceptibility of such a particle is given by \( k_o = k_{in}/(1+Nk_{in}) \) and thus \( \alpha = (1+N_k k_{in})/(1+N_k k_{in}) \). Hence \( p \) can be calculated as a function of \( N_o \) and \( k_{in} \) since \( N_p = 1-2N_o \).

Figure 7.4 plots the variation of the \( p \) intercepts with intrinsic susceptibility for different particle shapes with \( N_o \) values ranging from 0.05 (disk) to 0.50 (needle). In both prolate and oblate cases, for high values of \( k_{in} \) (MD case) \( p \) seems to be controlled more by the shape of the grains than by their sizes. On the other hand, as \( k_{in} \rightarrow 0 \) (fine-grained magnetite), \( p \) becomes more dependent on the size of the grains.

In multidomain particles (figure 7.4), it can be noticed that for reasonable values of the intrinsic susceptibility (=10-100 (MKS)), \( p \) lies between 0 and 1/3. This implies that the slope of the \( p-q \) linear correlation will be always positive and less than 1, which implies, in turn, that TRM anisotropy will be always greater than susceptibility anisotropy and that the maximum and minimum susceptibility principal axes will coincide with the maximum and minimum TRM principal axes respectively.

For the limiting case of prolate single-domain grains, for which \( M_o \rightarrow 0 \) and \( k_p \rightarrow 0 \) (\( \gamma = \infty \) and \( \alpha = 0 \)), the linear relationship will be given by \( p = 0.5(1-q) \) \( p = 0.5, s = -0.5 \) whose negative slope implies that unlike the MD case, minimum and maximum susceptibility principal axes will coincide with maximum and minimum TRM principal axes respectively. However TRM anisotropy will again be larger than susceptibility anisotropy.
Figure 7.4a, b Variation of the $p_o$ intercepts with intrinsic susceptibility for different particle shapes with $N_n$ values ranging from 0.05 (disk) to 0.50 (needle).
Figure 7.5 A comparison of the relative lengths of the principal axes of the susceptibility (p) and 5 mT IRM ellipsoids for six different ranges of grain sizes of magnetite particles after Stephenson et al (1986). A negative correlation between the p, intercept values and the grain size can be observed.
Experimental results, for some natural and synthetic samples containing magnetite particles of different sizes within the PSD and MD range and some synthetic SD samples, sec.m to support this simple model (Stephenson et al., 1986). Figure 7.5 (Stephenson et al., 1986) shows that similar correlations can be observed between susceptibility and low field (5 mT) IRM ellipsoids (p-irm correlation). These results come mainly from synthetic and some natural unimodal samples containing magnetite grain size fractions within the range 0.2 (PSD) to 90 µm (MD). In the same figure, it can be noticed that there is a negative correlation between the p_a intercept value and the grain size. Figure 7.5 is the only guide available in comparing the results of the Shawmøre anorthosite with those of samples whose grain sizes are well known.

Undemagnetized TRM ellipsoids induced at relatively high fields should be dominated by the MD grains, whereas demagnetized TRM ellipsoids induced at lower fields should reside in SD-like grains. Therefore, in the present study, in order to look at fractions of magnetite with different grain sizes coexisting in a single sample, in some cases TRM ellipsoids were determined using two different inducing fields: 0.06 and 0.16 mT. Also AF demagnetizations to 100 mT have been performed to monitor changes in the shapes and orientations of the TRM ellipsoids. ARMs induced at fields of 0.06 and 0.16 mT have been used in an alternative to the original test for samples whose primary magnetic mineralogies were considerably affected after prolonged heatings to 700°C (i.e., whose IRM acquisition and demagnetization curves changed significantly).

A careful description of the results obtained using this test in studying the magnetite grain sizes of pilot samples 39, 13, 15, LLL3 and LLL5, whose hysteresis parameters are known, follows in the next sub-sections. In addition, results for Shawmøre anorthosite pilot samples 16, SH1, LLL2, SH2 and 41 are reported as well. First order regression analyses were applied in order to find the best fitting straight line to the set of three experimental p-q pairs for an individual specimen. In most cases correlation coefficients were close to 1. However, in nearly isotropic samples the three experimental p-q pairs tend to lie very close to each other, thereby increasing the uncertainty of the intercept p_a. On the other hand, the theoretical relationship s = 1-3p_a is always satisfactorily verified from the experimental results. Error bars on p values in the graphs that follow are calculated from the instrumental precision of the susceptibility bridge. The error bars become large for weakly magnetic specimens, whose susceptibilities approach the instrument noise level (=30 mA/m-mT). Errors in q values are small because the TRMs intensities were all well above the noise level of the spinner magnetometer (=0.025 mA/m) used to measure them. An additional effect is the susceptibility
of the paramagnetic minerals, which can outweigh the ferromagnetic susceptibility if the ferromagnetic minerals have a very low concentration.

Site 39

Figure 7.6a shows that, for a pilot sample from site 39, the principal axes of susceptibility and remanence ellipsoids approximately coincide in direction and magnitude in the case of the 0.16 mT TRM. By contrast, in another specimen of sample 39 and for the 0.06 mT TRM ellipsoid, maximum and minimum susceptibility axes coincide with minimum and maximum remanence axes respectively (figure 7.6b).

SIRM acquisition and AF demagnetization curves of figure 7.7a reveal that no major changes of the primary magnetic mineralogies have taken place in this sample after prolonged heatings to 700°C, thus allowing a confident correlation of the TRM ellipsoids with their susceptibility counterparts. Figure 7.7b shows the p-q correlations for the two cases considered. Although the ranges of p and q values are very limited in both cases, correlation coefficients reveal good linear fits and the relationships \( s = 1 - 3p_s \) are verified (\( p_s = 0.16, \quad s = 0.54, \quad 1 - 3p_s = 0.52; \quad p_s = -0.47, \quad s = -0.42, \quad 1 - 3p_s = -0.41 \)).

SD behaviour is evidenced, as expected, by the lower field (0.06 mT) TRM ellipsoid, with a negative slope of -0.42, a \( p_s \) intercept of 0.47 and a correlation coefficient \( r = -0.92 \). These values do not differ significantly from the ones obtained in the limiting case of SD prolate particles with \( p_s = 0.5 \) and \( s = -0.5 \). On the other hand, the 0.16 mT TRM ellipsoid is controlled by a MD magnetite fraction. Its p-q diagram has a positive slope of 0.54 and an intercept \( p_s = 0.16 \) (\( r = 0.99 \)) characteristic of grain sizes > 90 \( \mu \)m according to figure 7.5. The PSD-like behaviour of this sample revealed from its hysteresis parameters could be a consequence of a mixture of two different magnetite fractions with a pronounced contrast of grain sizes.

Site 13

For a pilot sample from site 13, figure 7.8 shows interchange but still directional agreement of the principal axes of susceptibility and TRM ellipsoids. For a 0.06 mT TRM ellipsoid minimum, intermediate and maximum susceptibility axes coincide approximately with maximum, minimum and
Figure 7.6a, b  For sample 39, in 7.6a, the principal axes of susceptibility and remanence ellipsoids approximately coincide in direction and magnitude for an undemagnetized 0.16 mT TRM. By contrast, in 7.6b, for the 0.06 mT TRM ellipsoid, determined after demagnetizing to an AF peak field of 80 mT, maximum and minimum susceptibility axes coincide with minimum and maximum remanence axes respectively.
Figure 7.7a, b In 7.7a, SIRM acquisition and AF demagnetization curves for sample 39 reveal no major changes of the primary magnetic mineralogies after prologs heating to 700°C. In 7.7b are shown the p (susceptibility) - q (TRM) correlations for the two cases considered in two different specimens from the same sample 39: a 0.16 mT TRM ellipsoid dominated by the MD magnetite fraction with a positive slope of 0.54 and an intercept value of $p_s = 0.16$ ($r = 0.99$) characteristic of grain sizes > 90 μm, and a 0.06 mT TRM ellipsoid dominated by a SD fraction with a negative slope of -0.42, and a $p_s$ intercept of 0.47 ($r = -0.92$) (open and solid circles: correlations 1 and 2 respectively).
SAMPLE 13

Figure 7.8 For sample 13 a demagnetized (AF peak field = 50 mT) 0.06 mT TRM ellipsoid with minimum, intermediate and maximum susceptibility axes approximately coinciding with maximum, minimum and intermediate TRM axes respectively.
Figure 7.9a, b. For sample 13, in 7.9a, SIRM acquisition and AF demagnetization curves reveal no major changes of the primary magnetic mineralogies after prolonged heating to 700°C. In 7.9b the p (susceptibility) - q (TRM) correlation reflects the typical behaviour for SD magnetite with $p_x = 0.52$ and a negative slope of -0.56 ($r = -0.81$) for the 0.06 mT TRM ellipsoid.
intermediate TRM axes respectively. This interchange of axes gives rise to the p-q relationship of figure 7.9b, typical of the limiting case for SD magnetite, with $p_a = 0.52$ and negative slope of -0.56 ($r = -0.81$). SIRM acquisition and AF demagnetization curves of figure 7.9a show that no major changes have taken place in the magnetic phases of pilot sample 13 after heating to 700°C.

**Site 15**

For a pilot sample from site 15, figure 7.10 shows the directional agreement and interchange of the principal axes of susceptibility and TRM (0.16 mT) ellipsoids. As in the case of pilot samples 39 and 13, SIRM acquisition and AF demagnetization curves of figure 7.11a show that no major changes have taken place in the magnetic phases of pilot sample 15 after heating to 700°C.

The p-q correlation ($r = -0.96$) (figure 7.11b) gives unusually high values for the intercept (0.87) and the slope (-1.6). The unusually large uncertainties in the susceptibility readings (figure 7.11b) could explain the anomalous intercepts. As a matter of fact, the theoretical p-q relationship derived for the limiting case of SD behaviour in prolate magnetite grains lies within the experimental error of these susceptibility readings (figure 4.11b).

**Sites LLL-3 and LLL-5**

Pilot samples from the sites LLL3 and LLL5 in the Little Lemoine Lake, located on the northeastern end of the Shawmere anorthosite (figure 6.2), have been analysed using the Stephenson test. Figure 7.12 shows stereographic projections of the directions of the principal axes of the susceptibility and TRM ellipsoids for pilot samples LLL5 and LLL3. Figure 7.12a illustrates, for a 0.16 mT TRM ellipsoid in pilot sample LLL5, the directional coincidence of its intermediate, maximum and minimum axes with the maximum, intermediate and minimum susceptibility axes respectively.

For twin specimens of pilot sample LLL3, 0.06 and 0.16 mT TRM ellipsoids have been induced. Directions of the principal axes of susceptibility and TRM ellipsoids do not match well, especially between the 0.16 TRM ellipsoid and its susceptibility counterpart. Such a mismatch probably reflects the paramagnetic effect that dominates over the low concentration of magnetite, as evidenced by the
Figure 7.10  Directional agreement of the undemagnetized 0.16 mT TRM ellipsoid with its susceptibility counterpart for sample 15. Again an interchange of the principal axes, typical of SD particles, is observed, namely maximum and minimum susceptibility axes coincide with minimum and maximum TRM axes respectively.
Figure 7.11a In 7.11a, SIRM acquisition and AF demagnetization curves revealing that no major changes have taken place in the magnetic mineralogies of sample 15 after prolonged heating to 700°C. In 7.11b the $p$ (susceptibility) - $q$ (TRM) correlation ($r = -0.96$) for a 0.16 mT TRM, reveals unusual high values for the intercept (0.87) and the slope (-1.6). The $p$-$q$ relationship for the limit case of SD particles is shown as a dotted line that lies within the experimental error of the $p$-$q$ relationship for sample 15.
Figure 7.12a, b, c  Stereographic projections of the direction of the principal axes of susceptibility and TRM ellipsoids for samples LLL5 and LLL3. 7.12a illustrates a case of directional agreement but not a simple interchange of minimum and maximum principal axes of susceptibility and TRM (0.16 mT) for sample LLL5. For twin specimens of sample LLL3, 0.06 and 0.16 mT TRM ellipsoids have been induced (7.12b & c). For the undemagnetized 0.16 mT TRM ellipsoid, an interchange between the axes of intermediate and minimum susceptibility with the axes of minimum and intermediate TRM respectively, has been observed. For the undemagnetized 0.06 mT TRM ellipsoid, no interchange of the principal axes has been observed.
Figure 7.13a, b For sample LLL5, in 7.13a SIRM acquisition and AF demagnetization curves show that no major changes have taken place in the magnetic mineralogies of this sample after prolonged heating to 700°C. In 7.13b, the p (susceptibility) - q (TRM) correlations for samples LLL5 and LLL3 (open and solid circles: correlations 1 and 2 respectively; open triangles: correlation 3). For a 0.16 mT TRM, the intercept $p_0 = 0.25$ for sample LLL5 ($r = 0.70$) corresponds to grain sizes in the PSD range between 0.8 - 2.2 µm. Values of $p_0 = 0.13$ and 0.27 ($r = 0.89$ and 0.94) have been obtained for sample LLL3 using 0.06 and 0.16 TRM ellipsoids respectively. These intercepts correspond to grain sizes >90 µm (MD) and 0.8 - 2.2 µm (PSD) respectively.
hysteresis loop of figure A.4a. Axes of intermediate and minimum susceptibility coincide with the axes of minimum and intermediate TRM respectively in the case of the 0.16 mT TRM ellipsoid. For the 0.06 mT TRM ellipsoid no interchange of the susceptibility and TRM axes was observed.

SIRM acquisition and AF demagnetization curves before and after prolonged heatings to 700°C, are shown in figure 7.13a for pilot sample LLL5. As in the cases of pilot samples 39, 13 and 15, these curves evidence the stability of pilot sample LLL5 magnetic mineralogies with heating, allowing a safe use of the TRM ellipsoids in the Stephenson test.

The p-q correlations for pilot samples LLL5 and LLL3 are shown in figure 7.13b. All the three slopes and intercepts follow the expected relationship of \( s = 1 - 3p_e \) (\( p_e=0.27, s=0.21, 1 - 3p_e = 0.19 \); \( p_e=0.13, s=0.62, 1 - 3p_e = 0.61 \); \( p_e=0.25, s=0.25, 1 - 3p_e = 0.25 \)).

The intercept \( p_e = 0.25 \) for pilot sample LLL5 (\( r = 0.70 \)) corresponds to grain sizes in the PSD range between 0.8 - 2.2 μm according to figure 7.5. This result agrees with the PSD behaviour of LLL5 revealed from its hysteresis parameters (figure 7.3).

Two values of \( p_e = 0.13 \) and 0.27 (\( r = 0.89 \) and 0.94) have been obtained for pilot sample LLL3 using 0.06 and 0.16 mT TRM ellipsoids respectively. These intercepts correspond, according to figure 7.5, to grain sizes >90 μm (MD) and 0.8 - 2.2 μm (PSD) respectively. Such a result is opposite to what would be expected, namely that higher field TRM ellipsoids should bring into prominence the MD magnetite fraction, whereas lower field ones should reflect smaller grain contributions to the mixture. The dominant effect of the paramagnetic fraction in this sample (figure A-5) would cloud not only the shape and orientation of the susceptibility ellipsoids but also the actual value of its hysteresis parameters. In fact, for both diagrams of figure 7.3, pilot sample LLL3 plots in the threshold MD-SP.

Sites SH-1 and 41

Figure 7.14 shows the approximately exponential behaviour of the SIRM AF demagnetization curves before heating for pilot samples LLL2, SH-1 and 41. These curves suggest a dominance of large magnetite particles in the range of PSD-MD grain sizes. The small changes after prolonged
Figure 7.14a, b, c The approximately exponential shapes of the SIRM AF demagnetization curves of the unheated samples LLL2 (7.14a), SH-1 (7.14b) and 41 (7.14c) suggest a dominance of large magnetite particles in the range of PSD-MD grain sizes. A shift towards a harder intensity decay spectrum is observed in samples LLL2 (7.14a) and SH-1 (7.14b) after heating to 700°C. For sample 41 (7.14c) no major changes in the shape of before and after heating curves are observed.
heating to 700°C of these curves for samples LLL2 and SH-1 to slightly harder approximately exponential SIRM curves is mostly due to the diminution of the effective grain size of magnetite by partial or total oxidation to hematite. Thus, a conventional Stephenson test using TRM ellipsoids would tend to underestimate the original grain sizes of the magnetite carried by the unheated samples. In the case of sample 41 no major changes in the shape of these curves are observed after heating.

In order to obtain more accurate information about these original sizes of large magnetite grains and/or SD magnetite that would shrink to SP or undergo complete oxidation to hematite after heating, a modification of the Stephenson test using 0.06 and 0.16 mT ARM ellipsoids has been carried out on the unheated pilot samples LLL2, SH-1 and 41. For these samples, TRM ellipsoids are compared with their susceptibility counterparts measured after heating whereas ARM ellipsoids are compared with their susceptibility counterparts measured before heating. Stephenson test parameters for pilot samples LLL2, SH-1 and 41 are included in table 7.2 and a compilation of the p-q correlations for the different treatments applied to these samples is given in appendix B.

SIRM curves reveal that in most cases a considerable amount of SD magnetite is oxidized to hematite during heating; thus smaller grain size fractions than those reflected by the TRM ellipsoid should be detected using ARM ellipsoids. For pilot sample LLL2, the value of the intercept $p_e$ increases from 0.25 ($r = 0.92$) to 0.29 ($r = 0.6$) with AF demagnetization of the 0.16 mT ARM ellipsoid and up to 0.32 ($r = 0.6$) using a lower (0.06 mT) field ARM ellipsoid (figure B.1). As indicated in figure 7.5, there is a negative correlation between the values for the intercept $p_e$ and the grain sizes. Thus, the undemagnetized 0.16 mT ARM ellipsoid provides evidence for a PSD fraction of magnetite with grain sizes between 0.8-2.2 μm. The demagnetized (to 50 mT) 0.16 mT ARM ellipsoid switches the "image" towards smaller magnetite grain sizes (< 0.2 μm), probably close to the PSD-SD threshold. Finally a better "magnification" is obtained using a lower field ARM ellipsoid (0.06 mT) with a higher intercept value $p_e$ corresponding perhaps to "large" SD magnetite.

For pilot sample SH-1 three very distinct fractions of magnetite can be distinguished: a MD fraction ($p_e = 0.18$) with grain sizes in the range 63-75 μm, a PSD fraction ($p_e = 0.20$) with grain sizes between 13.1 and 25.5 μm and a fraction with grain sizes < 0.2 μm ($p_e=0.3$) probably close to the PSD-SD threshold (figure B.2).
Pilot sample 41 shows $p_s$ values between 0.25 (0.16 mT TRM) and 0.30 (0.06 mT ARM) corresponding to magnetite grain sizes in the PSD range going from approximately 2.2 μm to less than 0.2 μm (figure B.3).

Whereas hysteresis parameters lack the power to discriminate between magnetites with different grain sizes in n-modal mixtures, the Stephenson test seems to be more sensitive in separating the signals of these different fractions. Thus, ambiguous hysteresis results can be now explained in a new light.

Sites SH-2 and 16

Figure 7.15 shows the SIRM AF demagnetization curves for pilot samples from sites SH-2 and 16. In these cases the dominant fine-grained magnetite fractions turn into SP or undergo complete oxidation to hematite after prolonged heating to 700°C. Thus, the signal of a minor MD fraction characterized by a approximately exponential curve, becomes almost completely uncovered after heating, contrasting with its less exponential pre-heating counterparts.

TRM ellipsoids are compared here with susceptibility ellipsoids measured in the heated samples, whereas ARM ellipsoids are compared to susceptibility ellipsoids measured in the fresh samples before heating. Stephenson test parameters for pilot samples LLL2, SH-1 and 41 are included in table 7.2 and a compilation of the p-q correlations for the different treatments applied to these samples is given in Appendix B.

For pilot sample SH-2, two slightly distinct fractions of magnetite can be distinguished: a PSD fraction ($p_s=0.23$) with grain sizes in the range 2.2-4.4 μm and a PSD fraction ($p_s = 0.26$ or 0.27) with grain sizes between 0.2 and 0.8 μm (figure B.4).

For pilot sample 16, only a SD magnetite fraction can be detected with $p_s=0.4$ and a negative slope for the p-q correlations. The MD fraction evidenced by the approximately exponential shape of the SIRM AF demagnetization curve after heating passes completely undetected by the Stephenson test (figure B.5).
Figure 7.15a, b SIRM AF demagnetization curves for samples SH-2 (7.15a) and 16 (7.15b). The dominant fine-grained magnetite fractions turn into SP or undergo complete oxidation to hematite after prolonged heating to 700°C. Thus the signal of a minor MD fraction characterized by an approximately exponential decay curve, becomes uncovered after heating contrasting with its non-exponential pre-heating counterpart.
<table>
<thead>
<tr>
<th>Sample</th>
<th>Distance² (km)</th>
<th>p²₀</th>
<th>r²₀</th>
<th>±1-3p₀</th>
<th>r</th>
<th>Ellipsoid</th>
<th>Anis. No.²₀</th>
<th>Anis. RM²₀</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>4.5</td>
<td>0.16</td>
<td>0.54</td>
<td>0.52</td>
<td>0.99</td>
<td>0.16 mT TRM</td>
<td>1.08</td>
<td>1.15</td>
<td>0 mT</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.47</td>
<td>-0.42</td>
<td>-0.41</td>
<td>-0.92</td>
<td>0.06 mT TRM</td>
<td>1.10</td>
<td>1.25</td>
<td>80 mT</td>
</tr>
<tr>
<td>13</td>
<td>1.8</td>
<td>0.52</td>
<td>-0.56</td>
<td>-0.56</td>
<td>-0.81</td>
<td>0.06 mT TRM</td>
<td>1.16</td>
<td>1.25</td>
<td>0 mT</td>
</tr>
<tr>
<td>15</td>
<td>2.5</td>
<td>0.87</td>
<td>-1.6</td>
<td>-1.6</td>
<td>-0.96</td>
<td>0.16 mT TRM</td>
<td>1.89</td>
<td>1.45</td>
<td>0 mT</td>
</tr>
<tr>
<td>L1L3</td>
<td>16.0</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.70</td>
<td>0.16 mT TRM</td>
<td>1.14</td>
<td>1.19</td>
<td>0 mT</td>
</tr>
<tr>
<td>L1L3</td>
<td>-</td>
<td>0.13</td>
<td>0.62</td>
<td>0.61</td>
<td>0.94</td>
<td>0.06 mT TRM</td>
<td>1.29</td>
<td>1.41</td>
<td>0 mT</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.27</td>
<td>0.21</td>
<td>0.19</td>
<td>0.89</td>
<td>0.16 mT TRM</td>
<td>1.11</td>
<td>1.38</td>
<td>0 mT</td>
</tr>
<tr>
<td>L1.L2</td>
<td>-</td>
<td>0.14</td>
<td>0.57</td>
<td>0.58</td>
<td>0.75</td>
<td>0.16 mT TRM</td>
<td>1.79</td>
<td>2.19</td>
<td>50 mT</td>
</tr>
<tr>
<td>L1.L2</td>
<td>16.0</td>
<td>0.25</td>
<td>0.24</td>
<td>0.25</td>
<td>0.92</td>
<td>0.16 mT ARM</td>
<td>1.13</td>
<td>1.65</td>
<td>0 mT</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.29</td>
<td>0.12</td>
<td>0.13</td>
<td>0.6</td>
<td>-</td>
<td>1.13</td>
<td>1.75</td>
<td>50 mT</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.32</td>
<td>0.03</td>
<td>0.04</td>
<td>0.6</td>
<td>0.06 mT ARM</td>
<td>1.08</td>
<td>2.25</td>
<td>50 mT</td>
</tr>
<tr>
<td>16</td>
<td>4</td>
<td>0.39</td>
<td>-0.17</td>
<td>-0.17</td>
<td>-0.96</td>
<td>0.16 mT TRM</td>
<td>1.11</td>
<td>1.91</td>
<td>50 mT</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.40</td>
<td>-0.21</td>
<td>-0.2</td>
<td>-0.94</td>
<td>-</td>
<td>1.11</td>
<td>1.66</td>
<td>0 mT</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.37</td>
<td>-0.12</td>
<td>-0.11</td>
<td>-0.84</td>
<td>0.16 mT ARM</td>
<td>1.07</td>
<td>1.74</td>
<td>0 mT</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.37</td>
<td>-0.10</td>
<td>-0.11</td>
<td>-0.80</td>
<td>-</td>
<td>1.07</td>
<td>1.27</td>
<td>50 mT</td>
</tr>
<tr>
<td>S1I-2</td>
<td>4.5</td>
<td>0.24</td>
<td>0.27</td>
<td>0.28</td>
<td>1</td>
<td>0.16 mT TRM</td>
<td>1.11</td>
<td>1.46</td>
<td>50 mT</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.23</td>
<td>0.32</td>
<td>0.31</td>
<td>0.93</td>
<td>-</td>
<td>1.11</td>
<td>1.39</td>
<td>0 mT</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.26</td>
<td>0.21</td>
<td>0.22</td>
<td>0.82</td>
<td>0.16 mT ARM</td>
<td>1.17</td>
<td>1.71</td>
<td>0 mT</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.27</td>
<td>0.18</td>
<td>0.19</td>
<td>0.80</td>
<td>-</td>
<td>1.17</td>
<td>1.85</td>
<td>50 mT</td>
</tr>
<tr>
<td>S1I-1</td>
<td>5.3</td>
<td>0.18</td>
<td>0.46</td>
<td>0.46</td>
<td>0.96</td>
<td>0.16 mT TRM</td>
<td>1.17</td>
<td>1.36</td>
<td>0 mT</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.20</td>
<td>0.39</td>
<td>0.4</td>
<td>0.90</td>
<td>-</td>
<td>1.17</td>
<td>1.32</td>
<td>50 mT</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.31</td>
<td>0.07</td>
<td>0.07</td>
<td>0.51</td>
<td>0.06 mT ARM</td>
<td>1.13</td>
<td>1.49</td>
<td>75 mT</td>
</tr>
<tr>
<td></td>
<td>5.3</td>
<td>0.21</td>
<td>0.68</td>
<td>0.07</td>
<td>0.98</td>
<td>0.16 mT ARM</td>
<td>1.07</td>
<td>2.3</td>
<td>0 mT</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.32</td>
<td>0.05</td>
<td>0.04</td>
<td>0.90</td>
<td>-</td>
<td>1.07</td>
<td>3.25</td>
<td>50 mT</td>
</tr>
<tr>
<td>41</td>
<td>9.0</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.96</td>
<td>0.16 mT TRM</td>
<td>1.12</td>
<td>1.5</td>
<td>50 mT</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.26</td>
<td>0.22</td>
<td>0.22</td>
<td>0.96</td>
<td>0.16 mT ARM</td>
<td>1.18</td>
<td>1.76</td>
<td>50 mT</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.30</td>
<td>0.10</td>
<td>0.1</td>
<td>0.88</td>
<td>0.06 mT ARM</td>
<td>1.13</td>
<td>2.34</td>
<td>50 mT</td>
</tr>
</tbody>
</table>

(1) Distance from the hypothetical carbonate trend
(2) Experimental values
(3) Maximum eigenvalue/minimum eigenvalue

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
7.4 Analysis of thin sections

Analyses of thin sections in transmitted light microscopy reveal that, in general, alteration in the Shawmere anorthosite takes the form of veins and cracks that cut pervasively through the primary plagioclase crystals. In most cases, opaque minerals occur as a powder of fine grains associated with the alteration veins; hence their origin is probably secondary. Moreover, the degree of alteration seems to be related to the amount, and the size, of the opaque minerals observed.

For highly altered pilot samples 39 and 13 (figure 7.16), SD and the lower range of PSD magnetite grain sizes (< 10 μm) with p_o values > 0.22 cannot be seen at the magnification permitted by the optical microscope used for thin section analyses. Intercept values p_o>0.23 for pilot samples 41 and SH2 (figures 7.17 & 7.18) agree with the thin section observations of fine-grained opaque minerals filling veins and cracks in the plagioclase.

Most of the Little Lemoine Lake samples (figures 7.19 & 7.20) are fresh and it is difficult to find visible opaque minerals in thin sections for these samples. The few opaque minerals observed appear as a barely recognizable, very fine powder, filling inclusions and small veins within the plagioclase crystals, or as large isolated hematite or oxidized magnetite grains. The p_o intercepts for the Little Lemoine samples, ranging between 0.25-0.30 (PSD-SD) and also =0.13 (MD), agree with these observations.

7.5 Chemical overprinting in the Shawmere anorthosite

In order to test the hypothesis that crystallization and growth of magnetite in the Shawmere anorthosite was caused by late Proterozoic carbonatite intrusions, rock magnetic and thin section results and observations will now be examined as a function of distance from the hypothetical carbonatite trend of figure 6.2.

Figure 7.21a shows the Königsberger ratios for the Shawmere anorthosite samples plotted against distance from the carbonatite trend. With this approach, a correlation can be seen that was not apparent in the M_{FOM} vs. k_o x 0.6 diagram of figure 7.2. In fact, the broad ranges of Q_o values spanning at least two orders of magnitude seem to narrow progressively away from the carbonatite
trend. A similar correlation can be observed by plotting \( p_o \) values, derived from the Stephenson tests, against distance from the same trend. This plot is shown in figure 7.21b. Once more, a narrowing of the range of \( p_o \) values away from the trend is suggested by this diagram. Thus, it seems quite reasonable to suppose that these sort of variations of \( Q_o \) and \( p_o \) values (which have been independently determined) away from the carbonatite trend, are not fortuitous but are the direct consequence of the effects of proximity to a focus of hydrothermal alteration.

In fact, values for \( p_o \) corresponding to both MD and SD (0.87 to 0.5) magnetite fractions occur close to such a focus of hydrothermal activity or carbonatite trend reflecting the presence of different generations of coexisting primary and secondary magnetite. For these samples, secondary SD, PSD or MD magnetite have probably grown and/or crystallized from their primary PSD or SD counterparts.

At a critical distance of \( \approx 9 \) km from the carbonatite trend, \( p_o \) is restricted to values of \( \approx 0.3 \), typical of grain sizes around the PSD-SD threshold and probably corresponding to primary magnetite fractions that have survived hydrothermal alteration almost untouched. Finally, at \( \approx 16 \) km from the carbonatite trend, the range of grain sizes seems to widen again, probably due to the presence of the nearby Ivanhoe Lake Cataclastic Zone (ILCZ), a major zone of weakness that could also channel part of the fluids that accompanied the emplacement of the carbonatite intrusions in the region.

The simple approach used here of relating magnetic properties to distance from the carbonatite trend is prone to the disturbances produced by zones of weakness like the ILCZ that cut everywhere in the Chapleau block (figure 6.2) and act as alternative foci of hydrothermal alteration. In addition, systematic variations of the magnetic mineralogies in the Shawmere anorthosite away from the ILCZ and corresponding to the different lithological levels exposed in the KSZ cross-section can also be expected.

Analyses of thin sections show some trends that also seem to be significant. First, the occurrence of opaque minerals is, in most cases, associated with alteration veins in the plagioclases. Thus the degree of alteration seems to determine the amount, and the size of the opaque minerals observed. Secondly, samples like those from sites 39 and 13, relatively close to the carbonatite trend, show heavier alteration than those from sites LLL2, LLL3, LLL5 and 41 located further away. However, the relatively few samples analysed in thin sections do not allow any final conclusion about the reliability of these trends.
Figure 7.16a, b, c, d  Plane polarized photomicrographs of samples from sites 39 (a & b) and 13 (c & d). In a sample from site 39 (figures 7.16a & b), thick alteration veins show the association of a powder of fine-grained opaque minerals. The same situation is observed in a sample from site 13 (figure 7.16c). Also for this sample, figure 7.16d shows two large opaque grains that have been split by a crack in the plagioclase.
Figure 7.17a, b  Cross-polarized transmitted light photomicrographs for a sample from site 41. Figure 7.17a shows interstitial and fine-grained opaque minerals with rusty rims between the plagioclase crystals. Figure 7.17b shows a crack within a relatively fresh plagioclase crystal with associations of very fine-grained opaque minerals within (figure 7.17b).
Figure 7.18a, b  Cross polarized and plane polarized transmitted light photomicrographs for a sample from site SH2 showing very fine-grained opaque minerals growing within a fresh plagioclase crystal. Opaque minerals for this sample are even more difficult to distinguish than those from the sample from site 41.
Figure 7.19a, b, c, d  For a sample from site LLL5, the cross-polarized transmitted light photomicrograph of figure 7.19a reveals almost unaltered plagioclase crystals. Figures 7.19b, c (plane polarized) and d (cross polarized) are photomicrographs of samples from sites LLL5, LLL2 and LLL3 respectively showing a very fine powder of opaque minerals filling inclusions and thin veins within the plagioclase crystals.
Figure 7.20 In some cases, like the example shown in this cross-polarized transmitted light photomicrograph from a sample from site LLL3, large opaque grains can be observed in isolation between plagioclase crystals. In this case, the reddish rim surrounding the opaque mineral suggests that it could be a hematite grain or a hematite coating on an oxidized magnetite crystal.
Figure 7.21a, b 7.21a shows the Königsberger ratios for the Shawmere anorthosites plotted against distance from the carbonatite trend. The broad ranges of $Q_a$ values, spanning at least two orders of magnitude, seem to narrow progressively away from the carbonatite trend. In 7.21b a clearer correlation can be observed by plotting $p_o$ values, derived from the Stephenson tests, against distance from the trend. Once more a narrowing of the $p_o$ values, away from the carbonatite trend, is evidenced by this diagram. Variations of $Q_a$ and $p_o$ values away from the carbonatite trend could be a direct consequence of proximity to a focus of hydrothermal alteration.
7.6 Conclusions

In the search for guiding patterns that would allow an assessment of the hypothesized chemical or thermochemical overprints (B components) in the Shawmere anorthosite, a novel granulometric test (Stephenson test), especially suited to the study of natural samples, has been extensively used and developed.

Conventional granulometric methods, such as the study of alternating field demagnetization spectra of TRMs and SIRMs and hysteresis parameters, prove ambiguous when applied to natural samples with n-modal distributions of magnetite with different grain sizes. On the other hand, Stephenson’s granulometric test, based on the comparison of TRM and susceptibility anisotropy ellipsoids, although not yet completely controlled, seems to provide more alternatives and flexibility in the study of these n-modal distributions. The values of slope, s, and intercept, \( p_\alpha \), of the linear relationship between the relative lengths p and q of the principal axes in the susceptibility and TRM ellipsoids, are a guide to the sizes of the individual grains of magnetite.

Experimental modifications to the conventional Stephenson test can be applied in order to pinpoint different fractions of magnetite with different grain sizes coexisting in the same sample. 0.16 mT TRM ellipsoids and prolonged heating of the samples at temperatures to 700°C seem to enhance the signal produced by the larger magnetite grains, which is reflected by the lower values of the \( p_\alpha \) intercepts and the positive slopes of the p-q correlations.

On the other hand, progressively higher values of the \( p_\alpha \) intercepts reflecting progressively smaller magnetite grain sizes, can be obtained by working with the unheated samples using ARM ellipsoids; by observing their changes in orientation and shape after AF demagnetization, and/or by inducing different ARM ellipsoids with different fields in the same samples and looking at their changes in shape. All these experimental modifications of the original test have been applied in different situations to samples from the Shawmere anorthosite and the results obtained have been tested by thin section analyses and some of them compared to those derived from traditional granulometric methods (appendix B).

Finally, the hypothesis of a carbonatite trend that connects the different alkaline complexes in the Chapleau block of the KSZ and was responsible for major effects in the Shawmere anorthosite,
such as extensive hydrothermal alteration, growth and crystallization of magnetite and late Proterozoic magnetization overprinting, can be tested on the basis of these granulometric results. In fact, a plot of $p_a$ values against distance from the carbonatite trend shows a sort of variation, in which broad ranges of $p_a$ values seem to progressively narrow away from the major focus of hydrothermal alteration. A similar correlation is observed by plotting Königsberger ($Q_a$) ratios versus distance from the same carbonatite trend. These correlations are explained as the result of the diversification of magnetite grain sizes in those anorthosite samples that are close to the major foci of hydrothermal alteration, since in these cases secondary crystallized or hydrothermally grown magnetite would coexist with PSD-SD primary counterparts. Away from the carbonatite trend and the ILCZ, unaltered anorthosite samples preserve their primary PSD-SD magnetic mineralogies almost untouched, as reflected by the narrow ranges of the observed $Q_a$ and $p_a$ values.
CHAPTER 8

CONCLUSIONS

8.1 Summary of results

The main results and direct implications coming from the two test-cases studied in this thesis can be summarized as follows:

Red Lake greenstone belt

1.- Component RLR, a primary TRM dating from ≈2700 Ma \(^{40}\text{Ar}/^{39}\text{Ar} \) initial cooling age; McMaster, 1987), has been isolated in the largely unaltered batholiths of the Red Lake greenstone belt. This component seems to be carried mainly by fine-grained magnetite and deuterite hematite. Its primary origin and thermal nature are suggested on the basis of its high coercivities (>30 mT), high unblocking temperatures (>500°C), its strong intensity values (ranging approximately between 40 and 4500 mA/m) and the pristine appearance of the opaque minerals in thin section.

2.- Component RLG, a secondary TCRM probably ≈2580 Ma old, has been isolated from some units hydrothermally altered in the same event that affected the supracrustal units of the belt. The age of this component has been derived from the proximity of its paleopole to its well-dated counterpart for the Shelley Lake granite (Dunlop, 1984a; Berger and York, 1979). RLG could have been acquired at a temperature of ≈260°C according to the \(^{40}\text{Ar}/^{39}\text{Ar} \) ages corresponding to the latest stages of the cooling history of the Red Lake greenstone belt (Wright, 1989). RLG seems to be carried mainly by secondary hematite judging from the initial susceptibility values and the shape of the isothermal remanent magnetization acquisition
(IRM) and AF demagnetization curves of the samples that carry it. RLG-bearing hematite is probably a by-product of low temperature oxidation of primary magnetite. Its secondary chemical nature and origin are suggested on the basis of its high coercivities (>40 mT), high unblocking temperatures (>500°C), its characteristic weak intensity values (ranging approximately between 3-300 mA/m) and the high alteration of the opaque minerals and silicates observed in thin section which contrast dramatically with their RLR-bearing counterparts.

3.- Whereas RLR is one of the oldest ⁴⁰Ar/³⁹Ar dated paleopoles for North America, RLG probably represents one of the first documented paleomagnetic records indicating gold mineralization in Precambrian units.

4.- The positions of the paleopoles corresponding to RLR and RLG define a path in the northern hemisphere that goes from North America to central Asia through the North Pole (figure 4.12a). This path also includes the paleopoles for the Shelley Lake granite (2580 Ma, ⁴⁰Ar/³⁹Ar hornblende and biotite, Dunlop, 1984; Berger and York, 1979), the Matachewan/Heast dikes (2450 Ma U/Pb zircon, Heaman, 1988; and 2480 Ma U/Pb baddeleyite isochron, Smith and Farquhar, 1988), the Otto Stock in the Abitibi belt (Pullaiah and Irving, 1975; Buchan et al, 1989; Corfu et al, 1990) and the recently reported paleopoles for some intrusives in the Meens Lake-Dempster Lake greenstone belt in northwestern Ontario (Hale and Lloyd, 1989). The trend of this path redefines the late Archean and early Proterozoic apparent polar wander path (APWP) for Laurentia aging now in the opposite sense of that previously accepted (figure 4.12b).

5.- The redefined path suggests that most of the supposedly Archean paleopoles for North America are not of primary origin. It also suggests a rate of paleolatitudinal change for Laurentia of ≈2.5 cm/yr contrasting with a previous estimate of ≈4-5 cm/yr by Irving (1979). Such a result agrees with those drift velocities calculated for other Precambrian cratons at about the same period.
Shawmere Anorthosite

1.- Component B in the late Archean Shawmere anorthosite, previously interpreted by Symons et al (1988) as a TRM dating from the time of uplift and subsequent cooling of the Chapleau block (southernmost lobe of the Kapuskasing Structural Zone (KSZ)), has been interpreted by Costanzo-Alvarez and Dunlop (1988) as a Keweenawan (ca. 1100 Ma) remagnetization triggered by the late emplacement of a series of alkaline complexes adjacent to the Shawmere anorthosite. This last hypothesis is based on the initial observations of the proximity of the B paleopole to the Keweenawan section of the APWP for North America (Logan loop), the prominence of this component at Shawmere sites close to the Nemegosenda intrusion and the evidence provided by \(^{40}\text{Ar}^{39}\text{Ar}\) feldspars ages in the range 1200-1000 Ma in the Chapleau block (Farrar and Archibald, 1985; Lopez-Martinez and York, 1990). In this study a B-like component (B1) has been isolated from the alkaline complexes themselves, namely the Shenango River, Nemegosenda Lake, Lackner Lake and Borden alkaline complexes, thus confirming the hypothesis of Keweenawan remagnetization of the Shawmere anorthosite.

2.- Along with the B-like magnetization originally isolated from the Shawmere anorthosite by Costanzo-Alvarez and Dunlop (1988) and Symons et al (1988) (components B1N and R), another Keweenawan direction of remanence, B2 (N and R), has been found in both the alkaline complexes and the Shawmere anorthosite. Its corresponding paleopoles fall in younger positions on the Logan loop than those for component B1 (N and R). Thus, this component probably represents a later magnetization acquired during cooling of the alkaline intrusions, or more likely by intermittent alkaline magmatism, as suggested by the radiometric ages available and the different petrological phases observed in these complexes.

3.- A B1R-like direction of remanence with steeper inclinations and higher median destructive fields seems to underlie B1R in the Shawmere anorthosite. The directional proximity of B1R to this steep up magnetization makes difficult a characterization of each of these two components. However there is an obvious streaking between their two directions of remanence when site means are plotted together in the same stereonet. Magnetic isotropy of these anorthosites and their inability to pick up recent viscous overprints, both characteristics directly related to their dominant fine-grained magnetite fractions, rule out the possibility of
having an unique steep up component whose direction has been biased towards shallower BIR-like inclinations by magnetic fabric effects and PEF contamination. This high coercivity steep up component could be the older remanence interpreted by Symons et al as a \( \approx 2000 \) Ma TRM acquired during uplift of the Chapleau block.

4. A granulometric test (Stephenson test), especially suited to the study of natural samples, has been extensively used and developed in order to assess the nature of the B components in the Shawmere anorthosite. This test suggests that B remanences could be thermochemical overprints produced by growth and crystallization of magnetite as a consequence of extensive hydrothermal alteration.

5. Hydrothermal alteration probably took place along a hypothetical carbonatite trend that connects the alkaline complexes in the Chapleau block. The idea of such a line acting as a local focus of alteration assumes a rather extensive post-intrusion effect of the carbonatite bodies on the other units of the Chapleau block. Such an idea, however, is not only supported by the \(^{40}\text{Ar}/^{39}\text{Ar}\) feldspar ages (Farrar and Archibald, 1985; Lopez-Martinez and York, 1990), but also by evidence from oxygen isotopic disequilibrium in quartz-feldspar and feldspar-biotite pairs in the tonalitic rocks, which is a consequence of low temperature retrograde processes that took place after crystallization of the tonalites, and involving a hydrous fluid phase on a limited scale (Li et al, 1988).

6. Stephenson test parameters, along with Königsberger ratios and analyses of thin sections, allow a preliminary mapping of the extent of hydrothermal alteration in the Shawmere anorthosite. In fact, a plot of \( p_o \) values (Stephenson test parameter directly related to magnetite grain sizes) against distance from the carbonatite trend suggests a variation, in which broad ranges of \( p_o \) values progressively narrow away from this hypothetical focus of alteration. A similar correlation is observed by plotting Königsberger (\( Q_o \)) ratios versus distance from the same carbonatite trend. Moreover, thin section analyses suggest that alteration is related to the amount, and the size of the opaque minerals observed. In fact, both alteration and opaque minerals grain sizes seem to decrease with distance from the carbonatite trend. All these pieces of evidence together lead to the conclusion that the observed wide ranges of magnetic grain sizes close to the carbonatite trend could be associated with hydrothermal alteration, reflecting the presence of different generations of
coexisting primary and secondary magnetite. For these samples, secondary SD, PSD and MD magnetite have probably grown and/or crystallized from their PSD or SD primary counterparts. The primary magnetites, on the other hand, have survived hydrothermal alteration almost untouched in those sites far away from the carbonatite trend.

The modified Stephenson test

1.- The Stephenson test involves a comparison of the shape and orientation of TRM (or ARM in the modified version) and susceptibility anisotropy ellipsoids. Whereas traditional granulometric techniques such as the Lowrie-Fuller test and the analysis of hysteresis parameters lack in general the power to discriminate between magnetites with different grain sizes in n-modal mixtures, the Stephenson test seems to be more sensitive in separating the signals of these different fractions and thus more suitable for granulometric studies in natural samples.

2.- The values of slope, $s$, and intercept $p_x$, of the linear relationship between the relative lengths $p$ and $q$ of the principal axes in the susceptibility and TRM ellipsoids, are sensitive to the sizes of the individual grains of magnetite. In order to pinpoint different fractions of magnetite in an n-modal grain size mixture, experimental modifications to the original Stephenson test have been made. TRM or ARM ellipsoids induced at larger fields seem to be dominated by the larger magnetite grains, whereas those induced at progressively lower fields are dominated by progressively smaller grains. A TRM ellipsoid induced at fields of $\approx 0.16$ mT and prolonged heating of the samples at temperatures as high as $700^\circ$C seem to enhance the signal produced by the larger magnetite grains, as reflected by the lower values of the $p_x$ intercepts, and the positive slopes of the $p$-$q$ correlations. On the other hand, progressively higher values of these intercepts, reflecting progressively smaller magnetite grain sizes, can be obtained by working with TRM ellipsoids induced at a lower field of $\approx 0.06$ mT. They also can be obtained by working with the unheated samples using ARM ellipsoids; by demagnetizing these ellipsoids and observing their changes in shape and orientation; and/or by inducing different ARM ellipsoids with different fields in the same samples and looking at their changes in shape and direction.
8.2 General Implications and future work

Following the original goals described in chapter 1, the results of this thesis have demonstrated, in a general fashion, that:

1.- In order to recover Archean remanent magnetizations it is important to choose a test-region such as the Red Lake greenstone belt, with a well-documented cooling history. A careful analysis of the magnetic properties of the samples analysed is also required in order to pinpoint the real nature and origin of their remanent magnetizations.

2.- Precambrian chemical and/or thermochemical overprints can be evaluated by a careful and appropriate analysis of the magnetic properties of the carriers of these secondary remanences, even to the extent of constraining the timing of ore mineralization (Red Lake), or mapping out the source and scope of the hydrothermal alteration that gave rise to the acquisition of these CRMs or TCRMs (Shawmere anorthosite).

These two general conclusions lead to some ideas and considerations for immediate future work:

1.- A complete and careful re-evaluation of the age and type of magnetization for those paleopoles previously reported as ≈2700 Ma and ≈2400 Ma old in figure 4.12b is called for. Such an evaluation becomes important in the light of a re-defined late Archean-early Proterozoic APWP for Laurentia.

2.- The use of paleomagnetism and rock magnetism in order to constrain the timing of ore mineralization and to evaluate the regional effects of hydrothermal alteration plus a characterization of associated TCRMs, remains incomplete without a reliable way of estimating the real blocking temperatures at which those TCRMs were acquired. The use of oxygen isotope analysis directly on the altered magnetites has been widely employed in determining paleotemperatures of final equilibration of cogenetic oxygen-bearing minerals but seldom used in combination with paleomagnetism (Ellwood and Wenner, 1981; Criss and Champion, 1984; Hugstrum and Johnson, 1986). Current research at University of Toronto addresses this
problem in two different ways. Working with synthetic and natural samples Dr. H. Ueno is trying to decompose the thermal demagnetization curves of magnetite and hematite ores into their CRM and TRM components in order to determine the real temperatures of ore mineralization. In a less direct way, the preliminary results of $^{40}\text{Ar}/^{39}\text{Ar}$ dating of magnetites by Dr. Ö. Özdemir show a long range potential, if applied to ore magnetites, for directly determining their ages and Ar diffusion blocking temperatures, these latter probably close to the real magnetic blocking temperatures in which the TCRMs were acquired.

More specific considerations for future work are:

1.- A complete U/Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ study of the alkaline complexes in the Superior province is needed that would complement and clarify the real age and geological history of these complexes. In addition, such a study would be the final answer not only to the questions regarding the real age of component B but also to those regarding its origin in the Shawmere anorthosite.

2.- Applying the Stephenson test in an extensive study of synthetic samples with dispersed magnetites whose grain sizes are well-documented and well constrained to narrow ranges, would be useful to establish a reliable guide for comparison when working with natural n-modal samples of unknown magnetite grain sizes.
REFERENCES


Canadian Journal of Earth Sciences, 21, 879-886.


Halls, H.C.; & E.G. Shaw (1988) Paleomagnetism and orientation of Precambrian dikes, eastern


Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.


APPENDIX A
HYSTERESIS LOOPS FOR SOME OF THE SHAWMERE ANORTHOSITE SAMPLES

Hysteresis loops over the whole range of applied fields (to +/- 600 mT) for some of the Shawmere anorthosites are shown in the following figures. These loops were measured at room temperature with a saturating field of 600 mT. Accompanying diagrams are enlargements of the reduced ranges of applied fields where saturation isothermal remanence (M_r) and coercive force (H_c) were determined, and the linear relationships obtained between remanent magnetization versus DC demagnetization field for each sample previously saturated at 800 mT (chapter 3), which provide an estimate for the remanence coercivity (H_r).

The distortion observed in some of these loops, specially in those of samples 13 and LLL3, seems to be the consequence of the dominance of the paramagnetic fraction over very low concentrations of magnetite.
Figure A.1a, b, c  Hysteresis loop over the whole range of applied fields (to 600 mT) for anorthosite sample 39-5 (A.1a). Accompanying diagrams are: A.1b, an enlargement of the reduced ranges of applied fields where $M_{ax}$ (0.141 mA·m$^{-2}$) and $H_c$ (25.4 mT) were determined, and A.1c, the linear relationship obtained between magnetization versus DC demagnetization field for each sample previously saturated at 800 mT, which provides an estimate for $H_e$ (58.3 mT).
Figure A.2a, b, c  Hysteresis loop over the whole range of applied fields (to 600 mT) for anorthosite sample 13 (A.2a). Accompanying diagrams are: A.2b, an enlargement of the reduced ranges of applied fields where \( M_s \) (0.02 mA-m\(^2\)) and \( H_c \) (12.2 mT) were determined, and A.2c, the linear relationship obtained between magnetization versus DC demagnetization field for each sample previously saturated at 800 mT, which provides an estimate for \( H_s \) (51.7 mT). The distortion observed in the hysteresis loop of A.2a seems to be the consequence of the dominance of the paramagnetic fraction, due to a very low concentration of magnetite.
Figure A.3a, b, c  Hysteresis loop over the whole range of applied fields (to 600 mT) for anorthosite sample 15 (A.3a). Accompanying diagrams are: A.3b, an enlargement of the reduced ranges of applied fields where $M_s$ (0.006 mA·m$^2$) and $H_C$ (8.7 mT) were determined, and A.3c, the linear relationship obtained between magnetization versus DC demagnetization field for each sample previously saturated at 800 mT, which provides an estimate for $H_s$ (40.3 mT).
Figure A.4a, b, c  Hysteresis loop over the whole range of applied fields (to 600 mT) for anorthosite sample LLL3 (A.4a). Accompanying diagrams are: A.4b, an enlargement of the reduced ranges of applied fields where \( M_{ax} \) (0.004 mA-m²) and \( H_c \) (3.2 mT) were determined, and A.4c, the linear relationship obtained between magnetization versus DC demagnetization field for each sample previously saturated at 800 mT, which provides an estimate for \( H_c \) (31.5 mT). The distortion observed in the hysteresis loop of A.2a seems to be the consequence of the dominance of the paramagnetic fraction, due to a very low concentration of magnetite.
Figures A.5a, b, c  Hysteresis loop over the whole range of applied fields (to 600 mT) for anorthosite sample LLL5 (A.5a). Accompanying diagrams are: A.5b, an enlargement of the reduced ranges of applied fields where \( M_{rs} \) (0.038 mA-m²) and \( H_c \) (20.2 mT) were determined, and A.5c, the linear relationship obtained between magnetization versus DC demagnetization field for each sample previously saturated at 800 mT, which provides an estimate for \( H_c \) (63 mT).
APPENDIX B
P-Q CORRELATIONS (MODIFIED STEPHENSON TEST) FOR SOME SAMPLES FROM THE SHAWMERE ANORTHOSITE

The values of slope, s, and intercept p_n, of the linear relationship between the relative lengths p and q of the principal axes in the susceptibility and TRM ellipsoids, are sensitive to the sizes of the individual grains of magnetite. In order to pinpoint different fractions of magnetite in an n-modal grain size mixture, experimental modifications to the original Stephenson test have been applied. TRM or ARM ellipsoids induced at larger fields seem to be dominated by the larger magnetite grains, whereas those induced at progressively lower fields are dominated by progressively smaller grains. A TRM ellipsoid induced at fields of \approx 0.16 mT and prolonged heating of the samples at temperatures as high as 700°C seem to enhance the signal produced by the larger magnetite grains, as reflected by the lower values of the p_n intercepts, and the positive slopes of the p-q correlations. On the other hand, progressively higher values of these intercepts, reflecting progressively smaller magnetite grain sizes, can be obtained by working with TRM ellipsoids induced at a lower field of \approx 0.06 mT. They can also be obtained by working with the unheated samples using ARM ellipsoids; by demagnetizing these ellipsoids and observing their changes in shape and orientation; and/or by inducing different ARM ellipsoids with different fields in the same samples and looking at their changes in shape and direction.

Examples of p-q correlations for some Shawmere anorthosite samples are shown in the following figures for different types of TRMs or ARMs.
Figure B.1a, b, c  In B.1a, for sample LLL-2, the two p (susceptibility) - q (TRM) correlations corresponding to the demagnetized and demagnetized (to 50 mT) 0.16 mT TRM ellipsoids (open and solid circles: correlations 1 and 2 respectively). For the demagnetized case, an intercept of $p_s = 0.28$ ($r = 0.15$) has been derived. The fitting of this line is improved to a correlation factor of $r = 0.75$ using the demagnetized ellipsoid. For this line, the intercept of $p_s = 0.14$ suggests a fraction of magnetite grain sizes > 90 μm (MD). In B.1b & c, for the same sample, three p (susceptibility) - q (ARM) correlations corresponding to the three ARM cases considered (in B.1b, open and solid circles: correlations 1 and 2 respectively). The value of the intercept $p_s$ increases from 0.25 ($r = 0.92$) to 0.29 ($r = 0.6$) with AF demagnetization of the 0.16 mT ARM ellipsoid and up to 0.32 ($r = 0.6$) using a lower (0.06 mT) field ARM ellipsoid. The demagnetized 0.16 mT ARM ellipsoid evidences a PSD fraction of magnetite with grain sizes between 0.8-2.2 μm (B.1b). The demagnetized 0.16 mT ARM ellipsoid (to 50 mT) switches the "image" towards smaller magnetite grain sizes (< 0.2 μm) probably close to the PSD-SD threshold. The best "magnification" is obtained, however, using a lower field ARM ellipsoid (0.06 mT) with a higher intercept value $p_s$ corresponding perhaps to "large" SD magnetite (B.1c).
In B.2a, for sample SH-1, p (susceptibility) - q (TRM) correlations corresponding to a MD fraction ($p_1 = 0.18$) with grain sizes in the range 63-75 μm, using a demagnetized 0.16 mT TRM ellipsoid, and a PSD fraction ($p_2 = 0.20$) with grain sizes between 13.1 and 25.5 μm, using a 0.16 mT TRM ellipsoid demagnetized to 50 mT (open and solid circles: correlations 1 and 2 respectively). TRM ellipsoids are compared to the susceptibility ellipsoids measured in the heated samples. For the same sample, an SD fraction ($p_3 = 0.03$) with grain sizes < 0.2 μm can be distinguished using ARM ellipsoids instead of TRMs (B.2b & c). In B.2b the p (susceptibility) - q (ARM) correlations are derived from undemagnetized and demagnetized (to 50 mT) 0.16 mT ARM ellipsoids (open and solid circles: correlations 1 and 2 respectively). In B.2c the same correlation is derived from a demagnetized (to 75 mT) 0.06 mT ARM ellipsoid.
Figure B.3a, b In B.3a, for sample 41, p (susceptibility) - q (TRM) correlations show a p, value of 0.25 for a demagnetized (to 50 mT) 0.16 mT TRM ellipsoid, and corresponding to magnetite grain sizes in the range 2.2-0.8 μm. In B.3b, for the same sample, p (susceptibility) - q (ARM) correlations derived from undemagnetized ARM ellipsoids induced at fields of 0.06 and 0.16 mT (open and solid circles; correlations 1 and 2 respectively). The values for the intercepts p, of 0.26 and 0.3 for the 0.06 and 0.16 mT ARM ellipsoids respectively, correspond to magnetite grain sizes less than 0.8 μm.
Figure B.4a, b In B.4a, for sample SH-2, the p (susceptibility) - q (TRM) correlation reveals a PSD fraction ($p_s=0.23$), with grain sizes in the range 2.2-4.4 $\mu$m, using undemagnetized and demagnetized (to 50 mT) 0.16 mT TRM ellipsoids (open and solid circles: correlations 1 and 2 respectively). For the same sample, B.4b shows the p (susceptibility) - q (ARM) correlations derived from undemagnetized and demagnetized (to 50 mT) 0.16 mT ARM ellipsoids. The value for the intercept $p_s$ of 0.27 corresponds to magnetite grain sizes in the range 0.2-0.8 $\mu$m.
Figure B.5a, b  In B.5a, for sample 16, the p (susceptibility) - q (TRM) correlation reveals a SD magnetic fraction with p=0.4 and a negative slope using undemagnetized and demagnetized (to 50 mT) 0.16 mT TRM ellipsoids (open and solid circles: correlations 1 and 2 respectively). For the same sample, B.5b shows the p (susceptibility) - q (ARM) correlations derived from undemagnetized and demagnetized (to 50 mT) 0.16 mT ARM ellipsoids (open and solid circles: correlations 1 and 2 respectively). Once more, the values for the intercept p, of 0.37 and the negative slope suggest SD magnetic grain sizes.